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Pacific Northwest
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Light Water Reactor Sustainability Program

Bulk and Distributed Electrical Cable Non-Destructive Examination Methods for Nuclear Power Plant Cable Aging Management Programs

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Bulk and Distributed Electrical Cable Non-Destructive Examination Methods for Nuclear Power Plant Cable Aging Management Programs

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SUMMARY

This Pacific Northwest National Laboratory milestone report describes progress to date on the investigation of nondestructive test methods focusing particularly on bulk and distributed electrical test methods that provide key indicators of cable aging and damage. The work includes a review of relevant literature as well as hands-on experimental verification of inspection capabilities.

As nuclear power plants consider applying for second, or subsequent, 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 will age during that time and develop aging management programs to assure continued safe operation under normal and design basis events (DBE). Normal component and system tests typically confirm the cables can perform their normal operational function. The focus of the cable test program, however, is directed toward the more demanding challenge of assuring the cable function under accident or DBE. The industry has adopted 50% elongation at break (EAB) relative to the un-aged cable condition as the acceptability standard. All tests are benchmarked against the cable EAB test. EAB, however, is a destructive test so the test programs must apply an array of other nondestructive examination (NDE) tests to assure or infer the overall set of cable's system integrity. Assessment of cable integrity is further complicated in many cases by vendor's use of dissimilar material for jacket and insulation. Frequently the jacket will degrade more rapidly than the underlying insulation. Although this can serve as an early alert to cable damage, direct test of the cable insulation without violating the protective jacket becomes problematic.

Most utilities already have a program associated with their first life extension from 40 to 60 years. Regrettably, there is neither a clear guideline nor a single NDE test that can assure cable function and integrity for all cables. Thankfully, however, practical implementation of a broad range of tests allows utilities to develop a practical program that assures cable function to a high degree.

A number of other local tests are available and are being used to varying degrees to corroborate electrical and/or visual tests. In many cases, this allows the cable to remain in service until replacement can be conveniently scheduled.

These cable NDE programs vary in rigor and methodology. As the industry gains experience with the efficacy of these programs, it is expected that implementation practice will converge to a more common approach. Generally speaking, however, these programs all include:

- A structured database of all cables within the plant and a specific subset of cables that are subject to regular testing.
- Visual walk-downs looking for indications of age-related degradation. The visual walk-down may be supplemented by examining the cables and cable environments with infrared cameras to identify higher temperature areas that may be subject to accelerated insulation aging. Although visual walk-downs can provide a good indication of the condition of readily accessible cable, much of a plant's cable is not readily viewable. If there are bulk and distributed electrical test indications of cable

issues, more aggressive visual inspections may be undertaken. Where to focus these efforts may be guided by understanding the chemical, thermal, and radiation environment along the cable path and indications from some bulk electrical tests.

- Bulk electrical tests constitute the largest part of most utility cable aging management programs. This is the focus of this report. These tests confirm or provide indications of proper electrical function of the cables and can provide early indication of insulation degradation. In some cases, the test can also indicate the location of potential damage or degradation. These tests include:
  - time domain reflectometry
  - monitored withstand and partial discharge
  - tan-delta
  - Megger resistance
  - frequency domain reflectometry (FDR)
  - dielectric spectroscopy.

This report addresses the range of bulk and distributed electrical NDE cable tests that are or could be practically implemented in a field-test situation with a particular focus on frequency domain reflectometry. The FDR test method offers numerous advantages over many other bulk electrical tests including:

- It is a low-voltage test and therefore completely nondestructive and relatively safe to perform.
- The test inherently indicates the location of any detected cable degradation.

Two commercial FDR systems plus a laboratory vector network analyzer are used to test an array of aged and unaged cables under identical conditions. Conclusions from the test include:

- FDR spectra among the three instruments for identical cable test configurations are similar but are not identical.
- Some cable (particularly unshielded cable) show greater noise in the FDR spectra than other cable. Although degradation indications may be observed in a cable test, segregating noise from age-related damage indications can be challenging and can be aided by trending.
- Because FDR spectra from different instruments are subtly different, trend data may be more sensitive if the same type of instrument is used.
- FDR signals are complex to analyze. Both commercial systems examined had methods for normalizing the test results to aid in signal interpretation. Some form of signal normalization is recommended as a tool to aid in data interpretation.
- Direct FDR response spectra up to 100 MHz were possible for all three FDR systems. Generally speaking, lower frequencies can be used to test longer cables but higher frequencies (from 200 to 500 MHz) offered clearer indications of damaged areas as long as the cable end response could still be seen above the noise threshold.
- Pure FDR response spectra show reduced amplitude as the distance from the instrument connection point increases. This makes a simple threshold determination of any peak observed more difficult for analysts trying to interpret the FDR data. The two commercial systems also offered data presentation and normalization features to aid analysis.
- Global aging of a substantial cable length may not offer any clear FDR spectral peaks. The two commercial systems offered several metrics (overall capacitance, velocity factor, and Delta G) to assess global aging.

Knowledge gaps highlighted from this work are:

- Need for a better physics-based understanding to associate peaks in the FDR, TDR, and other distributed electrical test responses to better justify the tests and support more specific acceptance guidelines. One example is a specific understanding of the length of the damage as an absolute value or as a percent of the overall tested cable length.
- Dielectric spectroscopy and/or VLF Tan δ specific guidelines for low-voltage and unshielded cable tests similar to the guidelines already established for medium-voltage shielded cable.
- FDR responses identify locations of the most severe cable degradation but specific guidelines for dispositioning the cable as good, bad, subject to further investigation, or projections of remaining useful life are not available.
- New methods such as spread spectrum time domain reflectometry, nonlinear time domain reflectometry, and joint time-frequency-domain reflectometry were not specifically evaluated within this report except to note that literature references indicated promise and potential for improved cable testing. These methods should be considered as and if near-field deployable instrumentation becomes available.

Work continues to refine tests and simplify analysis (as for FDR tests), to evolve existing and new approaches, and to refine the guidelines to aid in final disposition of a broader set of cable conditions.

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ACRONYMS

AMP	Aging Management Program
AMS	Analysis and Measurement Services
CM	condition monitoring
CSPE	chlorosulphonated polyethylene (Hypalon)
DAC	damped alternating current
DBE	design basis event
DF	dissipation factor (alternate reference to tan δ)
DOE	U.S. Department of Energy
EAB	elongation at break
EMDA	Expanded Materials Degradation Assessment
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
FDR	frequency-domain reflectometry
FTIR	Fourier transform infrared (spectroscopy)
hipot	high potential
HV	high-voltage
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IAEA	International Atomic Energy Agency
IM	indenter modulus
K	Indenter relaxation coefficient
LIRA	line resonance analysis
LOCA	loss-of-coolant accident
LWRS	Light Water Reactor Sustainability Program
N	Newton (unit of force)
NDE	nondestructive evaluation
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PD	partial discharge
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
σ	compression indenter modulus
RTDR	reverse time domain reflectometry

SLR	subsequent license renewal
TDR	time domain reflectometry
TEM	transverse electromagnetic
TGA	thermogravimetric analysis
Uo	1 Uo is normal line voltage. 2 Uo is twice normal line voltage
VLF	very low frequency
VNA	vector network analyzer
XLPE	cross-linked polyethylene

1. OBJECTIVES

This Pacific Northwest National Laboratory (PNNL) milestone report describes progress to date on the investigation of nondestructive test methods focusing particularly on bulk and distributed electrical measurements that provide key indicators of cable aging and damage. The work includes a review of relevant literature as well as hands-on experimental verification of inspection capabilities. PNNL has developed capabilities for thermal, radiation, and combined thermal and radiation aging of small cable sample sets. Details of the aging facility and general laboratory test capabilities have been reported elsewhere (Glass et al. 2015) so this information is only noted as it relates to characterizing the inspection methods. Moreover, inspection methods are focused on approaches that can be deployed in-situ to nuclear power plants (NPPs).

The overall objectives of this project are to develop the technical basis for assessing the level and impact of cable insulation aging and degradation in NPPs. In July 2012, a workshop (Simmons et al. 2012) was held to lay the groundwork for a research and development roadmap to address aging cable management in NPPs, including methods for nondestructively measuring the condition of aging cables. The project addresses the overall gaps that were identified at the workshop in FY2012 using a phased approach. This phased approach addresses the three areas identified from the workshop:

1. Determination of key indicators of cable aging. This has largely been addressed in earlier reports (Simmons et al. 2014; Fifield et al. 2015; Ramuhalli et al. 2015).
2. Characterize and advance current nondestructive evaluation (NDE) methods and develop new NDE methods by using insights from the determination of key indicators. This activity was generally addressed by (Glass et al. 2015) describing the overall state of the art for both bulk electrical tests and local tests. A more focused report was prepared to address local NDE cable tests (Glass et al. 2016). This separate 2016 report addresses bulk electrical tests.
3. Develop models that use the advances in key indicators and NDE methods to assist in predicting remaining life of cables—ongoing.

This report is submitted in fulfillment of deliverable M2LW-16OR0404023 – Evaluation of Bulk and Distributed Electrical Test Methods for Nuclear Power Plant Cable Aging Management Programs.

2. INTRODUCTION AND BACKGROUND

As NPPs consider applying for second, or subsequent, license renewal (SLR) 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 will age during that time and develop aging management programs (AMPs) to assure continued safe operation under normal and design-basis events (DBE).

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 (EPRI 2015; Mantey 2015). 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. License renewal to 60 years and subsequent license renewal to 80 years, therefore, requires a cable AMP in accordance with regulatory guidance (NRC 2012) to justify cable performance under normal operation as well as accident conditions.

The aging of insulation and jacketing material in electrical and instrumentation cables is considered to be one of the factors that may limit the ability of light water reactors to continue operations beyond their licensed period (up to 60 and 80 years, depending on the specific plant). The focus for cable SLR qualification is the continued ability to withstand a DBE. Aging and subsequent degradation of insulation will impair the ability of cables to perform their function under all environmental conditions. Methods to nondestructively assess the level of aging and degradation in cable insulation and jacketing materials are therefore needed. In addition to providing an estimate of the level of aging and degradation, such condition assessment or condition monitoring (CM) methods for cable insulation can also provide critical inputs into condition-based qualification approaches, assess corresponding remaining useful qualified life of the cable, and ensure that the cables do not exceed a qualified level of degradation.

The U.S. Nuclear Regulatory Commission (NRC) commissioned the U.S. Department of Energy (DOE) to perform a detailed analysis of NPP material aging in this context. The results of this analysis, the Expanded Materials Degradation Assessment (EMDA) have been published in five volumes. The first provides a summary of the analysis process and results. The second through fourth volumes focus on the aging of individual systems of concern including core internals and piping systems, reactor pressure vessels, and concrete and civil structures. The fifth volume (NRC 2013) considers the aging of cable and cable systems. It identifies age-related degradation scenarios that could be important to the use of NPP electrical cable components over an 80-year timeframe and identifies issues for which enhanced aging management guidance may be warranted.

In July 2012, a workshop (Simmons et al. 2012) was held to lay the groundwork for a research and development roadmap to address aging cable management in NPPs, including methods for nondestructively measuring the condition of aging cables. This workshop brought together subject matter experts from the NRC, DOE national laboratories, the Electric Power Research Institute (EPRI), universities, and cable manufacturers and inspectors. The workshop focused on identifying key research needs in the NDE of aging cable insulation in NPPs and the associated technical gaps. Identifying measurable quantities due to changes in chemical structure of insulating materials that would be a precursor to eventual failure of an aging cable, and the current state-of-the-art in NDE methods that could be applied to estimate the remaining life of the cable, were determined to be key to addressing the aging management challenge for nuclear cables. The development of new NDE methods or development of new measurement techniques using existing NDE methods that target these types of changes is of significant interest. Further, the ability to perform nondestructive tests to determine chemical, physical, mechanical, and electrical properties of the cable jackets and insulation without significant disturbance of the cables and connectors as they lay in situ is essential. This cable aging management program is sponsored by

DOE under the Light Water Reactor Sustainability (LWRS) program to address knowledge and technique gaps to support the evolution of industry cable AMPs. Cable NDE methods comprise one topic of ongoing coordination and communication efforts on aging NPP cable research between the DOE, NRC, EPRI, and Iowa State University. Coordination of efforts helps to minimize duplication in research and to ensure that prioritized knowledge gaps are addressed.

Acceptance criteria that define the threshold for degradation below which cables may continue to be used are a challenge, because it is impractical to subject each cable system to loss-of-coolant accident (LOCA) or seismic simulation events following 40+ years of service. The report *Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets* (EPRI 2005) develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers. The report describes 50 percent elongation at break (EAB) as a conservative practical end-of-life threshold for cables that may be stressed during maintenance or subjected to LOCA exposure. The report also discusses the basis for cautious continued use of cables beyond the 50-percent EAB threshold. EAB inherently compromises the in-service cable use as it is a destructive ex-situ test so the challenge is to develop NDE methods that can reasonably be correlated with EAB. Reliable NDE in-situ approaches are needed to objectively determine the suitability of installed cables for continued service. A variety of tests are available to assess various aspects of electrical and mechanical cable performance, but none of the available tests are suitable for all cable configurations nor does any single test assess all features of interest. Nevertheless, the complete collection of test possibilities offers a powerful range of tools to assure the integrity of critical cables.

Cable test technologies may generally be divided into:

1. Bulk/distributed electrical measurements [resistance or impedance measurements, high voltage withstand tests, Tan δ (dissipation factor), time domain reflectometry, frequency domain reflectometry, partial discharge, and other techniques]. These tests are administered in-situ from the cable termination ends and test the full length of the cable. Normally both ends of the cable are isolated from the supply or from the indicating instrument and from the motor, actuator, or sensor to perform the test.

2. Local insulation measurements that include visual or optical inspection, indenter, infrared, or near infrared spectral measurement.

3. Laboratory sample tests – Virtually all local and bulk and distributed electrical NDE tests may be applied in a laboratory environment if the cable can be moved to that environment; however, the laboratory environment offers some additional test possibilities that are not practical to perform on in-situ cables. In order for these tests to aid the utilities in dispositioning in-service cables, these tests require samples from surrogate cables that may have been left in place but are no longer in service (rare) or a section of the actual in-service cable may be sampled, followed by a splice or termination repair. Such tests include EAB, oxidation induction time and temperature (evaluates loss of anti-oxidant compounds), insulation density measurement, temperature at maximum rate of weight loss and activation energy measurements using a thermogravimetric analyzer (TGA), swelling ratio and gel fraction measurements, atomic force microscope for micro-scale visco-elastic properties, nuclear magnetic resonance, and Fourier transform infrared spectroscopy. These tests are mentioned but are not addressed further in this report. Such tests can be useful to characterize general plant cable aging behavior, but their destructive nature and impracticality for field application makes them impractical for justifying continued use of in-service cables.

Cable test motivations may be grouped as follows:

4. Factory in-process and post manufacture acceptance test. These tests are designed to confirm the quality of the manufactured cable and catch any quality issues prior to releasing the cable to the ultimate customer.

5. Post-installation tests that prove the cable is fit for service and has not been damaged during installation.
6. Condition monitoring associated with the cable AMP. The primary focus here is to determine if the cable is currently acceptable and is expected to continue to be acceptable for a period of time. Usually the units or increments of time of interest are the number of operating/refueling cycle periods (typically 2 years).
7. Troubleshooting tests to determine the nature and location of degradation and to assess whether repair is possible or if replacement is necessary.
8. Failure and forensics assessments to identify reasons for failure or degradation and recommend mitigation or corrective action on similar applications and circuits.

3. CABLE AGING MANAGEMENT PROGRAM GUIDELINES

Cable safety factors offer significant margin for normal operation and consequently most cables can be expected to perform satisfactorily under normal loads. Cables are inherently tested as part of the regular system tests that are periodically performed on nuclear plant systems and active components. As emphasized in Regulatory Guide 1.218 (NRC 2012), cable aging management programs focus on the ability of cables to withstand the extreme stresses that may be experienced in a DBE and that may not be addressed with normal system tests. Degradation of electrical insulation and other cable components are key issues that are likely to affect the ability of currently installed cables to operate safely and reliably for another 20 to 40 years beyond the initial qualified operating life under a DBE. Although cable failures are rare, when they occur, the event can be dramatic; and if they involve critical safety systems, those systems are likely not to be available to the plant following cable failure.

Considering the extensive lengths, types, and integration of cables in a typical NPP, it would be a daunting undertaking to regularly inspect all of the cables. Licensees and regulators, however, are generally agreed that an aging cable management program can be developed to justify continued safe operation based on CM tests to reasonably assure the cables will perform their required function. Practical guidelines have been developed and are evolving in the United States and internationally that offer a manageable approach to sampling and screening cables based on accessibility, risk, history, and other factors. These include:

- NUREG/CR-7000, BNL-NUREG 90318-2009, *Essential Elements of an Electric Cable Condition Monitoring Program* (Villaran and Lofaro 2010)
- Regulatory Guide 1.218, *Condition-Monitoring Techniques for Electric Cables Used in Nuclear Power* (NRC 2012)
- NP-T-3.6, *Assessing and Managing Cable Aging in Nuclear Power Plants* (IAEA 2012)
- EPRI Low-Voltage Cable Aging Management Course (workbook) (updated 2015)[(a)]
- EPRI Technical Report 3002000557, *Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Revision 1* (Mantey and Toman 2013)
- *ADVANCE – Publishable Summary – Ageing Diagnostics and Prognostics of Low-Voltage I&C Cables*, Collaborative Project led by Electricity de France (ADVANCE 2013)
- Draft Regulatory Guide 1240, *Condition Monitoring Program for Electric Cables Used in Nuclear Power Plants* (NRC 2010)

Common themes from these reports include the following points:

- **CM assessment to estimate design margins under DBE**: The integrity and function of power, instrumentation, and control cables are monitored indirectly through the performance of in-service operability testing of safety-related systems and components. These tests can demonstrate the function of the cables under normal operating test conditions. However, such operability tests do not provide assurance that cables will continue to perform successfully when they are called upon to operate fully loaded for extended periods as they would under normal service operating conditions or under DBE conditions.
- **Multiple complementary test approaches**: A number of test approaches must be employed to reasonably assure the safe operation under the test condition and, by inference, safe operation under a DBE.

(a) EPRI. 2015. *Low-Voltage Cable Aging Management Course (workbook)*. Electric Power Research Institute, Palo Alto, California.

- **Continued operation based on condition monitoring**: The basis for justifying aged cables should be periodic condition testing. This is commonly referred to as monitoring and normally does not mean continuous monitoring. This is a practical way to assure cables are performing as designed, thereby justifying leaving them in service after their initial planned useful life.
- **Bulk/distributed electrical and local tests**: Bulk/distributed electrical end-to-end testing of a cable is preferred, but it is possible and even likely that cable condition can be locally masked by splices, blind spots at termination ends, etc. Bulk methods evaluate the whole cable as a single entity. Distributed methods (TDR, FDR, and partial discharge) evaluate all along the cable and support localization of any damage indication. Test tools can and should include both bulk/distributed and local tests.
- **Localization of damage**: Localization of areas of concern is important because practical management of areas of degradation may involve local tests, cable splices, and repair rather than replacement of a full cable length.
- **Structured program for aging cable management**: Although the same basic program elements are recommended from most of the above documents, NUREG/CR-7000 (Villaran and Lofaro 2010) outlines a clear nine-step aging management condition-based qualification approach.

4. CABLE DESIGN, CLASSIFICATION, AND LAYOUT

NPP cable designs typically include a conductor to carry power, instrumentation or control signals, and an insulating cover layer to isolate the conductor (Figure 4.1). They may include more than one insulated conductor within a bundle. Other components typically associated with the overall cable design include a semiconductor screen, a shield over each conductor, and/or over all conductors, binder tape, and a jacket. While the insulation provides electrical isolation, in jacketed cable configurations the jacket mainly serves to provide mechanical protection during installation and sometimes fire or moisture resistance depending on the cable construction. The materials for cable components are chosen based on the use environment, such as wet, dry, radiation, or sunlit conditions, and the application such as for power or instrumentation. Conductors, made from copper, aluminum, or tin, are relatively insensitive to age and related damage. Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) compose the vast majority of insulation materials in the nuclear industry, with silicone rubber also being of interest. The most significant jacket materials are chlorosulphonated polyethylene (CSPE – also known as Hypalon® [registered trademark of DuPont]), polychloroprene, and poly vinyl chloride (PVC). While installed cables with intact insulation may well be able to continue to provide safe operation with degraded jacket material, the tendency of jacketing materials to degrade more readily than insulation materials enables their use as lead indicators for local stress prior to insulation degradation and failure.

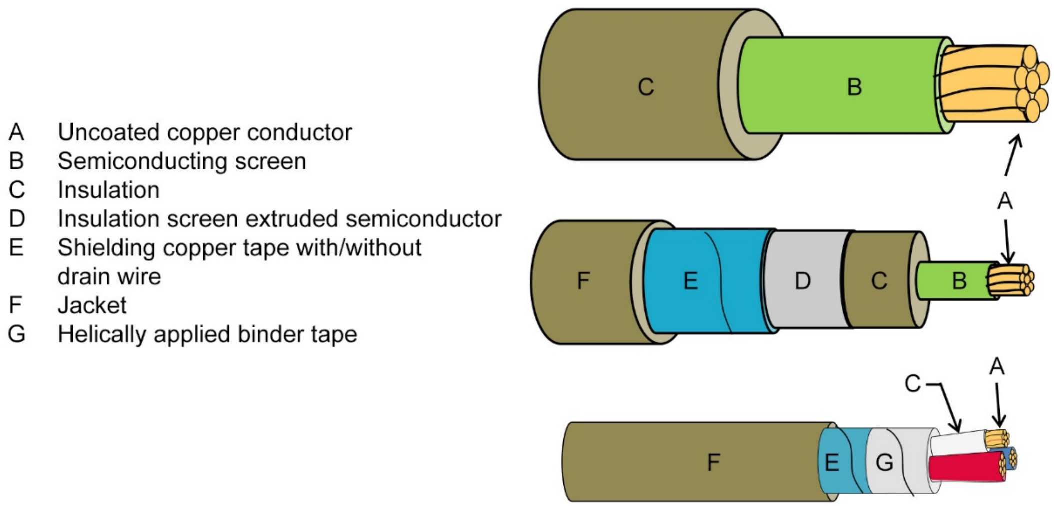


Figure 4.1. Configurations of typical cable designs used in NPPs.

A survey performed by EPRI in the mid-1990s established a representative distribution of insulation materials within the U.S. nuclear fleet (EPRI 1994) (see Table 4.1). Note that over 70 percent of the materials are XLPE or EPR.

Table 4.1. A Sort of Insulation Material for U.S. NPPs (from EPRI 1994)

Insulation Material	Database Entries	Percent of Total (%)	Insulation Material	Database Entries	Percent of Total (%)
XLPE	439	36	ETFE	39	3
EPR	434	36	Flame retardant	36	3
Silicone Rubber	63	5	CSPE	28	2
Kerite	61	5	Butyl rubber	20	2
Polyethylene	52	5	All others		Each ≤ 1%

Numerous standards have been developed over the years to group and categorize cables based on application, voltage, environment, and basic design type (Table 4.2). Exactly what grouping is used depends on the application but for cable aging management, generally the nuclear industry has focused on medium- and low-voltage cables. Low-voltage cables constitute the majority of NPP cables but many safety-critical cables exposed to moisture are medium-voltage cables. Most plants have a rigorous program to test and verify performance of safety-critical medium-voltage cables. Cable CM programs are encouraged through NRC's Draft Regulatory Guide 1240 (NRC 2010) with particular emphasis on medium-voltage cables citing examples of cable failures particularly for wet environment cables. Although this is not currently a required program, it is encouraged by the NRC "*to promote discussion between staff and licensees when a facility's operating experience indicates cable failure or degraded cable performance as a causal factor. The NRC staff will use this guidance to evaluate compliance with the Maintenance Rule*."

Table 4.2. Categories of Cable Grouping

Application	Voltage	Environment	Design
Power	Low (≤2 KV)	Normal operating temperature	Single/multi-conductor
Control	Medium (≤2–46 KV)	High temperature	Triplex
Instrument	High (>46 KV)	Fire/flame retardant	Thermocouple alloys
Thermocouple		High radiation	Coaxial
Communication		Submerged – water	Shielded/unshielded (and shield type – tape, braid, …)
Specialty Configuration		Aggressive solvents	Special jacket
Safety Related			Conductor/shield material (copper, tinned copper, aluminum, …)
Non-Safety Related			Insulation/jacket material (XLPE, EPR, PVC, …)

Cable termination and splice kits also represent sensitive sites for cable system failure. Designs include screw-clamp or crimp-clamp connections between the conductor and the solid metal part of the splice or terminations usually coupled with an insulating shrink-wrap or tape to seal and electrically isolate the metal parts. With respect to wet or dry aging, splices and terminations are expected to have very long lives if they are made in accordance with manufacturers recommended procedures. This means that crimps and bolted connections have been made properly and that the tapes have been properly applied to the correct thickness and with the appropriate tension, or that heat-shrink materials have been properly applied and completely shrunk in place. Given that no voids exist, the splice and termination insulation is thicker than that of the cable and generally has ratings equal to or greater than the cable insulation. Generally when splices or terminations fail, it is because of an installation error. Such errors include inadequate removal of semiconducting layers, cuts to the insulation under the splice, voids from inadequate taping or heat-shrink practices, and/or the presence of dirt in the splice layers. If mechanical metal-metal connections are not made properly, the connections can loosen over time thereby increasing the connection resistance due to vibration and/or corrosion based contact-force loss. Many of these workmanship related failures do not occur on initial energization and may take years to manifest themselves in a cable failure.

This aspect of the cable design has been studied and these junctions have been subjected to aging and LOCA performance tests (Lofaro and Villaran 2002) similar to the full tests. In fact, some form of termination must be included in the full cable tests. In addition, these cable terminations are subject to workmanship-based performance issues and are carefully considered as potential failure points during periodic CM activity. As a practical matter, whenever cables need to be de-terminated for testing, new termination kits are frequently applied. Because of the bulk of larger diameter cables and practical reel size limitations, splices may be necessary for long cable runs. The main concern for power connections is that a high-resistance connection does not occur. Infrared (IR)-camera thermographic-aided visual inspections are frequently employed to determine if problems (hot spots) exist. Such overheating can cause the insulation and connection tape or heat-shrink to degrade or the connection to burn open over time.

Cable layout in typical plants is not designed to facilitate access and inspection of much of the cable lengths. Cable trays and conduits are designed to protect the cables from environmental stresses as well as accidental damage from workers and equipment that may be moving either inside containment, auxiliary buildings, or control buildings. While cable ends are generally accessible at termination boxes and control panels, many cables are grouped together with other cables in trays that do not necessarily follow personnel access pathways, pass through penetration pipes and conduits that may be buried in concrete, under-ground, or even passing through areas that may be flooded (Figure 4.2).

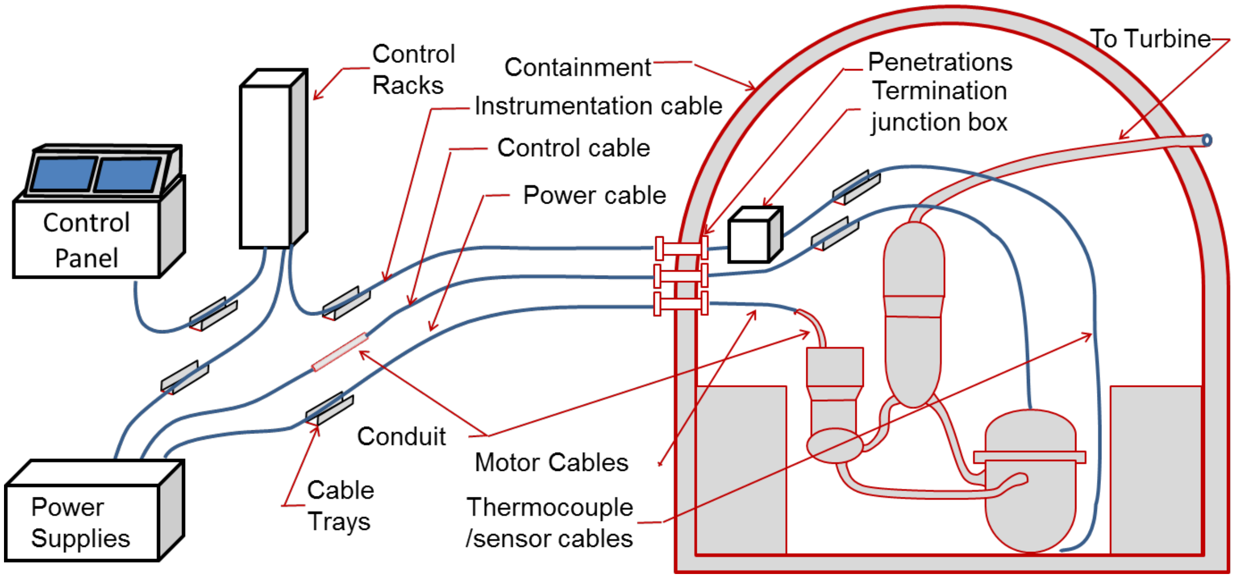


Figure 4.2. Typical cable layout allows access at control racks and termination junction boxes but much of the cable is protected within cable trays and conduit thereby limiting access for local inspections.

5. AGING AND ACCELERATED AGING

Stressors leading to cable degradation can generally be divided into three groups (Lindsay and Benson 2012):

- Environmental: radiation, heat, moisture, chemical, etc.
- Operational: high voltage, electrical transients, ohmic heating, flexing/vibration, mechanical damage, etc.
- Error-induced damage from inappropriate design/selection for the given environmental or operational stressors above, manufacturing, or maintenance deficiencies.

When CM techniques are being applied to evaluate cable condition, consideration of the stressors can be important to point out where to look and what to look for, but the tests are sensitive to changes in the cable material characteristics. These changes can generally be considered as follows:

- Various insulation and jacket polymers (XLPE, EPR, PVC) subject to elevated temperature from ohmic heating of the conductor, radiant or ambient acting on the outside of the insulation and jacket, water or chemical attack from the cable exterior, and/or radiation are prone to embrittlement, cracking, decrease in dielectric strength, increased leakage current, reduction in structural integrity, and susceptibility to intrusion of moisture or contaminants.
- PVCs (mostly related to jackets) are also subject to hydrogen chloride evolution and salt formation resulting from wet environments that can reduce dielectric strength and increase leakage currents. Because PVCs are rarely used for insulation however, this may be only a cosmetic issue limited to the jacket.
- Various insulation and jacket polymers are also subject to wetting and moisture intrusion in the form of "water trees" resulting in decreased dielectric strength and increased leakage currents.
- Copper conductors subjected to wetting may experience corrosion resulting in increased electrical resistance and corresponding ohmic heating that may accentuate the corrosion process.
- Various insulation and jacket polymers are subject to handling, physical contact abuse during maintenance, operation, or testing that may result in crushing, cracking, scuffing, cutting, bending deformation, etc. and may result in visually observed damage, reduced dielectric strength, and increased leakage current.

PNNL has developed (Glass et al. 2015):

- extensive capabilities for controlled accelerated aging of cable samples
- laboratory measurements of cable and particularly insulation characteristics, and
- a collection of laboratory and in-situ techniques that may be applied to cable CM assessment.

The principal concerns for adverse environments experienced by polymer insulated/jacketed electrical cables in the NPPs are elevated temperature, gamma radiation exposure, and the presence of moisture or other chemical environmental stress. Typical NPP temperatures and dose environments allow the cable to operate for 40+ years before material degradation is of sufficient concern to warrant specific tests and repair or replacement if necessary. Because it is not practical to wait 40+ years for suitably aged samples, the ability to accelerate aging is essential to the program. A series of aging ovens has been acquired with room to house either racks of samples inside or support pass-through intact cables. In addition, PNNL has a Co-60 gamma radiation facility that can subject samples to up to 1 kGy/hr. The facility can also combine the ovens and the radiation test source for combined thermal and radiation aging. The capability to specify both temperature and dose rate during sample preparation enables PNNL to address knowledge gaps in the understanding of degradation from combined exposure including synergistic effects and inverse temperature effects. These facilities have been used to generate the representative aged samples where PNNL and PNNL collaborators have performed verification or demonstration CM measurements.

6. ELECTRICAL SAFETY

This report is not intended as a specific procedure for performing any cable test. Such tests must be performed by technicians specifically trained in the test method as well as general good practice for performing work around electrical cables and other components. However, readers of this material should be mindful of best practice behavior and procedures for performing work related to cable testing. These best-practice behaviors include (UAW 2008):

- **De-energize**: Both the circuit one is working on/with as well as any circuits in close proximity to systems being tested should be de-energized.
- **Tagging and lock-out**: Any de-energized circuit should be tagged and locked out to prevent accidental re-energizing during the test. If conductors are de-terminated, they should also be clearly labeled to facilitate correct re-connection.
- **Protective personal equipment (gloves, boots, glasses, etc.)**: Protective personal equipment (PPE) should be worn as recommended for protection from both electrical and mechanical injury when working with cables. Recommended best practice includes careful inspection to assure no holes or defects in the PPE.
- **Insulated and shrouded test leads**: Most cable tests involve connections to conductors or shields with test leads. Such test leads should be insulated and protected from contact with adjacent circuits.
- **Clip on leads so focus can be on instrument**: Also if using pointed probes rather than clip leads, some probes have a remote capture button to allow reading capture without returning to the meter or shifting eye-focus to the meter.
- **Try to work with one hand in pocket**: This minimizes the chance that any accidental shock current path will pass through the heart and correspondingly minimizes the likelihood of a fatal injury.
- **Ground/discharge all conductors to ground**: This is particularly relevant to high potential (hipot) tests where high potential charges that may even be above the normal rated cable voltages are applied. Such potentials not only pose a safety hazard but may also adversely affect test instruments and tests of test object or adjacent cables.

7. RESISTANCE/IMPEDANCE TESTS

7.1 Low-Voltage, Low-Cost Multi-Meter Resistance Test

A non-faulted 600V rated cable should have an insulation resistance of 16 MΩ per 1000 ft. (305 MΩ/km) between conductors and from each conductor to ground (IEEE Std 525-2007). Actual resistance values will depend on temperature, moisture, and the specific cable being tested, as well as the influence of mechanical, environmental, or age-related damage. The multimeter test is likely to be useful as a first indication of a cable's condition. It requires only a simple battery-operated multimeter or volt-ohm meter commonly carried by plant electrical technicians. The applied voltage is typically ~10 VDC or less thereby presenting little or no safety hazard to test personnel or to most circuits being tested; however, this also does not represent a significant challenge to the cable insulation. Such a test would be expected to detect shorts and severely degraded insulation but may not detect subtle degradations that will only show with a high-voltage (HV) test or more sensitive reflectometry tests. The test is typically performed on a de-energized wire that has been de-terminated on both ends of the cable. Each insulated conductor should be tested separately and the results recorded. For a three-phase cable containing insulated conductors (A, B, and C) with a bare ground (G) the suggested tests would be:

- A to B
- B to C
- C to A
- A to G
- B to G
- C to G.

Expected resistance values would be in excess of those recommended from IEEE Standard 525 as shown in Table 7.1 (IEEE Std 525-2007).

Table 7.1. Minimum Acceptable Insulation Resistance for 600V Cable, from 100 to 1000 feet (from IEEE 515)

Length of Cable		Min. Acceptable Resistance Value, MΩ	Length of Cable		Min. Acceptable Resistance Value, MΩ
Meters	Feet		Meters	Feet	
30.5	100	16	183	600	2.7
61.0	200	8	213	700	2.3
91.4	300	5.3	244	800	1.8
122	400	4	274	900	1.8
152	500	3.2	305	1000	1.6

Table 7.2. Advantages and Disadvantages of Simple Multimeter Resistance Test

Advantages	• Low voltage safe test that can be implemented easily with inexpensive meter
Disadvantages	• Does not really challenge insulation. Only suitable for detecting gross failures or shorts. • Does not constitute a bonafide cable function verification

7.2 Simple Withstand Tests

Similarly to the low-voltage test discussed above, the insulation resistance measurement can be performed at a higher voltage where the insulation is challenged. The simple withstand test is applied for a fixed period and results in a pass/fail disposition of the cable (Figure 7.1). If the cable system continues to function with negligible leakage current among the potential current paths, the system is deemed to pass. Voltage levels are typically 1.5 to 3 Uo voltage levels where Uo represents the rated operating voltage. If the cable fails and the cable damage is limited, the cable may be spliced or repaired and the simple withstand test repeated until the cable system passes. The simple withstand tests are typically applied with the cable system off-line and de-terminated at both ends. The voltage may be applied in a number of different ways as discussed below.

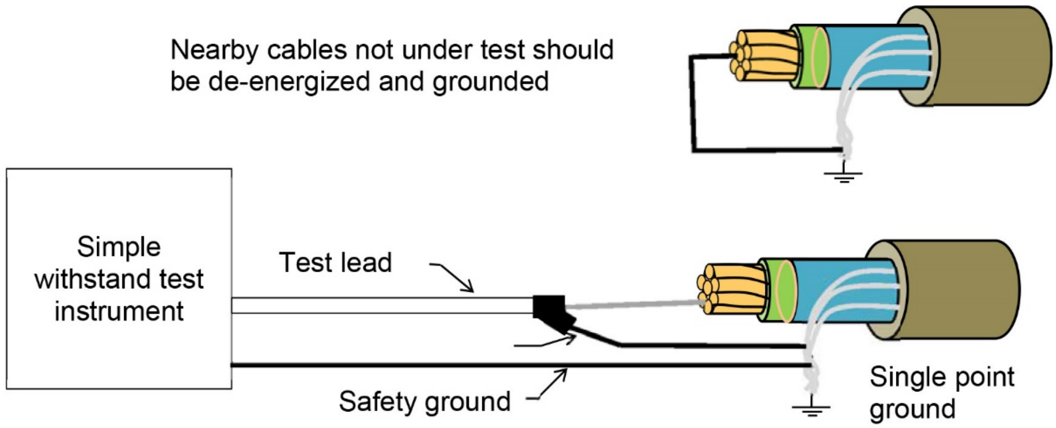


Figure 7.1. Simple withstand connection configuration for shielded cable with drain wire.

7.2.1 Direct Current Hipot Simple Withstand Test

The direct current (DC) hipot simple withstand test applies a DC potential from conductor to conductor for a period of time. This is commonly referred to as a Megger test. This name is either a reference to the expected outcome where resistance values will be in the multi-meg-ohm range or a reference to a well-known company named Megger, which sells instruments specifically designed for HV cable and motor resistance tests.

Tests are typically performed first at or close to the rated line voltage (Uo) and then at 1.5 × Uo to 3 × Uo. The voltage applied is typically a DC voltage applied for 15–60 minutes depending on the specific guideline and test procedure being applied. For a good cable, the initial resistance reading will be somewhat lower than the steady-state reading achieved after approximately one minute or less due to the initial capacitive leakage current. Smaller systems with shorter lengths of wire will have smaller capacitive and absorption currents and so will reach steady-state more quickly than larger wire systems. If the nominal resistance value starts to drop following the initial reading, this is indicative of increasing leakage current and the insulation beginning to fail. If the DC hipot test is intended to be a nondestructive test, the test should be terminated as soon as the drop in impedance is detected, and continued use of the cable system should be exercised with caution and appreciation that the system failed the test. DC hipot testing is typically performed during or following installation. Such tests are intended to reveal improper installations or mechanical damage and are not well suited to reveal deterioration due to in-service aging.

Although DC hipot tests have been the historical standard way to test cable systems, the majority of cable manufacturers have discontinued use of high-voltage direct current (HVDC) withstand in production tests. There is evidence that DC testing—particularly of aged XLPE—can lead to early cable failures. High DC voltages can create space charge accumulation in extruded materials if local electrical stresses exceed 10 kV/mm. Application of HVDC on aged XLPE cables can cause the cable to fail prematurely after returning to service (IEEE Std 400-2012). Advantages and disadvantages are summarized in Table 7.3.

Table 7.3. DC Hipot Test / DC Leakage Current Test Advantages and Disadvantages

Advantages	• Easy to deploy. Equipment is relatively low cost, portable, and simple. • Long history for medium/high-voltage shielded cables (this is now less popular) • The test can be automated
Disadvantages	• Duration of voltage application is not well established. Typically 15–60 minutes. • High (higher than operating) DC voltages can create space charge accumulation that can cause the cable to prematurely fail after returning to service • Before and after each test, cable should be completely discharged. The time required for complete discharge can be four times the test duration or longer.

7.2.2 HVAC Simple Withstand Test

Alternating current (AC) withstand testing or high-voltage AC (HVAC) represents similar voltage stresses that the cable would experience under service conditions (Gockenbach and Hauschild 2000). This type of sinusoidal waveform testing was introduced near the end of the 1980s as an alternative to DC test voltages. Mechanical defects as well as water trees reduce the breakdown voltage at DC to 0.1 Hz more than at 20 to 300 Hz so in this sense, the DC and very low frequency (VLF) tests impose a more severe stress on the cable than the HVAC test at the same voltage level. For on-site tests, frequency-tuned resonant test systems are recommended because they have a good weight-to-test power ratio and comparatively lower power demands. The power demands and size of the test generating equipment, however, have limited applications of this test approach (Table 7.4).

Table 7.4. HVAC Withstand Test Advantages and Disadvantages

Advantages	• Test waveform is comparable to operating frequency waveform • Less likely to induce damage than VLF or DC withstand tests at same voltage
Disadvantages	• Test equipment (frequency generators and transformers) are large and may demand high power • Test voltages are above rated line voltage so there is a chance of insulation degradation • Long cable lengths are difficult to test

7.2.3 Damped AC Simple Withstand Test

A damped AC (DAC) withstand test offers an alternative solution to a continuous AC withstand test whereby the resonant frequency of the inductive/capacitive circuit offers a similar frequency challenge to the cable without requiring the large high-power continuous excitation system. Damped alternating voltages are generated by charging the test object to a predetermined voltage level and then discharging the test object’s capacitance through a suitable inductance (IEEE Std 400.4-2015). During the charging stage, the test object is subjected to a continuously increasing voltage at a rate dependent on the test object and, during the discharging stage, an under-damped AC voltage at a frequency dependent on the test object and the inductance. The test circuit consists of a HV direct voltage source, an inductor, a capacitor, and a suitable switch. When the charging voltage is reached the switch is closed, generating on the test object a damped alternating voltage (Figure 7.2).

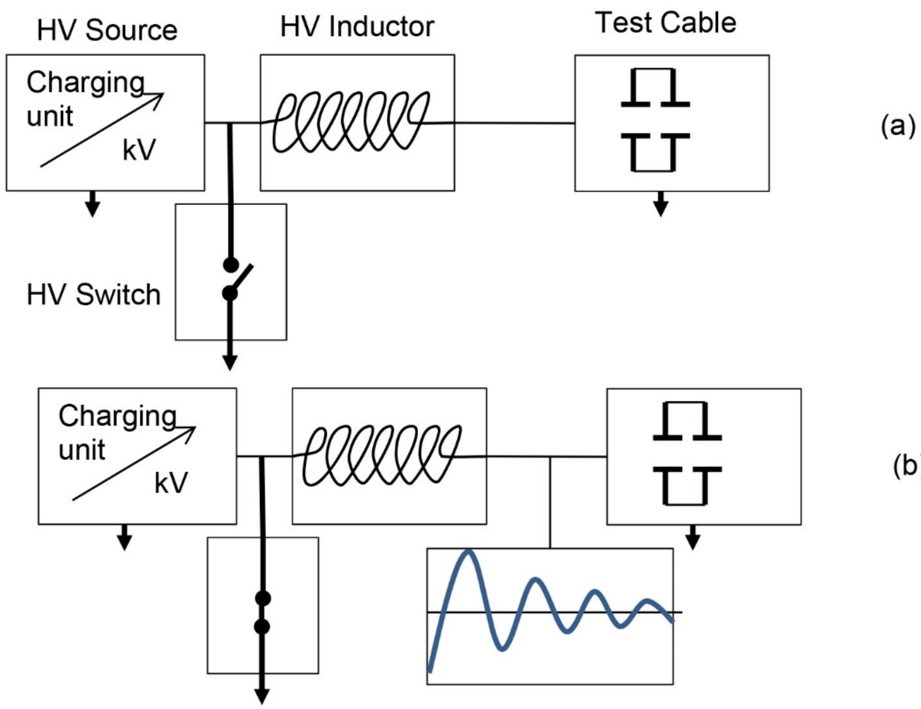


Figure 7.2. Schematic overview of DAC test circuit: (a) charging phase; (b) LC oscillation phase.

Table 7.5. DAC Advantages and Disadvantages

Advantages	• Compact test instrument comparable to DC or VLF circuits • Results are generally comparable to 50/60 Hz test results
Disadvantages	• Voltage breakdown field strengths can be different from continuous AC and may be difficult to precisely assess due to the signal's transient nature and variable voltage as the signal propagates along the cable • Fixed inductor coupled with variable cable capacitance results in natural frequency variation • Difficult for short cables and/or requires additional capacitive load • This test is typically reserved for 5 kV cable and above

7.3 Monitored Withstand with VLF and Tan δ

A monitored test measures subtle current changes indicative of insulation leakage current that would lead to cable insulation failure if allowed to proceed uninterrupted to completion. Because of these early indications, the test may be stopped before the cable actually fails. Moreover, at the end of the test, the data provides indications that the cable system is either in acceptable condition or the cable may be approaching failure. This is in clear contrast to simple withstand tests where there is little or no indication of whether the cable is in good condition or has just barely passed the test and is on the verge of failing.

7.3.1 VLF with Tan Delta

The very low frequency HV withstand test provides an alternative to the AC or DAC tests discussed above. VLF is typically defined as 0.1 to 1.0 Hz and the approach is typically used on medium- and high-voltage shielded cable systems. VLF tests can be applied as a simple withstand test but most modern VLF systems are available as a monitored withstand test where both voltage and current are monitored. Specific guidelines for such cable system tests are addressed in IEEE Standard 400.2-2013. The approach may also be used on low voltage and unshielded cables; however, this is less common and is not specifically addressed by an IEEE test guide as yet. Moreover, specific acceptance levels are not established as with the medium and high voltage shielded cables.

Excitation varies from instrument vendor to vendor and instrument to instrument. IEEE Standard 400.2-2013 addresses both sinusoidal and cosine-rectangular excitation and divides the test criteria into: installation, acceptance, and maintenance phase-to-ground test thresholds relative to the cable system phase-to-phase rating (in kV). Generally test criteria levels are:

• Installation 2–3 × Uo; • Acceptance 2–3 × Uo; • Maintenance 1.5–2 × Uo

For the tan delta (tan δ) test (alternatively referred to as dissipation factor [DF] or power factor), the specific monitored parameter is the ratio of the capacitive-to-resistive current or the tangent of the δ angle shown in Figure 7.3. The tan δ technique can be derived from one of Maxwell's four equations, which relates the magnetic field intensity to the electric field intensity. Expressed in phasor form, the equation contains the relationship between the conduction current density ($\sigma\mathcal{E}$) and the displacement current density ($j\omega\varepsilon'$) for dielectric materials.

$$\nabla \times \mathcal{H} = \sigma\mathcal{E} + j\omega\varepsilon'\mathcal{E}\left(\mathrm{Am}^{-2}\right) \tag{7.1}$$

where: $\mathcal{H}$ = magnetic field intensity (A/m)
$\mathcal{E}$ = electric field intensity (V/m)
σ = conductivity (℧/m)
ω = angular frequency (rad/sec)
ε' = real portion of the complex permittivity where $\varepsilon = \varepsilon' - j\varepsilon''$ (F/m)

The relative permittivity ε_r describes how a specific material will interact with an applied electric field. Known as the dielectric constant of the material, it is derived from the permittivity of free space $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m where $\varepsilon = \varepsilon_r \varepsilon_0$.

This complex permittivity can therefore be written as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ and shown on a simple vector diagram.

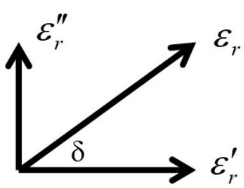


Figure 7.3. Phasor relationship between the real and imaginary components of permittivity.

The tangent of the angle δ between them is the ratio of these two vector quantities and is a measure of the ratio of energy from the applied electric field that is stored in a specific material to the amount dissipated or lost. This quantity is known as the loss tangent and defined as:

$$\mathrm{Tan}\ \delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{7.2}$$

The cable to be tested must be de-energized and each end disconnected and isolated. The network analysis is normally between the conductor and the shield but the measurement may be made from one conductor to another. Using a VLF (0.1 to 1 Hz) AC hipot exciter, the test voltage is applied to the cable while the tan δ controller takes measurements. Typically, the applied test voltage is raised in steps, with measurements first taken up to 1 Uo, or normal line to ground operating voltage. If the tan δ values indicate good cable insulation (i.e., very little change or a steady change as the voltage is increased up to 1.5–2 Uo), the test is continued to completion. If a knee or inflection in the current is noted as the voltage is increased, the test engineer may stop the test because a cable failure is indicated.

Commercial instruments are available to perform tan δ testing. These units are reasonably light-weight (<30 kg for a 34 kV unit) and portable and can be taken into an NPP for in-situ tests (Figure 7.4). Tan δ testing is beginning to be widely used in NPPs—particularly for medium-voltage shielded cable. Such tests have been shown to be particularly sensitive to water-tree degradation in medium-voltage cables (Lim et al. 2011; Mantey 2015).

Figure 7.4. Tan Delta Model 34K. Photo courtesy of High Voltage Inc.

With a marginal or damaged cable, there is a possibility for a cable failure with a tan δ test because the voltage potential is elevated above normal line voltage; however, cables typically have a comfortable safety factor well above the test voltage. Tan δ tests are not considered destructive because the data indicates that a cable is likely to have a margin of safety if the test is run to completion. By contrast, with un-monitored withstand tests, there is no early condition warning and the test could have been passed with little or no margin before the cable would have failed (Figure 7.5). EPRI and manufacturers have developed recommended guidance for acceptance thresholds for some cables, but sensitivity and reliability is best if used as a regular periodic test where results can be compared to baseline data and trended. Advantages and disadvantages for the VLF tan δ monitored withstand test are shown in Table 7.6.

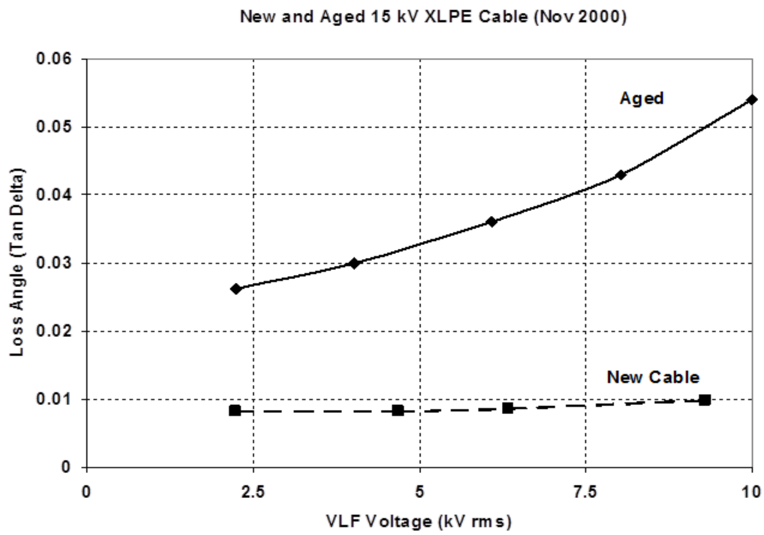


Figure 7.5. Example Tan δ test result of new and aged cable. Courtesy of High Voltage Inc.

Table 7.6. VLF Tan δ Advantages and Disadvantages

Advantages	• Simple and quick (30–60 minutes) to perform with minimal influence from external fields/noise • Results are available as the test is performed and test may be terminated on early indications of failure • Measurements are trendable, allowing regular monitoring of cables of concern
Disadvantages	• Cable must be removed from service for testing • The measurement is a weighted average of full length of cable. A single short-duration defect may not be detected. • No indication of the location of any defect • This test is typically reserved for 5 kV cable and above. Specific acceptance thresholds for low-voltage cables do not exist.

7.3.2 Partial Discharge Off-line

Partial discharge (PD) is an electrical breakdown of a small portion of a solid or liquid insulator under HV stress. PD tests have been used to detect voids, contaminants, and interface problems in cable systems. By design, the PD system detects small discharge leakage currents prior to a full discharge arc-flash that quickly escalates to a system failure. Such discharges and eventual failures are typically isolated to small regions of a system. Generally, PD tests are applied for shielded cable circuits above 3 kV, but the approach is theoretically applicable to lower voltage cables. PD testing is applied not only to condition assessment of cable systems, but virtually all of the other major electrical components in power plants (e.g., generators, motors, switchgear, transformers).

After isolating or de-terminating the cable system to be tested, a HV is applied between the conductor and shield and the response of an appropriate PD signal coupling device, connected to the test object, is monitored/recorded. PD signals are normally coupled from the system being tested using HV coupling capacitors connected directly to the cable conductor or radiofrequency current transformers or Rogowski coils applied at the cable shield ground connections.

A basic test procedure consists of first applying a TDR pulse to detect the cable end and determine the velocity propagation factor. A VLF operating potential or over-potential is then applied to the cable system being tested while monitoring for a PD perturbation (usually in the millivolt range) at the cable end. PD activity, if present, is recorded. The PD location may be determined by the arrival time difference between the primary PD signal and the secondary signal reflected from the cable's far end. If PD is detected then excitation voltages may be adjusted to determine PD inception voltage and PD extinction voltages (IEEE Std 400.3-2006).

Acceptance criteria for PD testing of cable systems do exist, such as ANSI/ICEA T-24-380-2007. However, they are exclusively concerned with factory testing of cables and accessories. Although some utilities have internal specifications based on PD measurements, at present there are no national or internationally accepted criteria. This situation is due to the wide range of PD measurement methods available and the complexity of interpreting PD test results (Schwarz et al. 2008). Generally, organic polymeric insulation has relatively low resistance to PD deterioration mechanisms, so detection of PD on any solid dielectric cable system is cause for concern and further investigation.

Table 7.7. Advantages and Disadvantages of Off-line VLF Partial Discharge Testing

Advantages	• The location of the PD activity can be detected and measured • Test sets are reasonably portable and comparable to standard cable fault test equipment • Testing can be completed in 30–60 minutes • Trending can be useful to monitor and track PD performance
Disadvantages	• The PD detection test may be of limited use when evaluating water-tree insulation unless the electric stress created by a water tree is sufficiently severe to initiate an electrical tree and there is PD activity at the test voltage • External surface discharges, PDs in joints and accessories, corona discharge, and cable attenuation may have a great influence on the PD test results • PD testing can be less sensitive on aged taped shielded cables due to corrosion of the shield overlaps that increases the impedance of the tape and increases the attenuation of the PD pulses • This test is typically reserved for medium-voltage shielded cable. Specific acceptance thresholds for low-voltage cables do not exist.

7.4 Dielectric Spectroscopy

Dielectric spectroscopy is a more sophisticated form of VLF DF testing (tan δ) in which both the voltage and applied frequency are varied in the test steps. The test is applied across the conductor and a shield. The test series is performed at different frequencies varying from 0.01 Hz to approximately 10 Hz, although much higher frequencies may be used in a laboratory. At each frequency, a number of voltage steps are applied, and the tan δ is measured at each step. One embodiment of this method—the broadband impedance spectroscopy (BIS)—has been developed by Boeing for condition monitoring of aircraft wiring. Extension of this technology was further explored for nuclear applications under an NRC program (Rogovin and Lofaro 2006). This effort included claims to use BIS for location of degradation within 10% of the overall cable length. To date, dielectric spectroscopy has not had broad acceptance within the power industry; however, it has attracted attention as a promising technique particularly for medium-voltage water-tree detection (Werelius et al. 2001; ADVANCE 2013). Dielectric spectroscopy is also recommended to be added to the next revision of NRC 1.128 (NESCC 2014). Observations have varied for this technique. EPRI observed the following (Toman 2011):

- For new or non-water tree deteriorated cables, results are nearly frequency independent. The loss is low and both the real and imaginary components of the relative permittivity are independent of applied voltage.
- For water treeing degradation that is significant but not yet penetrated the whole insulation, the dielectric spectroscopy test is voltage-dependent.
- Transition to leakage current indicates that the water trees penetrate through the insulation wall and breakdown strength is significantly reduced.

Table 7.8. Advantages and Disadvantages of Dielectric Spectroscopy Cable Test

Advantages	• Provides tan δ information across a broad frequency band (typically 0.1–10 Hz or in some cases up to 1000 Hz)
Disadvantages	• Requires more equipment and more time than a simple Tan δ • Whereas guidance on acceptance criteria for VLF Tan δ are reasonably clear particularly for medium-voltage shielded cables, guidance on acceptance criteria for the additional information associated with the full spectral response is weak

8. TIME DOMAIN REFLECTOMETRY

A time domain reflectometry (TDR) system measures reflections of a stepped or impulse signal along a single conductor to detect and locate any changes in the conductor impedance (Strickland 1973; Cole 1977; Agilent 2013). In order to measure those reflections, the TDR transmits a step or pulse incident signal onto the conductor and subsequently senses the signal reflections from impedance changes along the conductor. If the conductor is a uniform impedance network and is properly terminated to matching impedance, then there will be no reflections as the transmitted signal will be completely absorbed at the far end by the termination. Instead, if there are impedance variations as in a short or open at the cable end, or a damaged or reduced cross-sectional area or a splice with a different resistance along the conductor, then a portion of the incident signal will be reflected back to the source (Agilent 2013).

The reflected signal arrives back at the TDR instrument at an instant in time that is proportional to the signal propagation velocity in the cable and the distance traveled along the cable, thereby allowing an assessment of the location of any reflector observed. The amplitude of the reflected signal coupled with the inherent cable attenuation characteristics also allows an estimate of the magnitude of the impedance change. The time domain display inherent in a TDR measurement is generally perceived as an intuitive method to view the reflected signals associated with localized cable impedance changes including defects. TDR is based on transmission line theory and is categorized as a distributed inspection method because it uses pulsed signals that propagate along the entire length of the cable to interrogate the cable condition.

TDR technology is widely used to diagnose and locate cable faults—particularly in cable conductors and to locate splices or termination points. The technique however is known to be relatively insensitive to subtle changes in insulation properties (thermal and radiation aging, water trees, cuts, and cracking). The instrument performance (pulse rise time, duration, time accuracy, etc.) can also be quite different for estimating an overall cable length vs. looking for subtle impedance changes. Figure 8.1 shows several portable instruments for cable diagnostic testing. The automated TDR system shown in Figure 8.1(b) has a rise time of 150 ps, pulse amplitude of 0.3 V, adjustable pulse width of 1–100 µs, and a distance measurement accuracy of 1 cm or ±0.5% (whichever is greater) that are suitable for cable tests (Mohr and Associates 2009).

The test is a low-voltage test so there is virtually no risk to the cable. The main emphasis, however, of a TDR test is to assess the condition of anomalies detect, locate, and characterize impedance changes in the conductor. Very little information is provided regarding subtle changes in the insulation as would be anticipated cable aging insulation degradation except as the change in the conductor surrounding dielectric results in an impedance change in the conductor. It can be challenging to obtain clean signals with a high signal-to-noise ratio from long runs of cable with multiple reflections as more of the signal is attenuated along the cable and reflected back to the source from each discontinuity.

(a) (b)

Figure 8.1. Example TDR instruments for cable fault detection.

A TDR data display consists of a plot of the reflected voltage signal versus distance, where the cable's velocity factor is used to convert time to distance along the cable. The reflection coefficient ρ is the ratio of the reflected and incident pulse amplitudes:

$$\rho = \frac{V_{\text{reflected}}}{V_{\text{incident}}} \tag{8.1}$$

The reflection coefficient can also be written as a function of the cable characteristic impedance Z_0 and the load impedance Z_L:

$$\rho = \frac{(Z_L - Z_0)}{(Z_L + Z_0)} \tag{8.2}$$

This expression shows that the reflection coefficient can range from −1 to +1, depending on the load impedance value. A value equal to the cable impedance produces a perfect impedance match, which corresponds to a reflection coefficient equal to zero. A short circuit corresponds to a reflection coefficient of −1, and an open circuit (infinite load impedance) corresponds to a reflection coefficient of +1.

When there is no impedance mismatch encountered on the cable pair, the trace displays a flat line. However, any increase in impedance produces an upward deflection from the baseline, and decrease in impedance produces a downward deflection. Several locations along the cable length are highlighted in Figure 8.2 where upward deflections are created by impedance discontinuities at each location. An example TDR display of Figure 8.2 shows several wire pairs of a three-conductor cable. The data is from a TDR test of an instrumentation cable with a 3-wire RTD on the end. The data shows a clear issue with one of the wires on the RTD, but no real issues with the cable itself up to the RTD connection. This type of information informs plant maintenance personnel of the expected fault and allows repairs to be planned with high confidence that replacing the RTD sensor will address the system fault.

Another factor that impacts the use of TDR systems is conductor and dielectric loss. Conductor loss typically dominates and is due to the resistance of the conductors used in the cable. Signal attenuation is frequency-dependent due to the skin effect and can limit the length of cables that can be tested using TDR. The skin effect refers to the concentration of AC current nearer the outer diameter of the conductor. With DC or at very low frequencies, current is evenly distributed within the conductor, but as frequency increases to 60 Hz, the skin depth is approximately 8 mm (Raven 2015). The skin effect is due to opposing eddy currents induced by the changing magnetic field resulting from the alternating current.

A proprietary TDR-based cable testing method referred to as Reverse TDR (RTDR) has been developed by Analysis and Measurement Services Corporation to test the condition of the shielding material in coaxial or triaxial cables (Campbell et al. 2012). Figure 8.3 shows the measurement configuration for a coaxial cable. In this approach, the signal is injected onto the shield to locate degraded connections that allow electromagnetic interference to influence the signal being carried by the cable. By monitoring the coupling of the test signal from the shield to the center conductor of the cable, this test is particularly suited for cables in which the signal levels are small and easily influenced by external noise sources. This technique has been integrated into the CHAR system for cable condition monitoring and fault detection and may be complementary to FDR analysis discussed in the next section.

Spread spectrum TDR is beginning to be applied and accepted in the aircraft industry for on-line continuous monitoring for cable faults and failures (Smith et al. 2005). For this test, a broad-band signal is applied to the cable and reflections are sensed based on the correlation with the applied broad-band excitation. (Although not specifically tailored to find insulation damage, the spread spectrum technology offers opportunities for improved signal-to-noise ratios and the possibility to superimpose the test signal onto active signal cables.) There are other variants of TDR that may enhance the TDR response including nonlinear time domain reflectometry (Bryant 2007), spread spectrum time domain reflectometry, and joint time-frequency domain reflectometry (Coats et al. 2011) that are mentioned but not specifically discussed as they are not currently available or near commercialization for industrial power plant use.

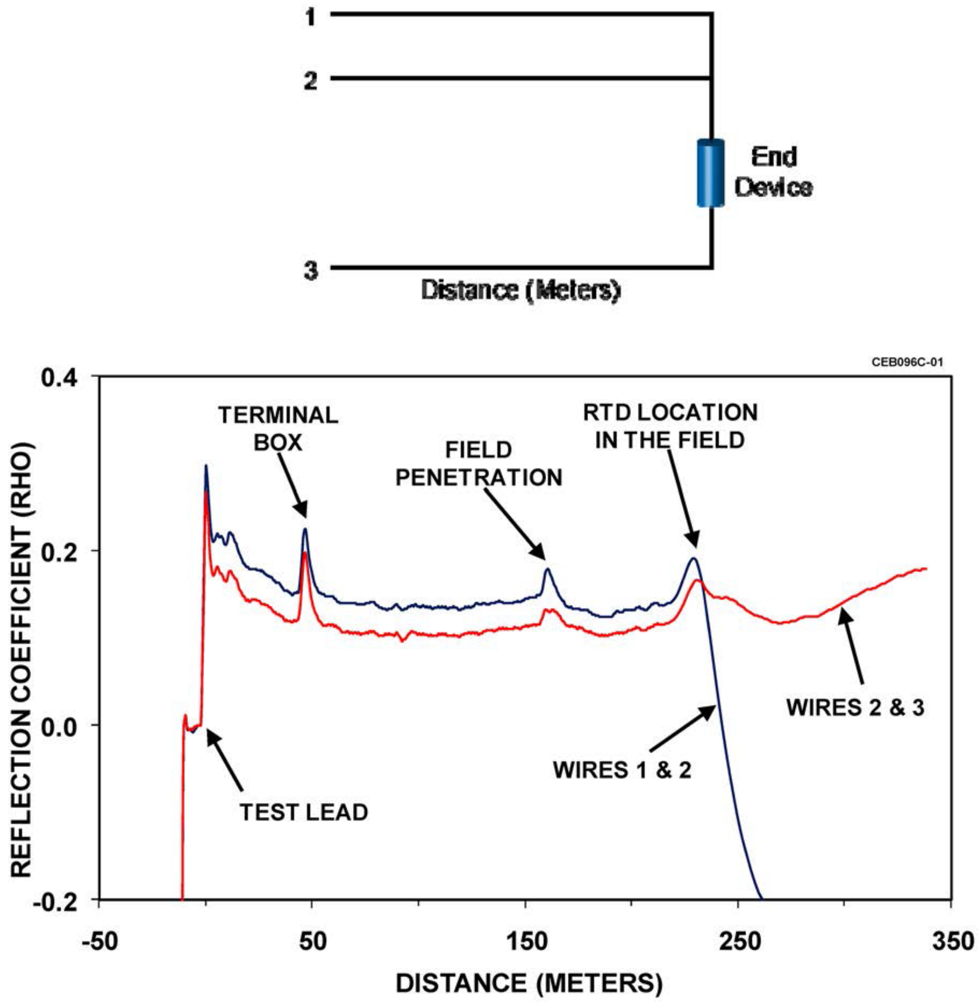


Figure 8.2. Typical TDR 3-conductor test plot. Courtesy of IAEA Assessing and Managing Cable Aging in Nuclear Power Plants.

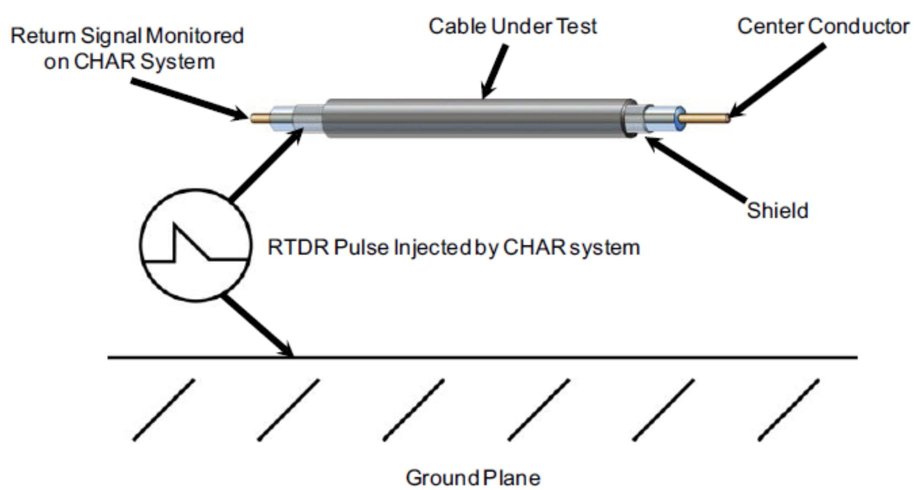


Figure 8.3. Reverse TDR measurement setup. Courtesy of IAEA Assessing and Managing Cable Aging in Nuclear Power Plants.

Table 8.1 summarizes various advantages and disadvantages of the TDR method for cable testing.

Table 8.1. Advantages and Disadvantages of TDR Testing

Advantages	• Inspection of entire cable length from single-ended access • Low voltage safe, nondestructive test • Rapid inspection times (several minutes) • Systems commercially available • Best-suited for testing and troubleshooting of conductor short-circuits, open-circuits, and splices. May be useful for detection of severe insulation faults.
Disadvantages	• Lack of established global aging indicators • Baseline signatures needed to assess cable condition trends

9. FREQUENCY DOMAIN REFLECTOMETRY

Frequency-domain reflectometry (FDR) is a nondestructive electrical inspection technique used to detect, localize, and characterize subtle impedance changes 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 (Gledhill 1999; Furse et al. 2003; Minet et al. 2010; Agilent 2012). FDR theory is addressed generally in this section and then the implementation of this theory is addressed specifically for each of three instruments used to measure the FDR response.

For the measurement, two conductors in the cable system are treated as a transmission line through which a low-voltage swept-frequency waveform is propagated. 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. The remote end of the cable can be terminated in 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 completely nondestructive and poses no special safety concerns to operators assuming that routine electrical safety procedures are followed. Note that 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 be an advantage to shortening the required testing time and minimizing the risk of improper re-termination. Frequently, cable systems are de-terminated anyway to minimize the risk of residual charge shock.

Figure 9.1 shows a linearly increasing “chirp” sinusoidal waveform that is representative of the type of excitation signal used in the FDR technique. The excitation signal can be generated for transmission into the cable using an analog circuit such as a voltage-controlled oscillator or using a digital circuit such as a direct digital synthesizer.

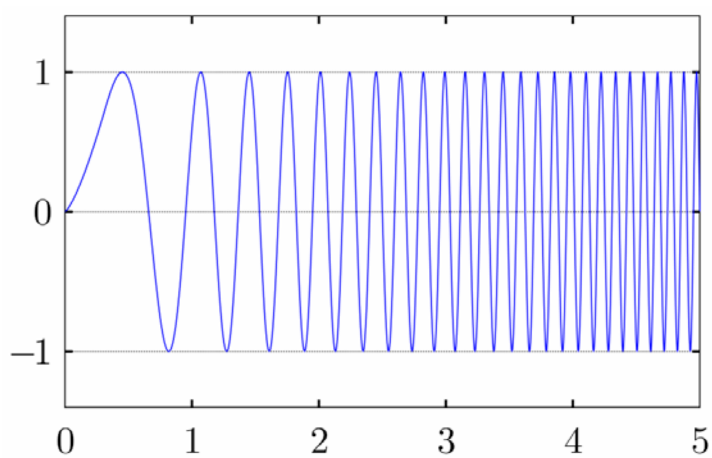
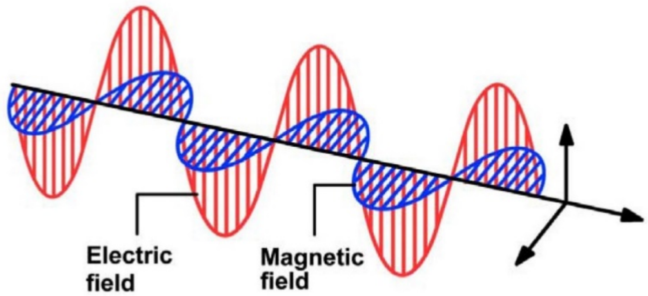
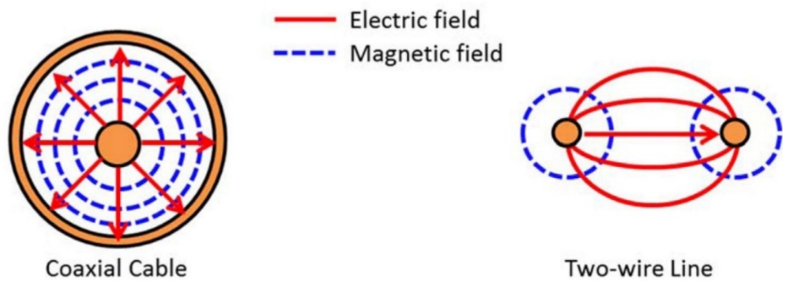


Figure 9.1. Example FDR excitation waveform in which the signal frequency linearly increases as a function of time.

Figure 9.2(a) shows a representation of 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 9.2(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.



(a)



(b)

Figure 9.2. (a) Electric and magnetic field configurations for generalized sinusoidal TEM wave propagation. (b) Electric and magnetic field configurations for specific cable types.

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 Figure 9.3, 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 (Minet et al. 2010; Mohr and Associates 2010).

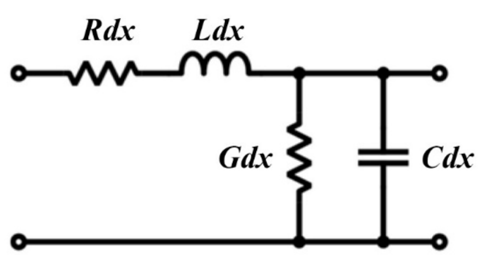


Figure 9.3. Transmission line circuit model consisting of distributed impedance elements over an infinitesimally short length.

The FDR technique has inherent advantages that can potentially yield better sensitivity to cable degradations than traditional time-domain reflectometry (TDR) which is best-suited for identifying open and short circuit conditions in the conductors (Murty 2013). 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 (IEC 2002). 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 than TDR because TDR pulses may have difficulty continuing in the forward direction after 2–3 significant reflections.

Previous FDR measurements demonstrated that the method is sensitive enough to detect changes in cable routing such as reversals in direction (Glass et al. 2015). A test was performed for a RG-174 coax cable that showed a cable bend with a radius of curvature at least 10 times the cable diameter can prevent any detectable increased reflection at the bend location (Table 9.1). This result is consistent with general guidance provided for the use of commercially available FDR systems; however, manufacturers' recommendations for minimum bend radius are typically from 3 to 8 times their jacket outside diameter.

Table 9.1. FDR Peak Response for RG-174 Coax Cable to Various Bend Radius

Influence of Cable Bend Radius on 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

Additionally, it has been observed that the removal of conductor insulation can produce capacitive changes large enough to be detected when the measurement is performed for conductor pairs affected by the insulation removal. 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 or absence of cable shielding, can also impact the ability to obtain consistent results using FDR. Measurements for an unshielded multi-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 for unshielded cable were measured with the cable resting on various dielectric materials and metals (Figure 9.4). Corresponding measurements for a multi-conductor shielded cable with a short section of the shield removed showed no noticeable changes for the different environmental conditions (Figure 9.5). Because unshielded cables are susceptible to electromagnetic interference from close proximity to conductive material, electrical machines, and power lines, environmental factors should be considered for unshielded cables. These parameters may be static and explainable within the FDR spectra such that each peak may not be indicative of a cable fault. Recognition of insulation degradation may be easier and more reliable if FDR responses are trended and carefully examined for change rather than focusing on absolute peak values. The FDR measurement detects discontinuities in the electrical impedance that arise due to cable splices or similar changes along the path of the conductor pair. The method is 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 from the FDR technique. Example changes that impact the insulation capacitance include exposure to heat, radiation, water damage, corrosion, or mechanical fatigue. A previous report (Ramuhalli et al. 2015) showed that the dielectric properties of EPR insulation specimens change as a function of aging. Those changes in age-related polymer dielectric properties can contribute to measureable changes from an FDR measurement. The results from one study show varying degrees of success for different detection scenarios and environmental factors (IAEA 2012). One area of ongoing work is to evaluate the ability of FDR techniques to provide in-situ predictions of cable remaining useful life, which can be correlated to an established method such as EAB.

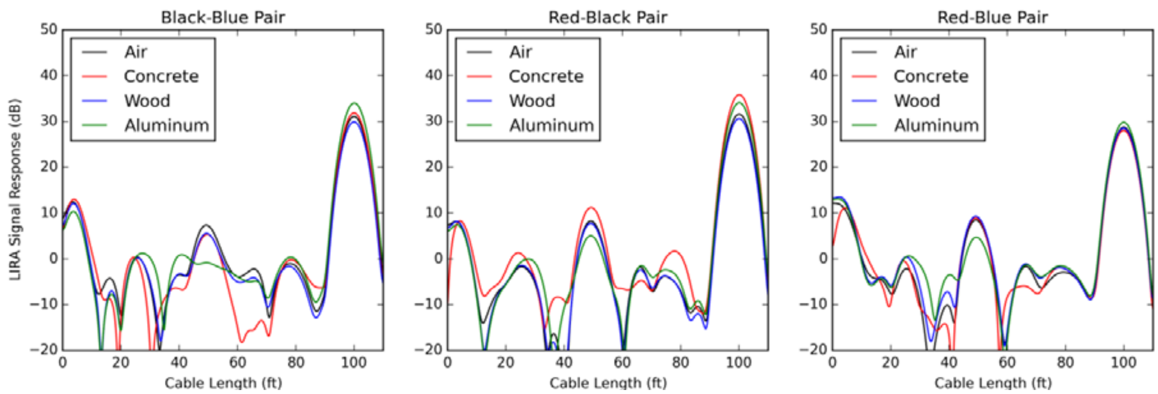


Figure 9.4. Unshielded cable shows differences among air, concrete, wood, and particularly aluminum at the 50 ft. location where both the damaged section is and where the underlying supporting material is.

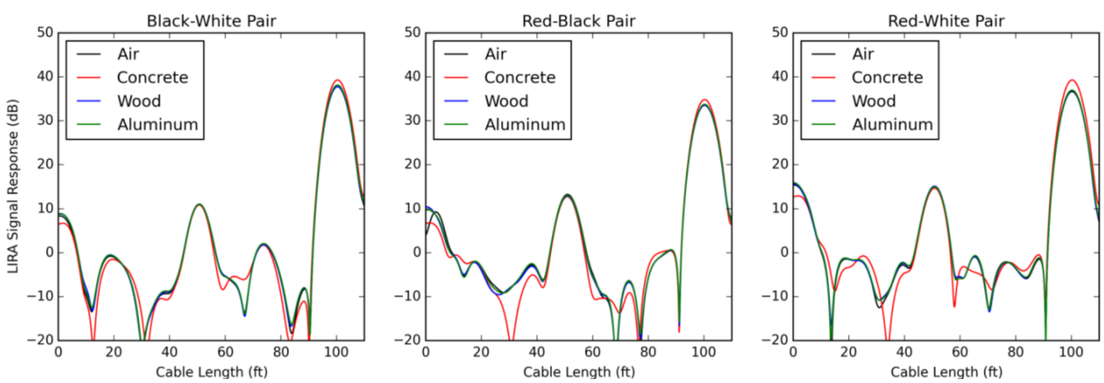


Figure 9.5. Shielded cable has virtually no different response to air, concrete, wood, or aluminum but the damaged area at 50 ft. still shows as a clear peak.

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 (Mohr and Associates 2010):

$$\text{Resolution (m)} = (c \times \text{VF}) / (2 \times \text{BW}) = 1.5\text{E}8 \times (\text{VF}/\text{BW}) \tag{9.1}$$

where c = 3E8 m/s. The cable's velocity factor is a value less than unity and is inversely related to the square root of the dielectric constant of the insulation material. The maximum unambiguous (alias-free) range is also a factor for interpreting FDR results, and is a function of the resolution and the number of frequencies (NF) used to cover the bandwidth (Mohr and Associates 2010):

$$\text{Range (m)} = \text{Resolution} \times \text{NF} \tag{9.2}$$

An important parameter in the implementation of the FDR method is the bandwidth of the swept-frequency signal that propagates along the cable. 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 radio-frequency transmission line theory. Thus, higher frequencies are required to characterize shorter cables in order to satisfy the cable length requirement, and lower frequencies are required to characterize longer cables in order to prevent the insertion loss from overcoming the measurement signal.

Commercially available systems based on FDR implementations are being applied in research environments to investigate sensitivity to local cable insulation degradations as well as global cable health estimation for application to NPP cable inspection and monitoring. They are also beginning to be used for power plant diagnostics. This investigation has evaluated two commercial field-adapted FDR systems plus one general-purpose laboratory instrument adapted for FDR measurements as discussed in the following sections.

9.1 Vector Network Analyzer

FDR measurements can be made by connecting a cable to a vector network analyzer (VNA) and appropriately post-processing the frequency-domain data. A VNA is a standard versatile laboratory instrument that measures the complex-valued network parameters used to characterize an electrical network. As examples, a high-performance four-port benchtop VNA is shown in Figure 9.6 and several portable VNA systems are shown in Figure 9.7. Technological advances in the test and measurement industry have enabled the introduction of rugged, lightweight, handheld units for field use. Vector network analyzers have several advantages for cable inspection including:

- Excellent system dynamic range (as high as 100 dB)
- Measurement times as short as 1–2 minutes
- Ability to automate data collection using well-developed scripting languages
- Flexibility in using native time-domain transforms included with the instrument or exporting frequency-domain data for custom processing and analysis
- Ability to generate wide range of frequency sweeps to explore cable signatures versus frequency (with spans of up to multiple GHz)
- Competing commercial vendors with variety of product offerings including benchtop and portable systems.

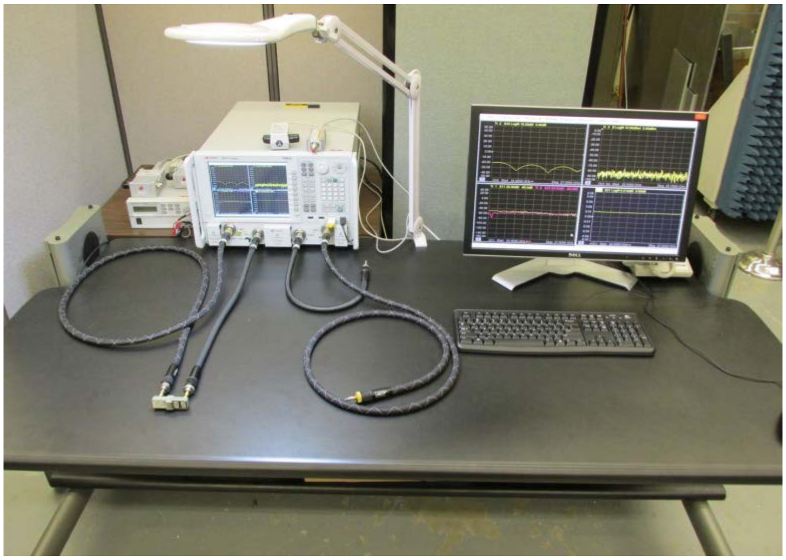


Figure 9.6. A benchtop vector network analyzer was used to acquire FDR measurements with appropriate post-processing of the frequency-domain data.

Figure 9.7. Portable VNA systems are commercially available for cable testing. Images courtesy of Rohde & Schwarz and Keysight Technologies.

The VNA used for these measurements was a Keysight Technologies E5061B VNA included options for the 5 Hz–3 GHz frequency range, the high stability time base, and the time-domain/fault location analysis. The VNA was connected to each test cable with a 3 ft. coax cable with BNC-to-alligator clip connectors and calibrated to place the measurement reference plane at the instrument port. A Python script was used to automate the collection of frequency-domain and time-domain data sets for each test cable 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 measurement bandwidth. To perform a cable FDR measurement using the VNA, an instrument calibration is first performed to place the reference location at the measurement plane corresponding to the instrument port or connecting cable as outlined in the instrument application note (Keysight Technologies 2014). Then the complex-valued reflection coefficient of the cable under test is acquired in the frequency domain over the specified bandwidth. Finally, the inverse Fourier transform is used to mathematically convert the reflection coefficient to the time domain and display the resulting data for analysis of cable faults and defects. The conversion to the time domain is commonly performed on the same instrument in an integrated graphical user interface environment, but may be implemented separately by exporting the frequency-domain data.

In either case, the operator may specify settings for windowing functions, frequency-domain filters, and time-gating and apply compensation for signal loss along the cable.

Figure 9.8 shows an example of the process from converting the collected frequency-domain data to the time-domain FDR signature for a cable with a mechanical defect. Figure 9.8(a) shows a photo of the General Cable FR-EPR/CPE 600 V shielded triad instrumentation cable with a 3.5 in. section with the shield and jacket removed. The total cable length is 100 ft., and the damaged section is located at 50 ft. Figure 9.8(b) and (c) show the amplitude and phase of the cable impedance response measured using a VNA swept over a bandwidth from 10–100 MHz. The reflection coefficient (ρ) measured by the instrument can easily be converted to an impedance (Z) spectrum using the following relationship:

$$Z = Z0 \times (1+\rho) / 1-\rho \qquad (9.3)$$

where Z0 is the cable characteristic impedance value used as a reference. Note that the frequency-domain impedance response shows multiple resonances where the amplitude reaches peak values and the phase shift is zero. These frequencies are related to the physical and electrical parameters of the cable. The phase response at higher frequencies can be influenced by the selection of the probe used to connect the VNA instrument to the cable under test. Generally, it is recommended to use the shortest probe available for high-frequency measurements in order to avoid parasitic impedance effects.

Finally, Figure 9.8(d) shows the FDR signature obtained from transforming the frequency-domain response to the time domain. A velocity factor of 0.59 was used to convert the time axis to distance along the cable. The plot shows an increased reflection of over 10 dB at the damaged location, as well as the reflection from the open-circuited end of the cable. The downward slope of the FDR signature versus cable length can be used to calculate and compensate for the signal loss along the cable. Practically, one can either assume a velocity factor based on the nominal cable characteristics (if known) or the velocity factor may be calculated based on the known, nominal, or assumed cable length.

To illustrate the effects of swept-frequency bandwidth on the FDR signature, a 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 9.9 shows a photo 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 end of the cable was open-circuited during both measurements. A velocity factor of 0.63 was used to convert the time axis to distance along the cable. Note that the use of the higher bandwidth sweep provides a clearer indication of the local degradation present at 100 ft.

To further investigate the effects of bandwidth, a VNA was used to acquire FDR responses for swept-frequency bandwidths as high as 500 MHz as part of an accelerated aging study. The test cable was a 100 ft. Okonite-FMR 600 V unshielded power and control cable for which a 1.5 ft. section was thermally aged for 1280 hours at 140°C. The test configuration is shown in Figure 9.10 (a) in which the cable is routed through the oven at 50 ft. and reverses direction along the wall at 25 and 75 ft. EAB and indenter modulus (IM) tests on EPR witness samples with similar formulation from a shielded cable simultaneously aged with the unshielded cable showed significant changes after approximately 850 hours. Figure 9.11 shows the EAB and IM data versus aging hours.

The FDR responses are shown in Figure 9.10(b), where the baseline data set was recorded at 318 hours due to unavailability of the VNA instrument until that time. Both measurements were acquired with the cable at room temperature. The 500 MHz response shows an approximate 10 dB increase at the thermally aged location over the 962 hour difference between the two measurements. The two reversals in the cable direction shown in the photo are also evident in the high-frequency FDR response. Although not shown, the same comparison for measurements performed with 100 MHz bandwidth did not produce any significant features at the thermally aged location or at the reversals in the cable routing direction.

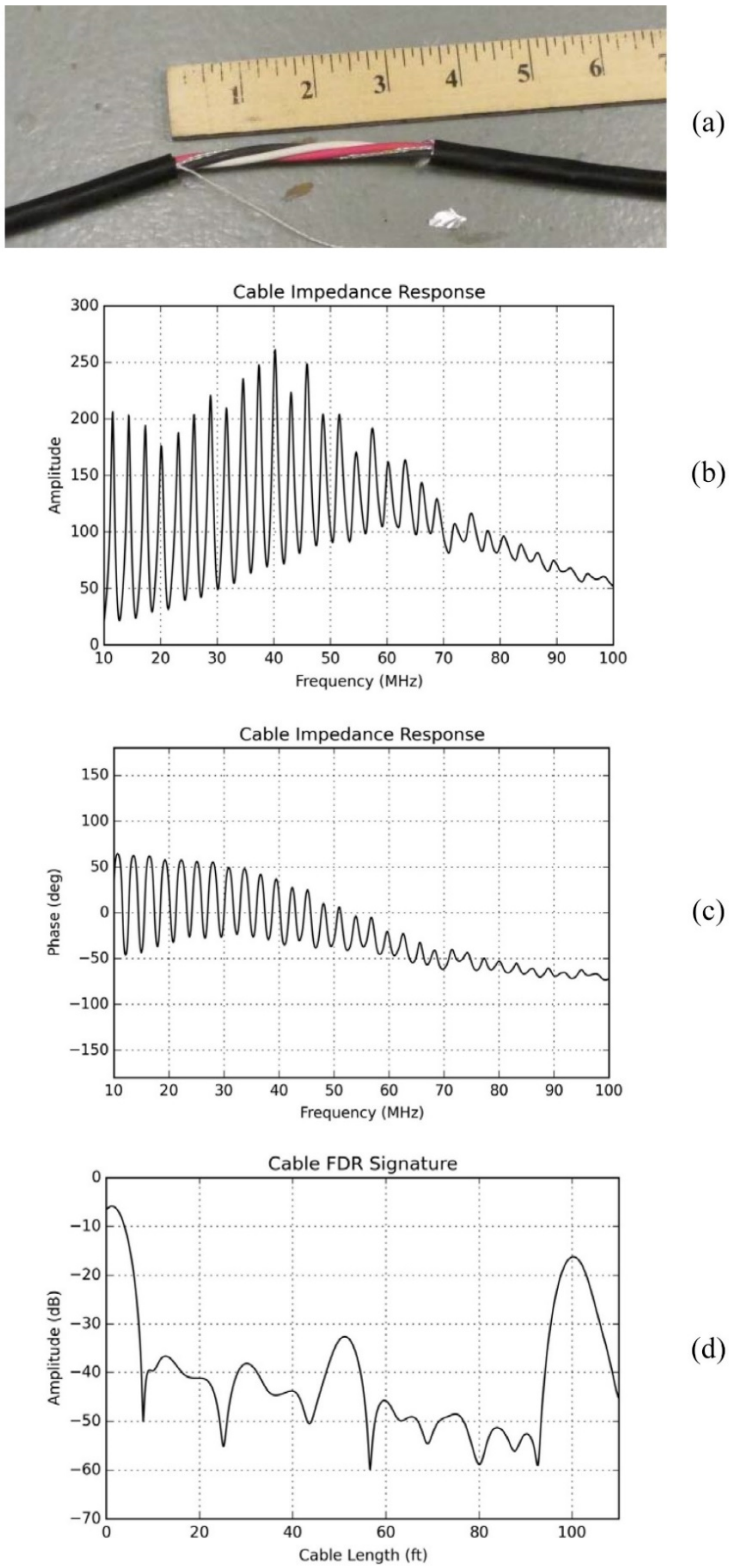
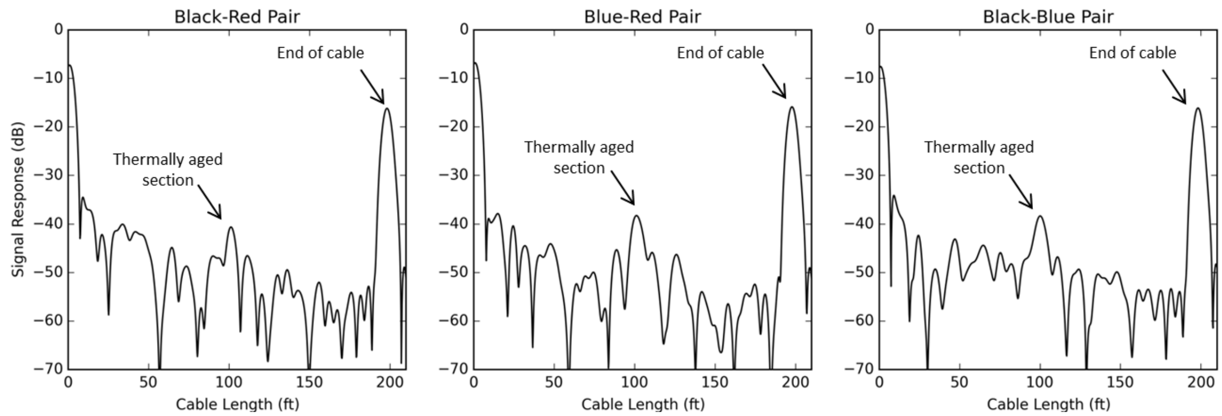
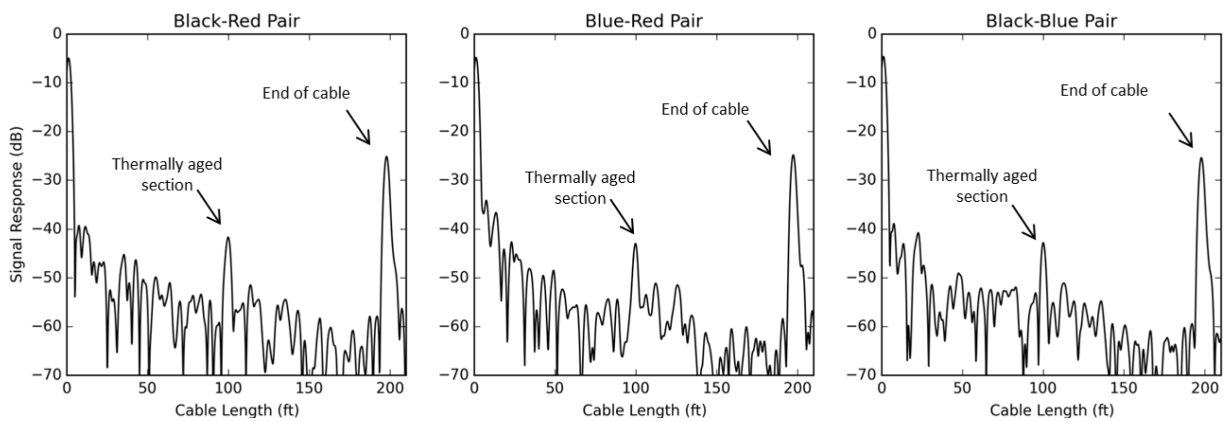


Figure 9.8. (a) Section of cable with shield and jacket removed. (b) Magnitude of 100 MHz FDR impedance response acquired with VNA. (c) Phase of 100 MHz FDR impedance response acquired with VNA. (d) FDR signature obtained from transforming the frequency-domain impedance response.

(a)



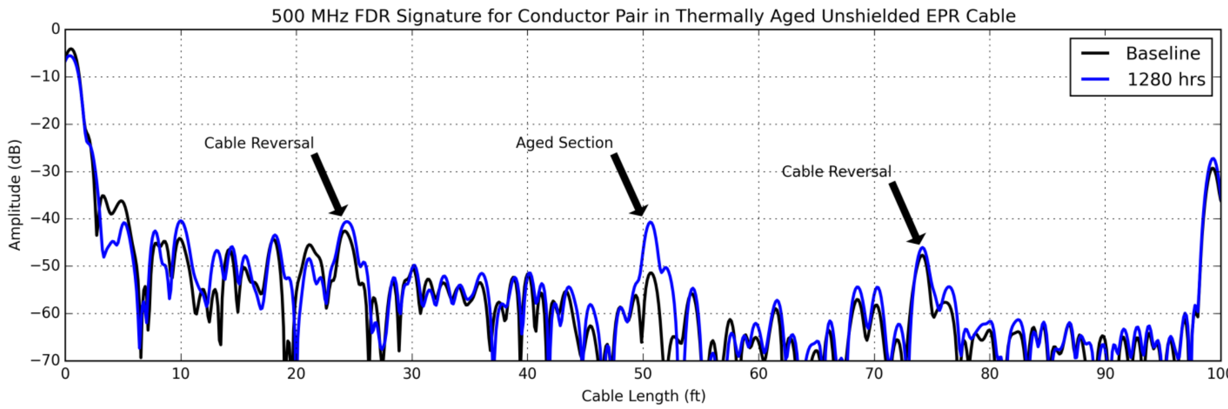
(b)



(c)

Figure 9.9. (a) Aged section of unshielded power and control cable. (b) 100 MHz FDR response acquired with VNA. (c) 200 MHz FDR response acquired with VNA.

(a)



(b)

Figure 9.10. (a) Cable test configuration for accelerated thermal aging study. (b) FDR responses acquired with VNA using 500 MHz bandwidth. Note that the baseline data set was taken at 318 hours.

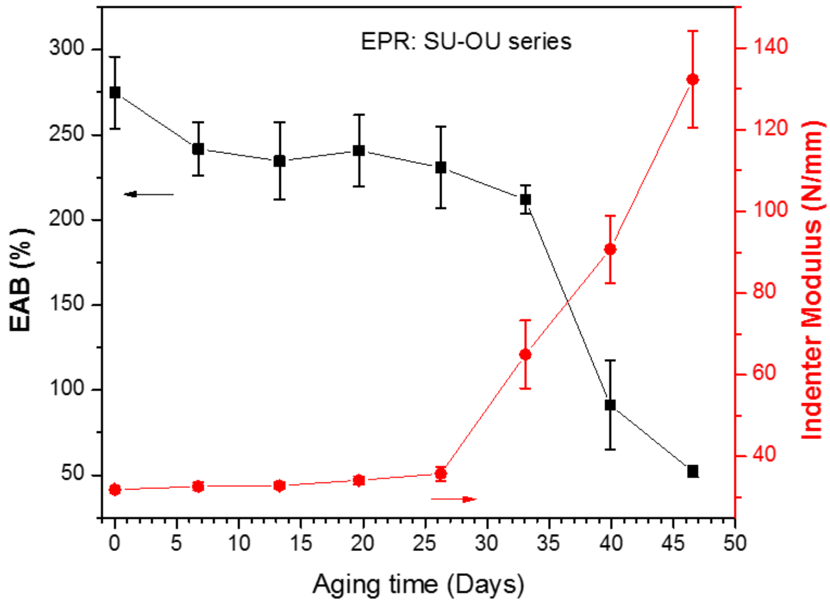


Figure 9.11. EAB and IM measurements for EPR insulation material witness samples used in cable aging experiment.

9.2 Line Resonance Analysis (LIRA)

Line resonance analysis (LIRA) is an FDR measurement technique originally developed by the Institute for Energy Technology in Norway. The LIRA technology has been patented (Fantoni 2011) and commercialized by Wirescan AS in Norway for fault location, condition assessment, and condition monitoring of transmission lines in the energy transmission and distribution, offshore wind, oil and gas, and nuclear power industries. Fauske and Associates, LLC, is the partner for developing and deploying the LIRA technology in NPPs in the United States. As shown in Figure 9.12, the technology is currently available in the first-generation LIRA Portable and the second-generation LIRA Acquire ruggedized systems. The LIRA Portable is approximately the size of a small suitcase and is a self-contained measurement system with all hardware and software included. The LIRA Acquire is smaller and lighter (approximately the size of a wireless router) and has improved electronics performance compared to the LIRA Portable. It also includes three measurement ports for ease in performing measurements on three-phase power systems, but requires a separate computer to operate the system software.

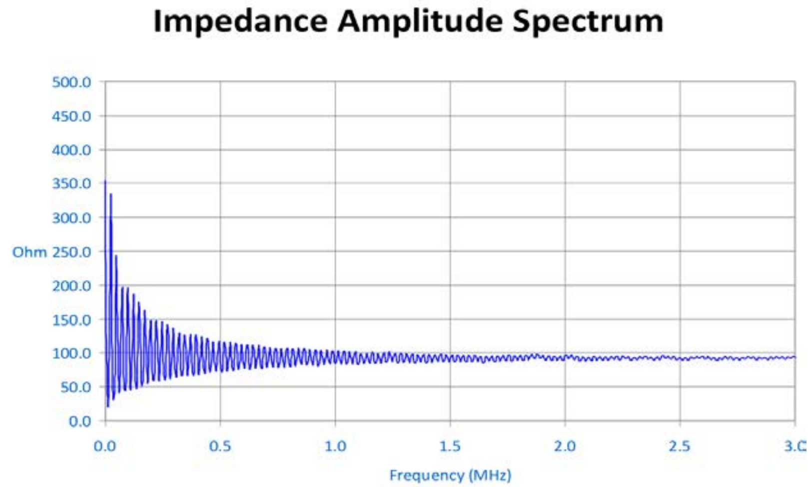
(a) (b)

Figure 9.12. (a) Wirescan LIRA Portable and (b) LIRA Acquire systems for assessing the condition of electrical cables. Images courtesy of Wirescan AS.

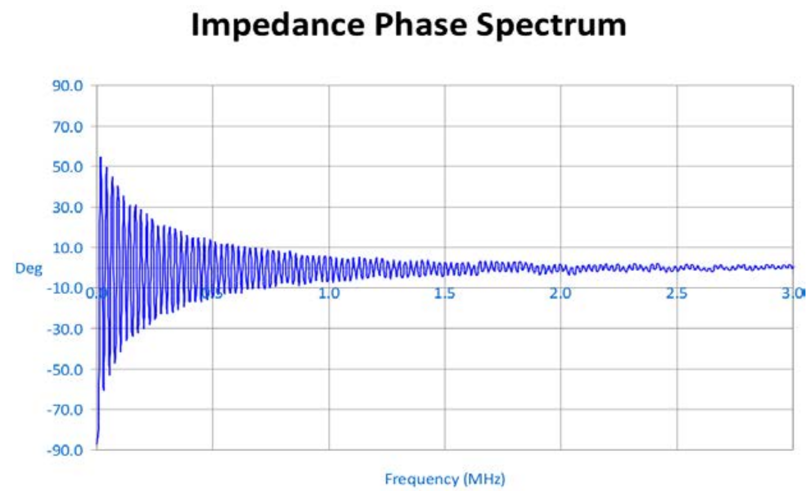
The LIRA technology has been shown to detect changes in electrical impedance along a cable from a measurement made by connecting to one end of a de-energized cable. These changes are generally from changes in the dielectric properties of the insulation material or to irregularities in the wire geometry. LIRA has been used to diagnose and assess damage along AC and DC signal and power cables for various industries for a number of years. Previous work has indicated that local changes of approximately 10 pF/m in the line capacitance or 0.2 µH/m in the line inductance can be reliably detected (Fantoni and Nordlund 2006). The sensitivity of LIRA to dielectric capacitance changes is much higher than 10 pF/m so if considered as a percent of the normal cable capacitance value (~ 100 pF/m for low voltage cable), it is around 1%. Medium and high voltage cables have higher capacitance and 10 pF/m could be a realistic sensitivity in a medium or high voltage cable noisy environment. Example changes that impact the insulation capacitance include cable joints and splices as well as locations that have been subject to heat, radiation, water damage, corrosion, or mechanical fatigue.

During operation, the system injects a low-voltage (5 Vpp) signal into the cable via a probe connection to two conductors. The far end of the cable can be terminated in any impedance different than the cable characteristic impedance. The measurement process only takes a few minutes and the data can be stored for offline post-processing.

As an FDR technique, the LIRA signal processing is based on transmission line theory and is valid when the cable length is at least comparable to the wavelength of the electromagnetic signals propagated along the cable. The LIRA system can generate frequency sweeps having up to 100 MHz of bandwidth and can be used on cables as short as approximately 35–50 ft. Available output data consists of a complex impedance spectrum for the user-defined frequency range; this data is used to calculate cable parameters and signatures, which can indicate both local and global degradations. Figure 9.13 shows amplitude and phase components of a complex impedance spectrum for a cable measurement using a frequency bandwidth of 3 MHz (Wirescan 2016).



(a)



(b)

Figure 9.13. (a) Amplitude and (b) phase components of example complex impedance spectrum, which forms the basis for cable evaluations performed by the LIRA system. Courtesy of Wirescan AS.

Post-processing operations available in the LIRA software include compensating for parasitic impedance effects of the connecting probe, applying an offset to the impedance phase spectrum to maximize the number of zero crossings (resonances), and modifying the bandwidth setting to a value lower than the setting used in the measurement. The optimum phase spectrum has a perfectly centered and symmetrical appearance over the highest possible bandwidth. Information available from a cable measurement includes the following:

- Cable signature plot
- Dynamic normalized (DNORM) display
- Cable characteristic impedance
- Cable velocity factor
- Cable distributed capacitance, inductance, resistance, and attenuation
- Delta-G indicator of global condition

The LIRA system offers the ability to dynamically normalize the cable signature plot so that the 0 dB value on the amplitude axis is set to one standard deviation above the average fluctuation in the data set. The average fluctuation is obtained by a statistical calculation to account for the stochastic noise resulting from impedance amplitude variations along the cable. This feature is activated by default and can prevent the occurrence of false alarms when interpreting the cable signature data for a given inspection.

A separate bar chart display (DNORM) is available for severity assessment in which the identified features that exceed the DNORM threshold setting along the cable length are color-coded by severity rating (Figure 9.14). The direction of the DNORM hotspot indicators (positive or negative) is a function of the type of impedance change producing the reflection and can be used to identify the local condition such as moisture ingress or thermal degradation.

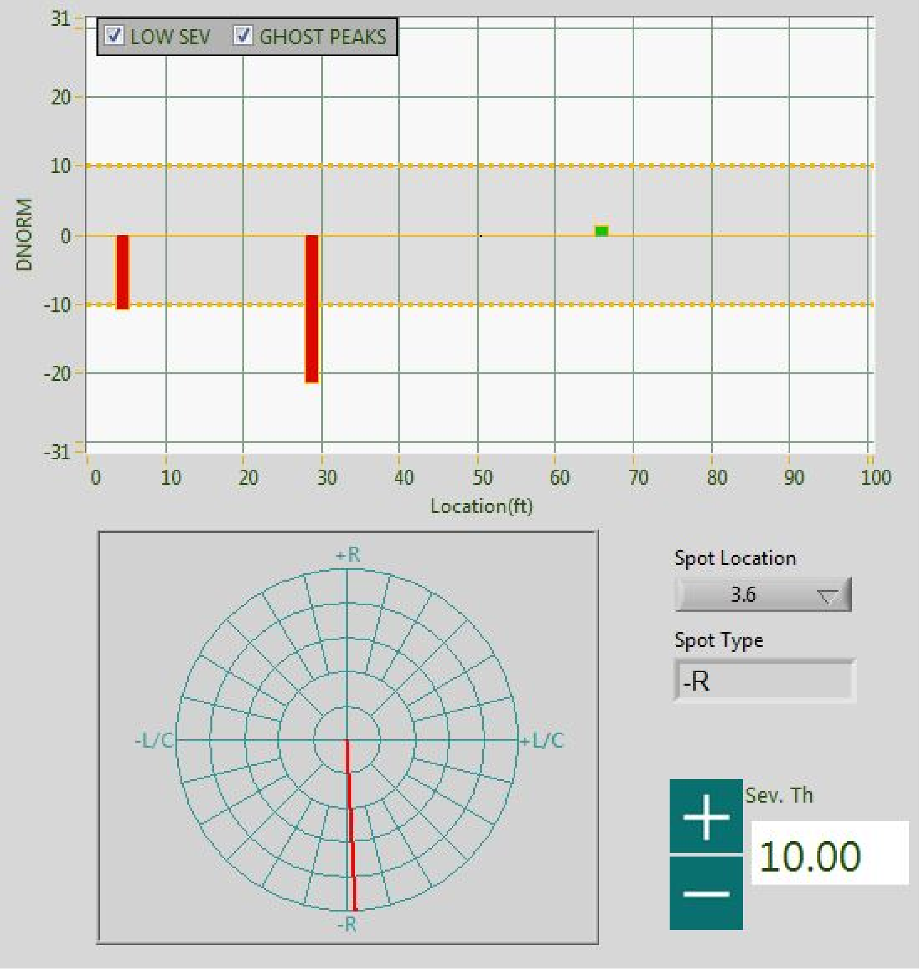


Figure 9.14. Cable XRL4 DNORM plot with reflection of probe-cable interface at 5 ft., thermal damage at 28 ft., and a small, below-threshold signal at 65 ft.

As part of the normalization procedure, the LIRA software automatically corrects for the per unit length cable attenuation in the cable signature plot. The software compensates for the downward slope caused by the conductor resistance and dielectric loss in the insulation.

Example signature plots are shown in Figure 9.15 for the unshielded power and control cable shown in Figure 9.9(a). The measurement used a bandwidth setting of 100 MHz and can be compared to the VNA plots shown in Figure 9.9(b), although the cable loss was not compensated for in the VNA plot. The thermally aged section of the cable at 100 ft. is clearly evident in the LIRA signature plot and exceeds the 0 dB dynamic normalization threshold for all three conductor pairs. Some indication is also present of a cable routing reversal at approximately 130 ft.

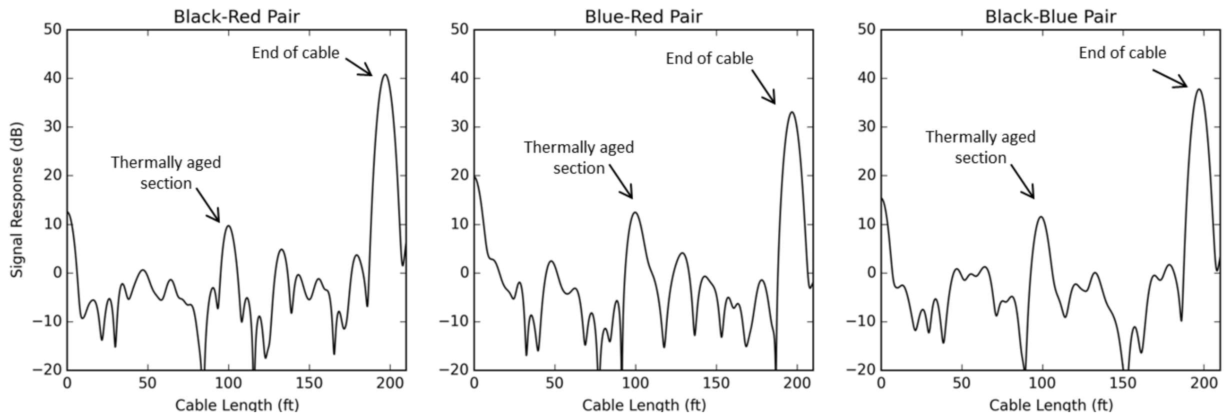


Figure 9.15. LIRA signature plots for thermally aged cable shown in Figure 9.9(a).

The LIRA software includes a simulator module to perform parametric studies for cable degradation scenarios. A screenshot of the simulator module is shown in Figure 9.16. Currently the cable geometries available for analysis in the simulator include multi-segment coaxial and twisted pair cables. The results from the simulator can be analyzed by the system as if they were obtained from an actual measurement. This allows the operator to compare measured and predicted results for a given cable under test. Stochastic noise can also be included in the simulation engine to represent the level of cable impedance variation caused by fluctuations in fabrication tolerance as well as electronic noise generated by the system.

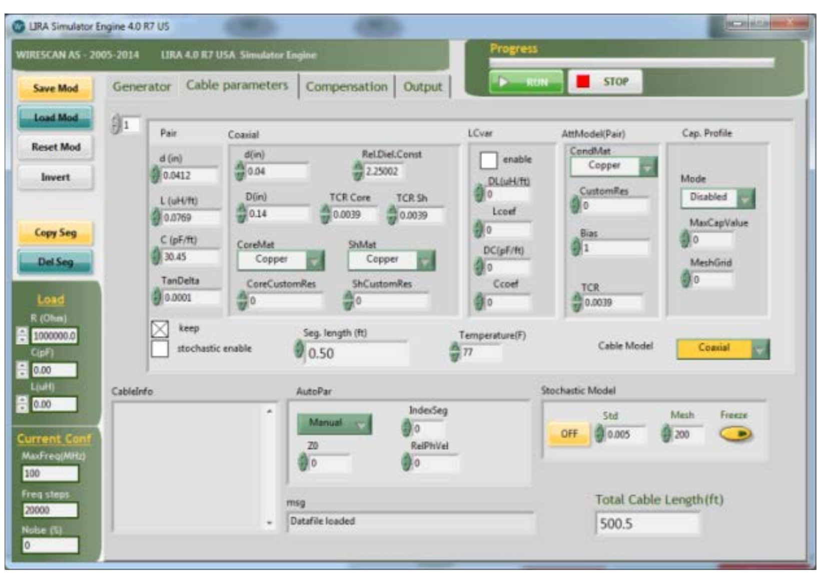


Figure 9.16. LIRA simulator module for analysis of multi-segment transmission lines.

The cable velocity factor, distributed capacitance, inductance, resistance, and attenuation are generally treated similarly among the three systems but are most clearly described based on example data taken by AMS and as discussed in Section 9.3.

The Delta-G parameter is designed to be a global cable aging indicator based on insulation dielectric loss computed from the impedance spectrum acquired by the LIRA system. In this context, G denotes the cable insulation conductance, which is one of the four primary parameters in transmission-line theory. It represents the leakage current through the cable insulation material and is obtained from a comparison of the measured and calculated characteristics of the cable at multiple resonances in the impedance spectrum. The calculation is performed to obtain the expected skin effect contribution, which LIRA cannot measure and is not affected by aging. This contribution is then subtracted from the total measured attenuation in the specified bandwidth, leaving the contribution due to the dissipation through the insulation dielectric material.

Figure 9.17 shows an example of the user interface used to calculate the Delta-G parameter. The calculation is based on non-linear regression and requires information about the cable parameters such as the conductor material, conductor size, and temperature to calculate the expected loss due to the skin effect. The regression algorithm defaults to fit the attenuation profile for the lower portion of the impedance frequency spectrum in order to avoid parasitic effects. An ideal cable would have a value of zero, and the numeric value increases with cable degradation. The Delta-G indicator is currently under development and evaluation by Wirescan for correlation with other condition indicators such as tan δ.

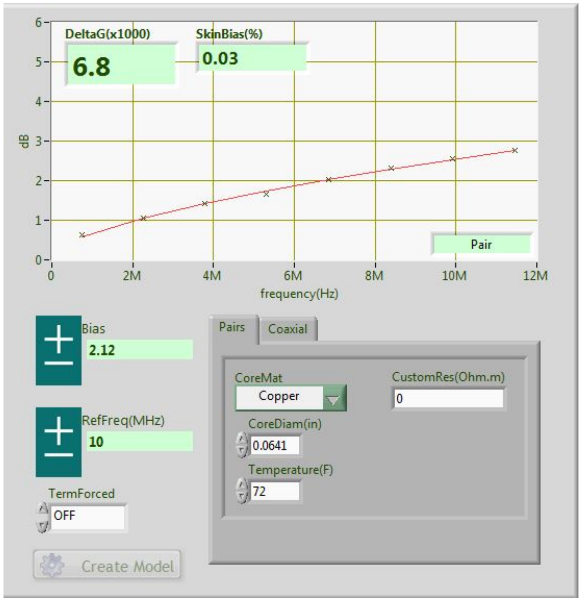


Figure 9.17. The user interface for calculating the Delta-G global cable assessment and aging indicator.

Figures 9.18 and 9.19 show a series of Delta-G values obtained from periodic measurements of an Okonite-FMR 600 V unshielded power and control cable and a General Cable FR-EPR/CPE 600 V shielded triad instrumentation cable, which were thermally aged for 1165 hours at 140°C. Both cables were 100 ft. in length, and all measurements were performed at room temperature for each of the three conductor pairs in the cables. At each measurement time, the Delta-G value for each conductor pair was recorded to provide a composite value to represent the cable condition. The measurement bandwidth was 100 MHz and the Delta-G reference frequency was approximately 20 MHz. The overall upward trend in each data set illustrates the increase in the Delta-G global aging indicator associated with the insulation dielectric loss due to the accelerated aging process.

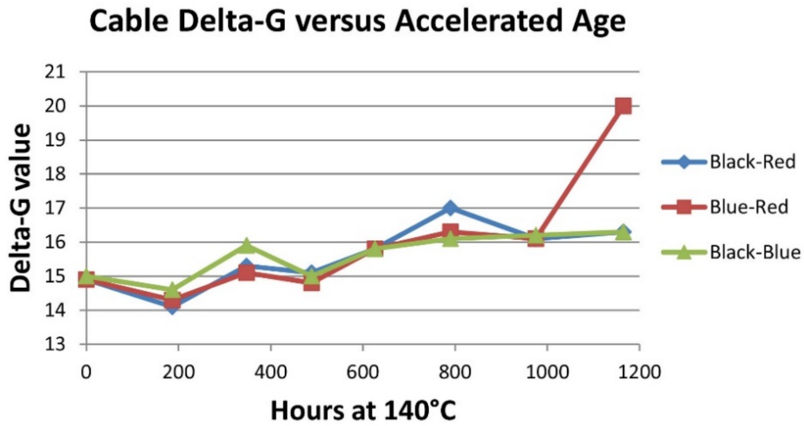


Figure 9.18. Delta-G values obtained from three conductor pairs for a globally aged unshielded cable.

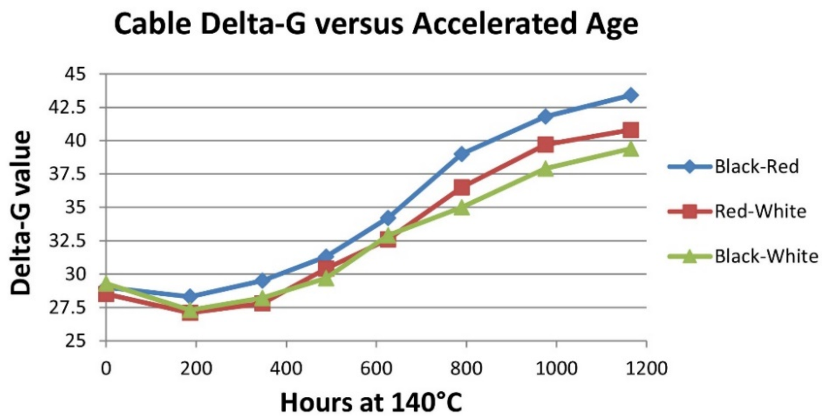


Figure 9.19. Delta-G values obtained from three conductor pairs for a globally aged shielded cable.

9.3 AMS CHAR System

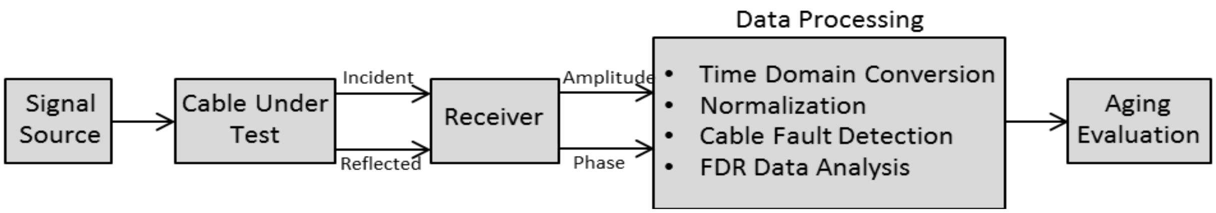
The CHAR integrated cable testing system developed by Analysis and Measurement Services (AMS) Corporation is a compact field measurement system designed to characterize cable health and integrity using a suite of nondestructive electrical tests. Bulk data available from the system includes lumped impedance and insulation resistance, and distributed data includes TDR, reverse TDR, and FDR. All measurements can be performed with single-ended access to the cables. The system is shown in Figure 9.20.

Figure 9.20. AMS CHAR system for monitoring cable condition. Courtesy of AMS Corporation.

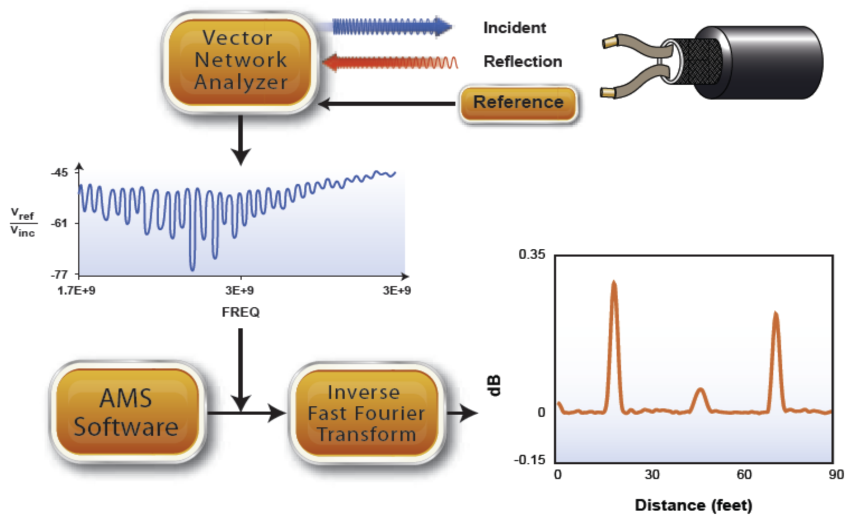
The FDR measurements included in the CHAR system can be used to measure and quantify insulation aging as well as detection of local “hot spot” degradations due to thermal and radiation exposure in support of troubleshooting, condition monitoring, and predictive maintenance programs. The frequency range of the swept sinusoidal signal can be selected from a minimum frequency of 100 kHz to a maximum frequency of 8.5 GHz with a frequency resolution of 1 Hz. The FDR testing of most plant cables uses frequency sweeps of 100 kHz to 500 MHz or 1 GHz. The test signal amplitude may be varied from -30 dBm to +15 dBm (~3.5 Volts peak to peak) across the typical frequency sweep. The dynamic range of the receiver is approximately 100 dB. The system includes custom software, which is installed on a separate control computer to analyze and plot measured data and performance trends.

The FDR test involves transmitting an incident wave ($V_{incident}$) of varying frequencies from a signal generator into the cable consisting of two conductors, a conductor and cable shield, or a conductor and ground plane. Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity in the cable. These reflected waves ($V_{reflected}$) are measured from differences in magnitude and phase to the original incident wave. The resulting reflected signal is typically measured in terms of amplitude versus frequency to create a spectrum of data.

Figure 9.21 shows a simplified diagram and example data processing flow for the AMS FDR system, which collects and processes the cable data for aging evaluation. After the data is collected, it is processed using a four-step procedure that includes time domain conversion, normalization, fault detection, and data analysis. Once the data processing steps are complete, an evaluation is performed for the specific polymer type of the cable being tested to quantify the age-related degradation.



(a)



(b)

Figure 9.21. (a) Block diagram and (b) data processing flow of AMS CHAR FDR system for monitoring cable condition. Courtesy of AMS Corporation.

The signal reflections measured by the AMS FDR system are caused by changes in the characteristic impedance (Z0) along the length of cable that can be attributable to physical changes such as cuts, gouges, and excessive bending or aging-related degradation of the cable insulation material caused by thermal and radiation aging. As an example, the characteristic impedance of the twisted pair cable shown in Figure 9.22 can be calculated using the following equation:

$$Z_0 = \frac{120}{\sqrt{\varepsilon_r}} \times \ln\left(\frac{2S}{D}\right) \tag{9.4}$$

where S is the distance between the two conductors, D is the conductor diameter, and ε_r is the relative permittivity of the insulation material.

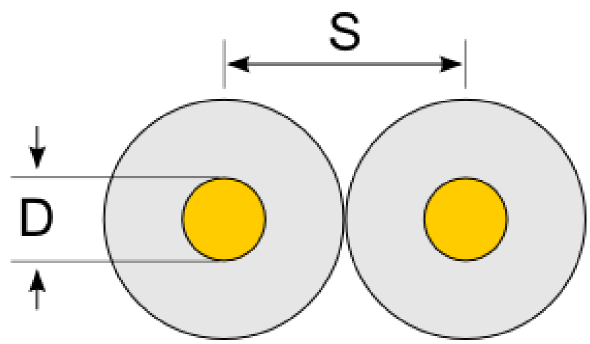


Figure 9.22. Cross-section view of commonly used twisted pair cable.

Based on this equation, the parameters that could create a change in characteristic impedance are the physical dimensions and the relative permittivity of the insulation material. Physical damage to the jacket material or excessive bending would cause changes in the spacing of the cable conductors. Because there is no significant change in the spacing or diameter of the conductors during the aging process, the relative permittivity is the only remaining variable that could change the impedance and cause reflections in FDR data. The relative permittivity is directly related to the capacitance of the cable using the insulation material as the dielectric media:

$$C\left({}^{pF}\!/_{inch}\right) = \left(\frac{0.7065}{\ln\frac{2S}{d}}\right) \times \varepsilon_r \tag{9.5}$$

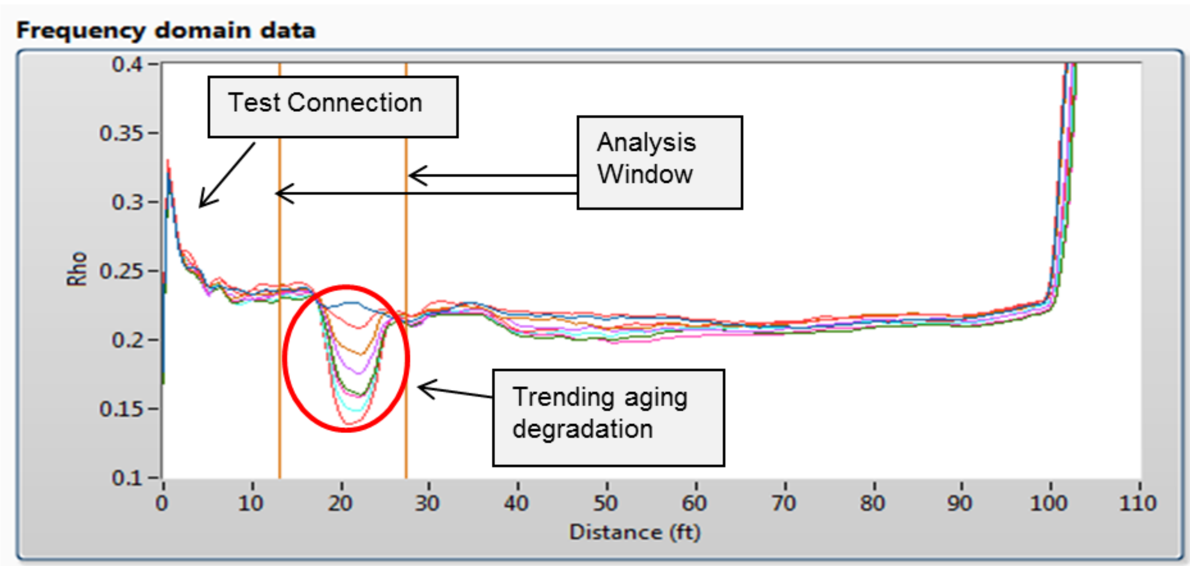
The capacitance changes from insulation aging can be trended over time using the FDR measurement software in the AMS CHAR system. The reflections of the FDR signal are converted from the frequency to the time domain using an inverse fast Fourier Transform. In the time domain, the impulse response data is further enhanced by integrating over time to obtain the step response. The result of the integral is expressed in terms of the reflection coefficient (ρ) as:

$$\rho = \frac{V_{reflected}}{V_{incident}}. \tag{9.6}$$

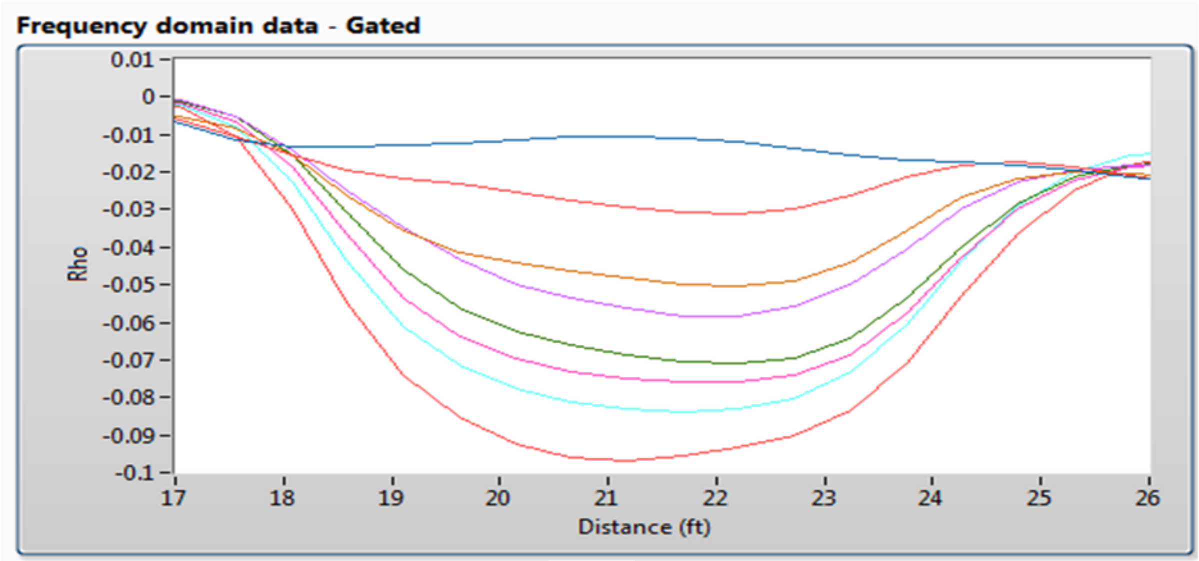
The distance to fault is calculated using the velocity factor for the cable, which is a percentage of the speed of light in a vacuum and is determined by the relative permittivity of the cable’s insulating material. Distance to fault can be determined by multiplying the signal propagation velocity of the cable (V_P) by half the time it takes for the incident wave to travel to the impedance change and be reflected back to the signal generator:

$$\text{Distance} = \frac{V_P T}{2}. \tag{9.7}$$

Figure 9.23(a) shows FDR measurements from the AMS CHAR system for a cable with XLPE insulation subjected to locally induced thermal aging at 135°C. This localized aging indicates changes in impedance relative to the cable's characteristic impedance (shown in ρ) as the cable ages. Figure 9.23(b) shows a detailed view of the data that was collected periodically during the accelerated aging process. The effects of thermal aging to the XLPE polymer are evident by the decrease in ρ throughout the aging process and can be trended over time to quantify cable degradation.



(a)



(b)

Figure 9.23. (a) Overall and (b) detailed view of reflection coefficient measured for local degradation versus accelerated aging for cable with XLPE insulation.

For a cable that has been aged uniformly over its entire length, both commercial systems can monitor additional characteristics that are affected to quantify aging degradation. Figure 9.24 shows an example measurement in which the characteristic impedance (expressed in ρ) decreases as a cable with XLPE insulation and CSPE jacket is aged at 135°C. In addition, the globally aged cable appears to increase in length with increased aging as shown in the FDR data overlays in Figure 9.25. The degradation of the cable insulation material effectively changes its permittivity, which causes the FDR signal to propagate slower along the cable giving the appearance of a longer cable during aging or a slower velocity factor. The propagation velocity originally determined for the unaged cable may be applied and then the result is an apparent lengthening of the cable as it is globally aged. Conversely, the cable length may be fixed in the software and the global aging will be reflected as a slower velocity factor. Only if the correct velocity factor value is used will the cable length be correctly assessed.

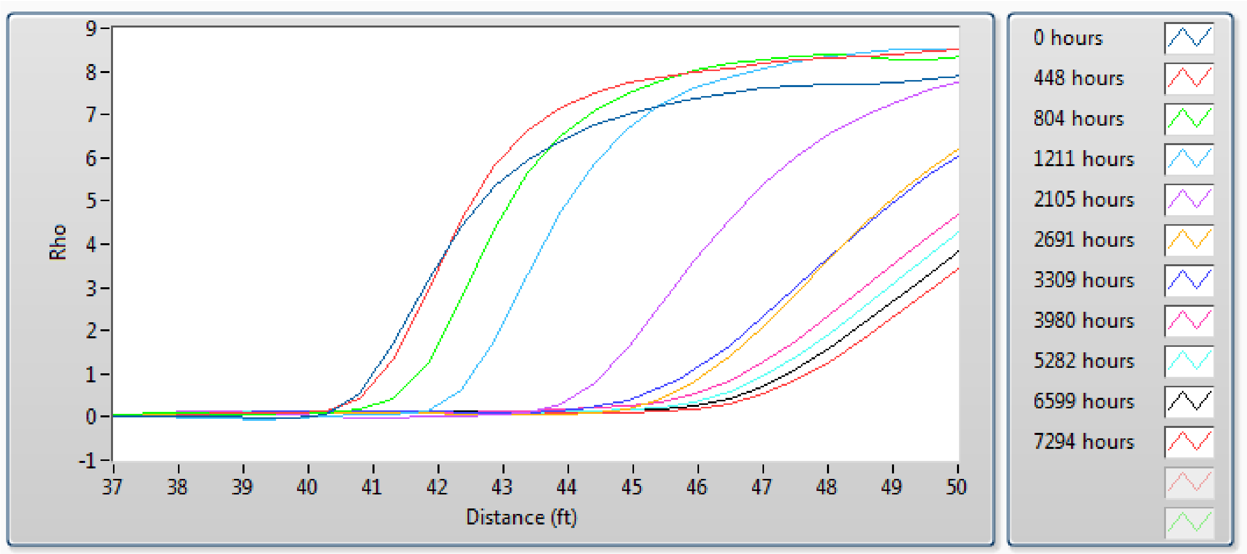


Figure 9.24. FDR global data versus accelerated aging hours for XLPE/CSPE cable showing a decrease in characteristic impedance (expressed as ρ).

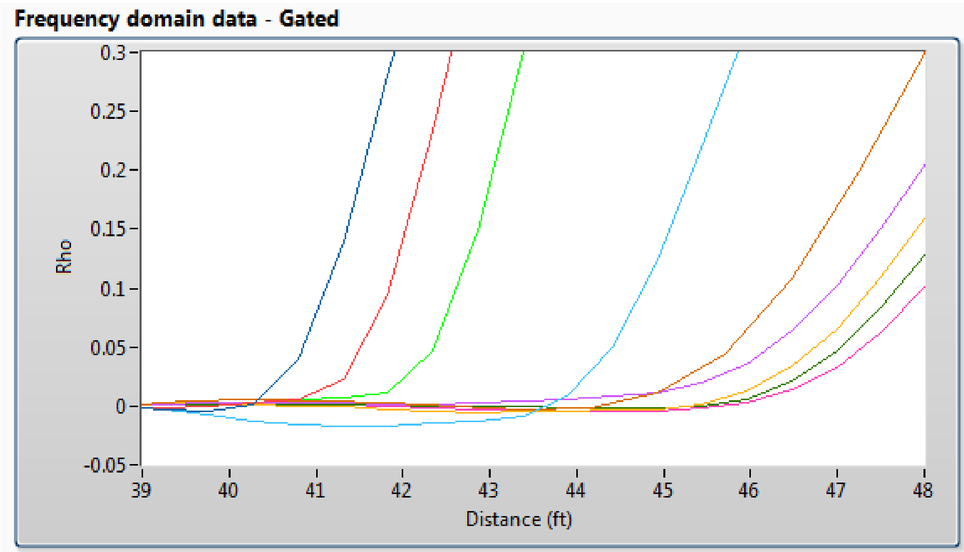


Figure 9.25. FDR global data versus accelerated aging hours for XLPE/CSPE cable showing an increase in apparent length.

Table 9.2 lists the change in apparent length that was measured throughout the aging process and the equivalent change in propagation velocity for the data plotted in Figure 9.25. The last measurement indicates a change of approximately 13% in these parameters compared to the baseline measurement. This example data set demonstrates that the FDR measurement capability can be effective in identifying and trending global cable aging.

Table 9.2. Changes in Apparent Length and Propagation Velocity of Globally Aged XLPE/CSPE Cable throughout the Aging Process

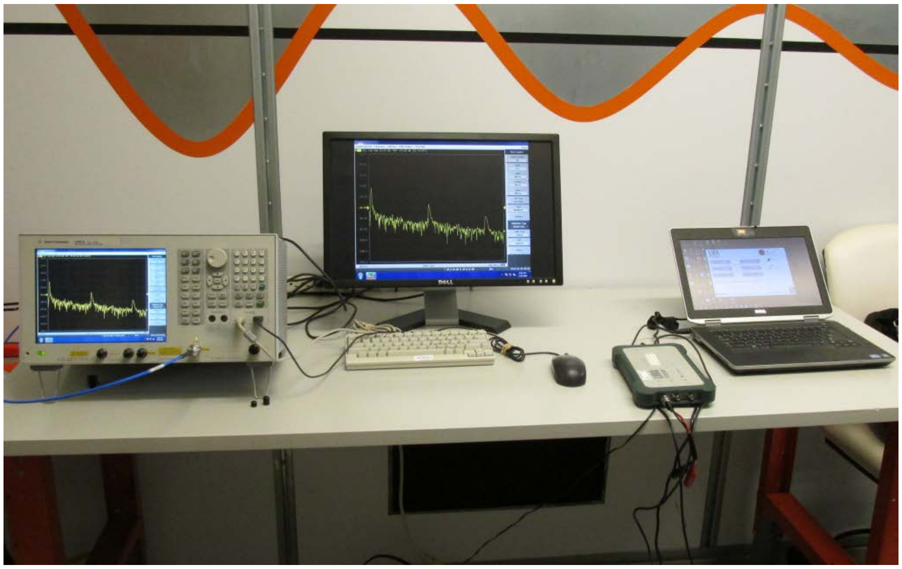
Hours Aged	Apparent length (ft.)	Δ ft. (%)	V_P	ΔV_P (%)
0	40.3	0.00	0.630	0.00
804	40.8	1.37	0.621	−1.37
1211	41.8	3.85	0.606	−3.85
2105	43.4	7.83	0.581	−7.83
3309	44.2	9.81	0.568	−9.81
3980	44.5	10.56	0.563	−10.56
5282	45.1	12.05	0.554	−12.05
6599	45.4	12.80	0.549	−12.80
7294	45.6	13.17	0.547	−13.17

9.4 Comparison of FDR Systems

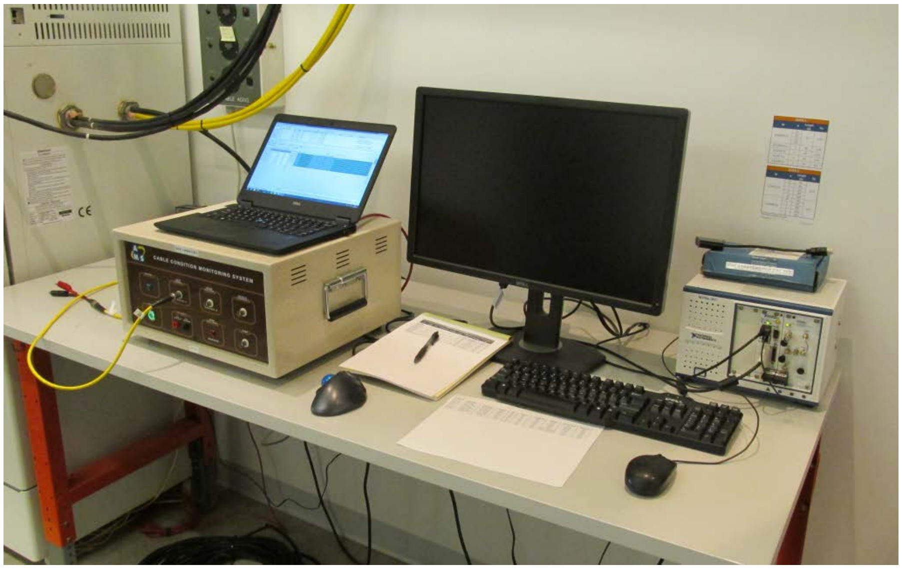
The FDR measurement systems described in the previous sections were used to measure a common series of cables that had experienced mechanical damage, thermally induced accelerated aging, or radiation-induced accelerated aging. Several cables without damage were also measured. The specific systems that participated in the test consisted of a Keysight Technologies E5061B VNA, the Wirescan LIRA Acquire system, and the AMS CHAR system. The test configuration and data acquisition settings of each instrument were as follows:

- The E5061B VNA options included the 5 Hz–3 GHz low-frequency to radiofrequency range, the high stability time-base, and the time-domain/fault location analysis. The VNA was connected to each test cable with a 3 ft. coax cable with BNC to alligator clip connectors. The VNA was calibrated to place the measurement reference plane at the instrument port. A Python script was used to automate the collection of frequency-domain and time-domain data sets for each test cable 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 measurement bandwidth.
- The Wirescan LIRA Acquire system was connected to each test cable with a short (~0.5 ft.) test lead with BNC to alligator clip connectors. A laptop computer with the LIRA software (Version 4.1 R7) 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.
- The AMS CHAR system was connected to each test cable with a 6 ft. coax cable with BNC to alligator clip connectors. A laptop computer with the CHAR FDR software was used to control the hardware. A standalone National Instruments VNA was also used to acquire data under control of a previous release of the CHAR FDR software. These two systems were able to produce conventional FDR signature plots as well as the reflection coefficient display from the step response shown in Figures 9.23–9.25. 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.

The measurements were performed at the same time with the cables laid out in long paths on the concrete floor of a large laboratory at room temperature. Figure 9.26 shows a photo of the three systems used in the measurement campaign. Figure 9.26(a) shows the VNA and external monitor on the left and the LIRA Acquire with its control computer on the right. Figure 9.26(b) shows the AMS CHAR system with its control computer on the left and an additional VNA used in the AMS system connected to a separate monitor.



(a)



(b)

Figure 9.26. (a) Keysight Technologies E5061B VNA and Wirescan LIRA Acquire systems. (b) AMS CHAR FDR system and standalone VNA used with CHAR FDR software.

A total of 18 cables ranging in length from approximately 100–200 ft. were measured over a two-day period. For a given cable measurement, the data from each system was recorded before moving on to the next cable. As shown in Figure 9.27, the cables were oriented side by side on the floor as a track layout around the perimeter of the laboratory.

Figure 9.27. Example layouts of test cables during FDR comparison study.

Table 9.3 lists the cables that were tested as part of the study. All of the cables were owned either by EPRI or PNNL. A single conductor pair was tested for each cable.

Direct comparisons were performed among the systems for a common bandwidth setting of 100 MHz by exporting the FDR signature from each system's measurement of a given cable. Several adjustments were necessary to enable a method of directly comparing the data sets. First, the cable attenuation as calculated by LIRA was also used to compensate for the cable loss in the VNA and AMS 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 AMS 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 which appear below or on the order of 0 dB were not interpreted as significant.

Table 9.3. Properties of Cables Tested during FDR Comparison Study

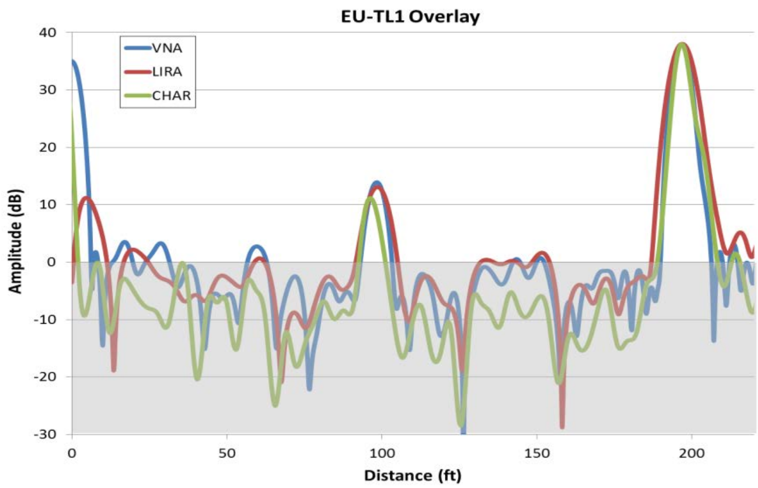
Owner	ID	Manufacturer	#C	Shield	Insulation	Jacket	Length (ft.)	AWG	Fault Type	Fault Length (ft.)	Fault Extent	Location (ft.)	Fault Detected by 100 MHz Systems	Fault Detected with Higher Bandwidth
PNNL	EU-TL1	Okonite	3	N	EPR	PVC	196.8	14	Local thermal aging	1.5	1269 hrs. @ 140°C	95	Y	Y
PNNL	EU-TL2	Okonite	3	N	EPR	PVC	100	14	Local thermal aging	1.5	1281 hrs. @ 140°C	50	N	Y
PNNL	EU-TG1	Okonite	3	N	EPR	PVC	100	14	Global thermal aging	100	1165 hrs. @ 140°C	All	N	N
PNNL	EU-B	Okonite	3	N	EPR	PVC	101	14	None	N/A	N/A	N/A	N/A	N/A
PNNL	ES-TL1	General Cable	3	Y	EPR	CPE	100	16	Local thermal aging	50	1281 hrs. @ 140°C	50	N	N
PNNL	ES-TG1	General Cable	3	Y	EPR	CPE	100	16	Global thermal aging	100	1165 hrs. @ 140°C	All	N	N
PNNL	ES-RL1	General Cable	3	Y	EPR	CPE	100	16	Local radiation exposure	1	60k Gray	50	N	N
PNNL	ES-B	General Cable	3	Y	EPR	CPE	100.8	16	None	N/A	N/A	N/A	N/A	N/A
PNNL	XS-RL1	RSCC	2	Y	XLPE	CSPE	101	16	Local radiation exposure	1	60k Gray	50	N	N
PNNL	XS-B	RSCC	2	Y	XLPE	CSPE	100.5	16	None	N/A	N/A	N/A	N/A	N/A
EPRI	EDC3	Dekoron	2	Y	EPR	CSPE	101.6	16	Cut	<1	Part way to conductors	19.7	Y	Y
EPRI	EIL4	BIW	2	Y	EPR	CSPE	100.6	16	Local thermal aging	3.5	500 hrs. @ 150°C	72.2	Y	Y

Owner	ID	Manufacturer	#C	Shield	Insulation	Jacket	Length (ft.)	AWG	Fault Type	Fault Length (ft.)	Fault Extent	Location (ft.)	Fault Detected by 100 MHz Systems	Fault Detected with Higher Bandwidth
EPRI	EOG3	Okonite	3	N	EPR	CSPE	92.3	12	Gouge	<1	1 conductor	19.7	N	Y
EPRI	XRL1	FW III	3	N	XLPE	CSPE	99.75	12	Local thermal aging	3.5	1000 hrs. @ 150°C	26.25	Y(2/3)	Y
EPRI	XRL3	FW III	3	N	XLPE	CSPE	101.9	12	Local thermal aging	3.5	1300 hrs. @ 150°C	26.25	Y	Y
EPRI	XRL4	FW III	3	N	XLPE	CSPE	100.7	12	Local thermal aging	3.5	1450 hrs. @ 150°C	26.25	Y	Y
EPRI	XRW1	FW III	3	N	XLPE	CSPE	101.5	12	Local thermal aging	3.5	504 hrs. @ 150°C	29.3	Y	Y
EPRI	X5G2	FW III	3	N	XLPE	CSPE	99.9	12	Gouge	<1	0.02 in. depth into insulation of 2 conductors	19.7	N	Y

Using this approach, signature plots for each cable were generated and analyzed. Each system produced a significant reflection at the degraded location for five of the eight cables that had undergone local thermal aging. Three of these cables were aged at PNNL. Good agreement was obtained among all the 100 MHz FDR measurements as shown in Figures 9.28–9.32 except for the XRL1 EPRI cable where both the CHAR system and the VNA instrument detected the thermal degradation but LIRA did not. This test however was just before a test-lead failure, and it is suspected that the test-lead failure may have introduced noise that obscured the indication.

Figure 9.28 shows a photo and common signature plot for the PNNL cable designated EU-TL1. Good agreement was observed for the detection of the local thermally aged section at 100 ft.

(a)



(b)

Figure 9.28. (a) PNNL cable EU-TL1 with thermally aged section at 100 ft. (b) 100 MHz FDR signature plot for PNNL cable EU-TL1 using three measurement systems.

Figure 9.29 shows the common signature plot for the EPRI cable designated XRL3. Good agreement is shown for the detection of the local thermally aged section at 26.25 ft.

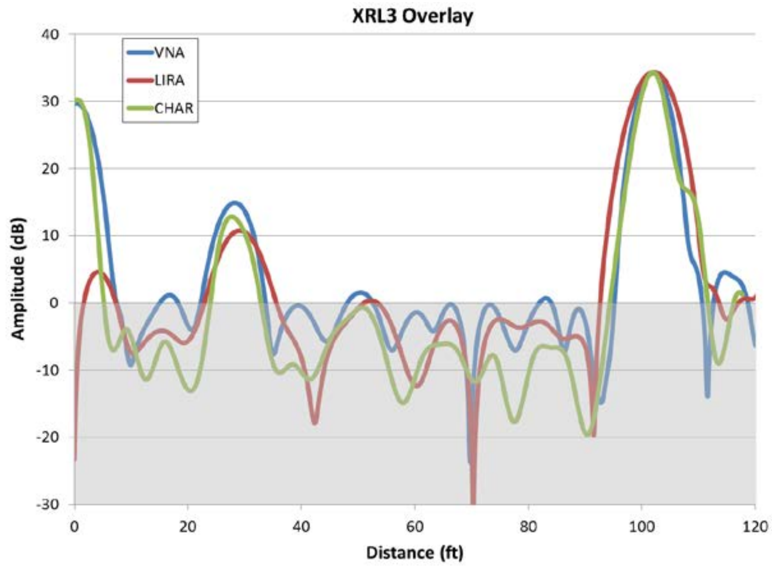


Figure 9.29. 100 MHz FDR signature plot for EPRI cable XRL3 using three measurement systems.

Figure 9.30 shows the common signature plot for the EPRI cable designated EIL4. Good agreement was observed for the detection of the local thermally aged section at 72.2 ft.

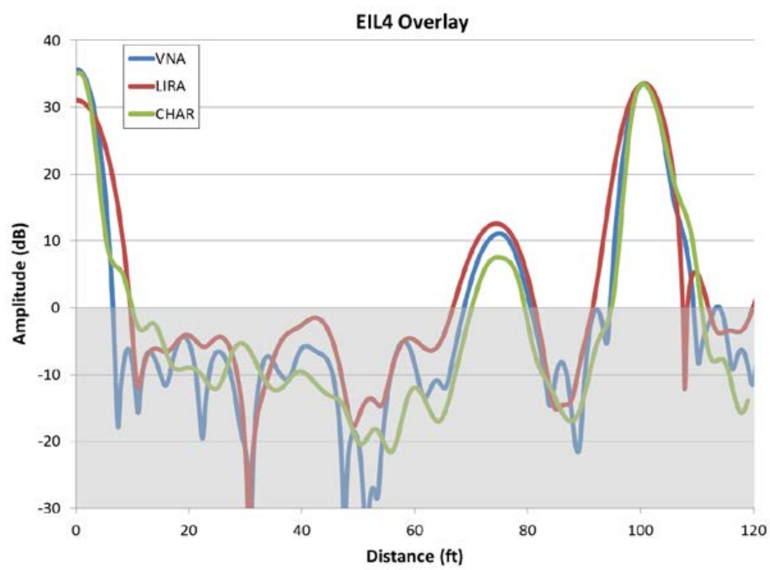


Figure 9.30. 100 MHz FDR signature plot for EPRI cable EIL4 using three measurement systems.

Figure 9.31 shows the common signature plot for the EPRI cable designated XRL4. Fair agreement was observed for the detection of the local thermally aged section at 26.25 ft.

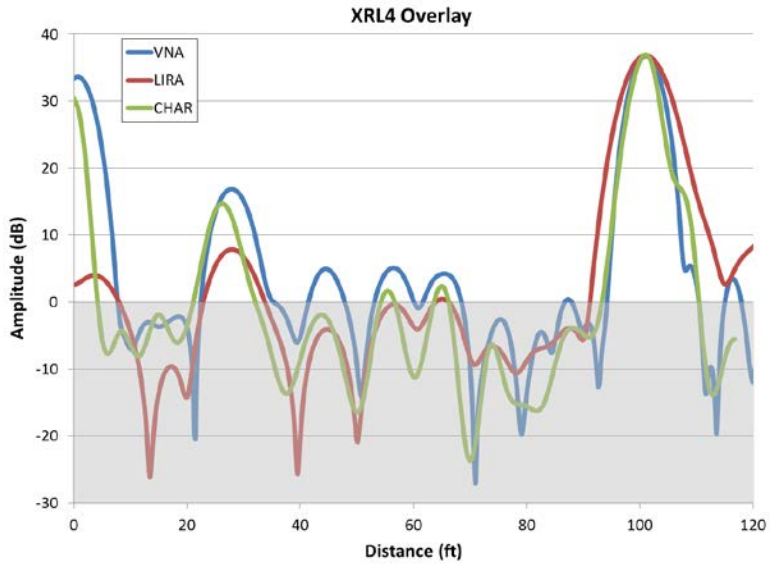


Figure 9.31. 100 MHz FDR signature plot for EPRI cable XRL4 using three measurement systems.

Figure 9.32 shows the common signature plot for the EPRI cable designated XRW1. Good agreement is shown for the detection of the local thermally aged section at 29.3 ft.

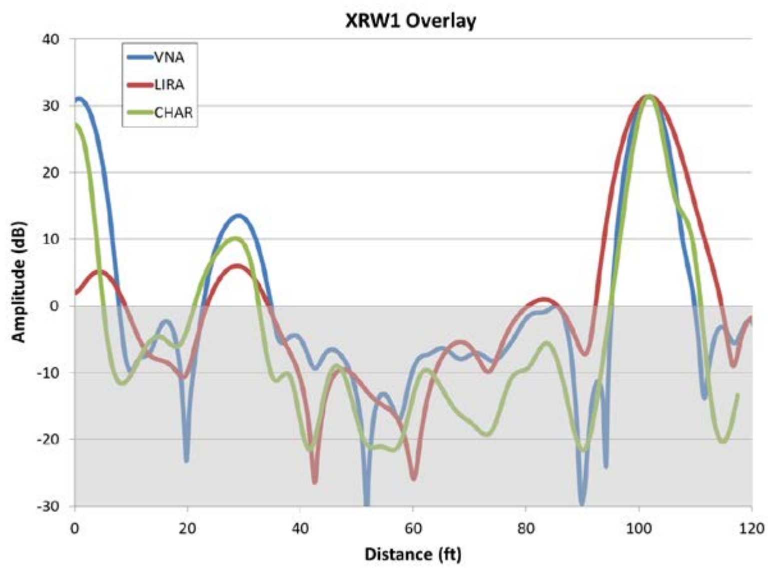
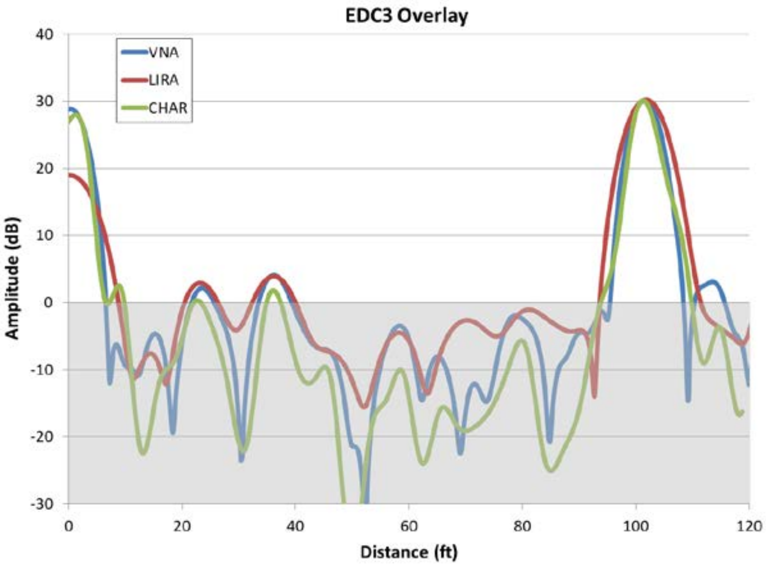


Figure 9.32. 100 MHz FDR signature plot for EPRI cable XRW1 using three measurement systems.

Neither of the two PNNL cables that had undergone local radiation exposure showed detectable spot signatures in any of the FDR systems at the degraded location. This represented good agreement among these measurements for a total dose of 60,000 Gray showing that this was not sufficient to produce detectable FDR peaks at the exposed location. This test was not particularly significant or surprising, however, because 60,000 Gray for this material would not be expected to show significant changes in EAB or indenter modulus.

The FDR systems showed a low-level spot signature for only one of the three cables with mechanical defects. This data and a photo are shown in Figure 9.33 for EPRI cable EDC3, which had a cut partway to both conductors at 19.7 ft. The measurements also indicated that an undocumented issue may exist at approximately 36 ft. A visual inspection of the cable did not produce any signs of damage at this location, and the cable was marked for x-ray analysis to further investigate the internal condition.

(a)



(b)

Figure 9.33. (a) EPRI cable EDC3 with cut to both conductors at 19.7 ft. (b) 100 MHz FDR signature plot for EPRI cable EDC3 using three measurement systems.

None of the systems detected significant local hot spots for the two PNNL cables that had undergone global thermal aging. Similarly, the three systems did not detect any significant hot spot reflections along the length of the PNNL baseline cables. As expected, these cables did not appear to have any locations of concern.

In addition to the 100 MHz comparisons, the VNA and AMS CHAR systems were used to acquire data sets using higher bandwidths up to 500 MHz. As indicated in Table 9.3, 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. Figure 9.34 shows results from the VNA measurements for EPRI cable EOG3, which had a gouge to one conductor perpendicular to the layer at 19.7 ft. The higher frequency plots also show a reflection from an undocumented feature at approximately 35 ft.

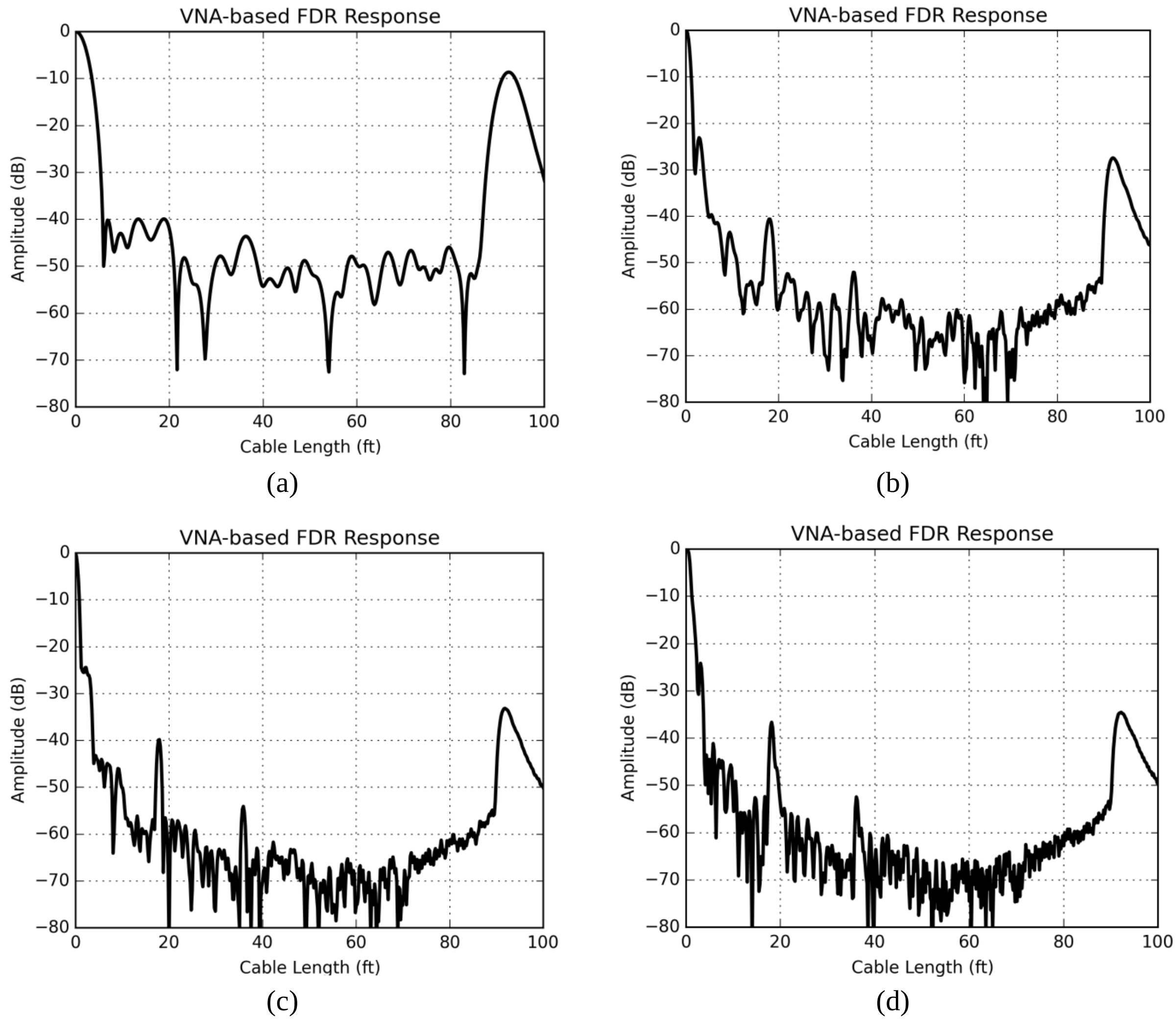


Figure 9.34. FDR signature plots acquired using VNA for EPRI cable EOG3, which has a gouge to one conductor at 19.7 ft. (a) 100 MHz, (b) 300 MHz, (c) 400 MHz, and (d) 500 MHz.

Figure 9.35 shows the equivalent data from the AMS CHAR measurements of cable EOG3 at 100 MHz and 500 MHz. Again, the higher frequency data shows a significant reflection from the gouge defect as well as other undocumented locations along the cable.

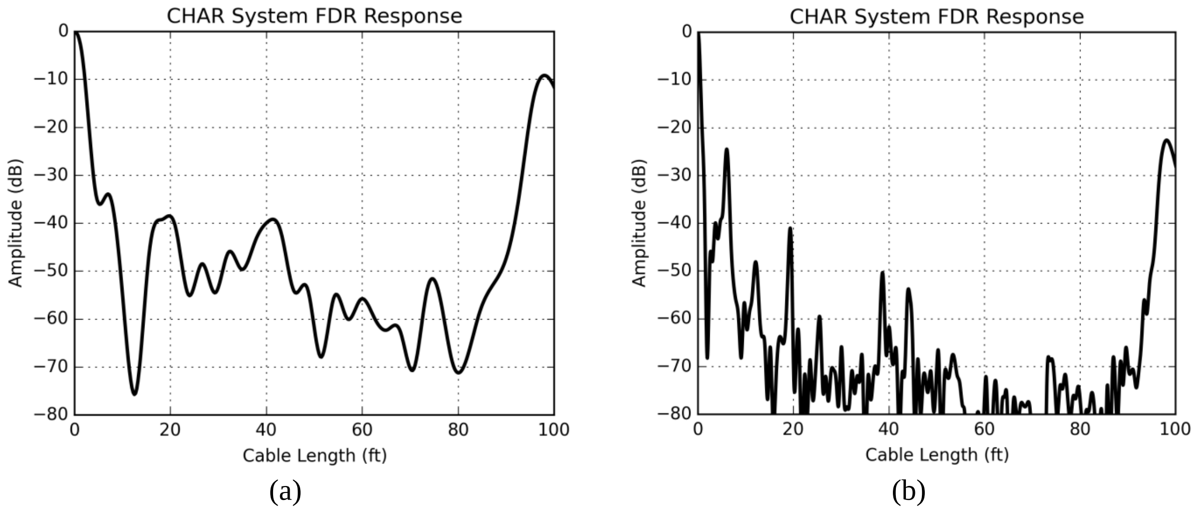


Figure 9.35. FDR signature plots acquired using AMS CHAR system for EPRI cable EOG3, which has a gouge to one conductor at 19.7 ft. (a) 100 MHz, (b) 500 MHz.

As another example, Figure 9.36 shows the comparison of VNA results for PNNL cable EU-TL2 for a series of FDR bandwidths between 100 MHz and 500 MHz. In this case, the thermally aged section at 50 ft. produced a large reflection for bandwidths above 300 MHz.

In addition to the signature plots, the LIRA and AMS CHAR systems can extract cable parameters such as inductance, capacitance, and impedance from the FDR measurement. These values can be tracked as a function of cable age to monitor for aging effects. Figure 9.37 shows a comparison of distributed capacitance for the cable measurements. The AMS CHAR system data is calculated at a frequency of 1 kHz. The LIRA system data is calculated at one of the lowest resonance frequencies used in each measurement, which is in the range of 1–2 MHz. Overall, good agreement is shown for the calculated capacitance of the measured cables.

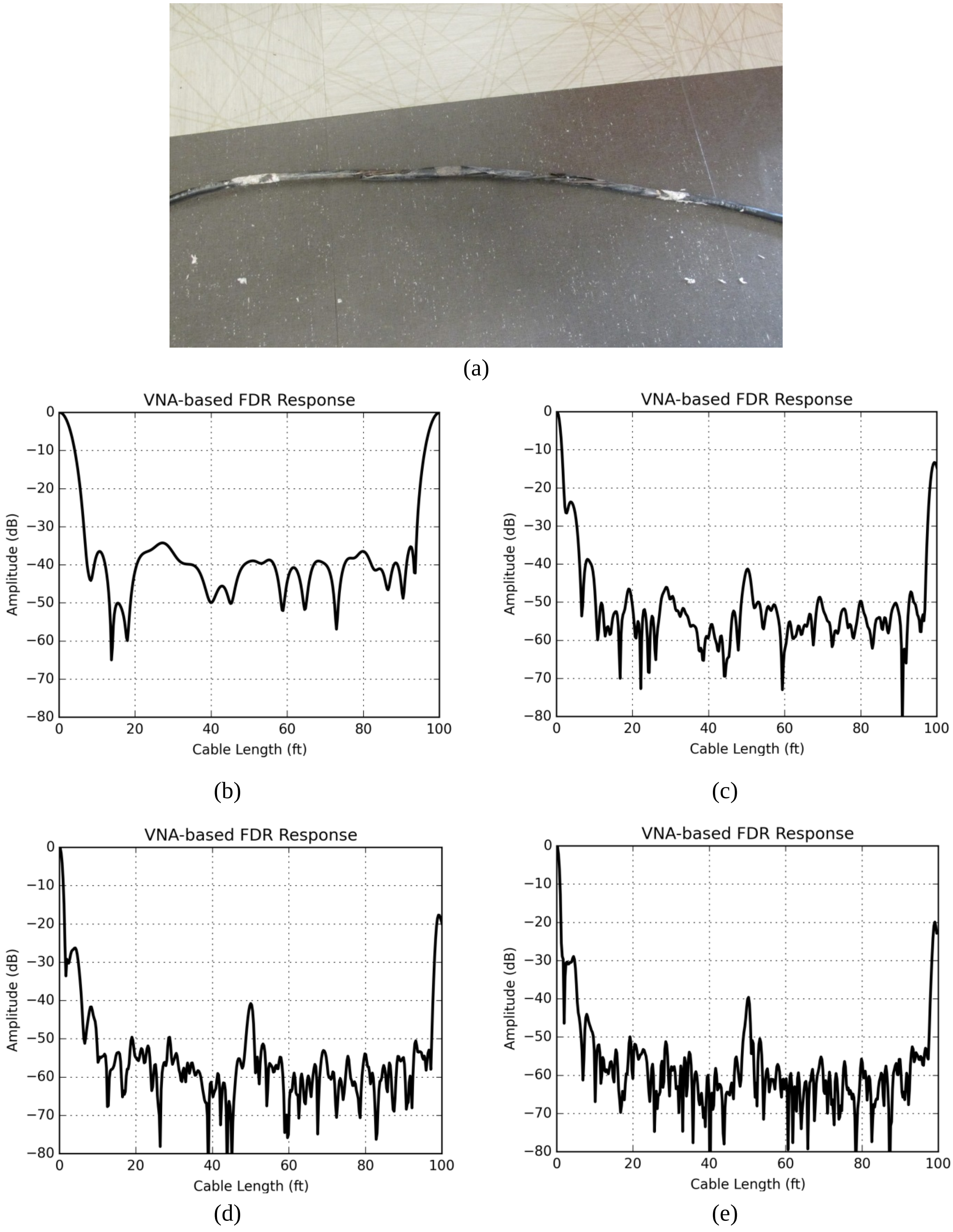


Figure 9.36. FDR signature plots acquired using VNA for PNNL cable EU-TL2, which has a thermally aged section at 50 ft. (a) photo of thermally aged section; data for bandwidths of (b) 100 MHz, (c) 300 MHz, (d) 400 MHz, and (e) 500 MHz.

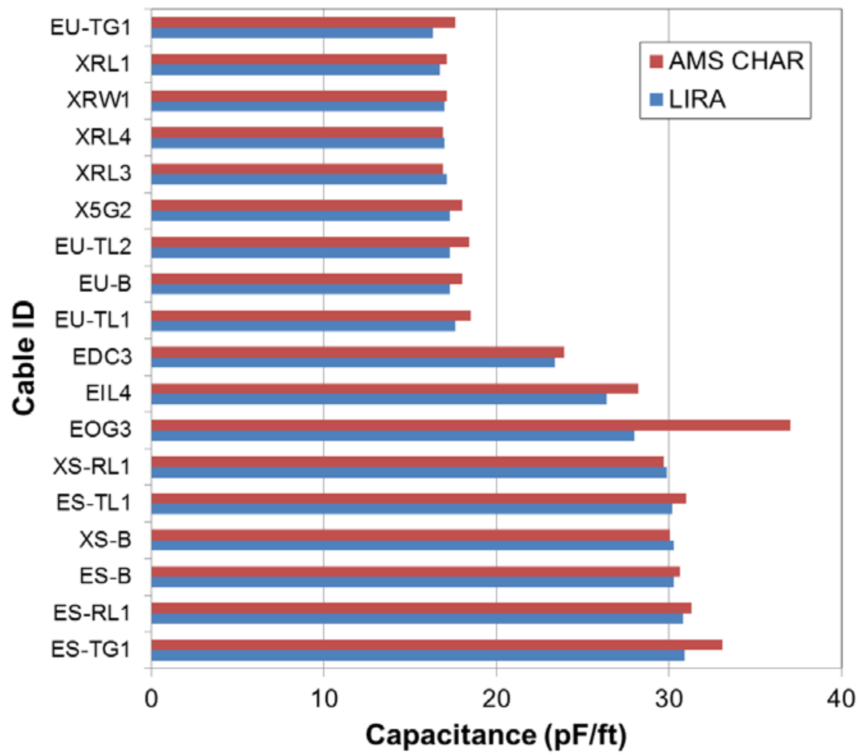


Figure 9.37. Extracted distributed capacitance of the measured cables from the two commercial FDR systems.

A comparison of velocity factor, distributed capacitance, and the Lira Delta G parameter from unaged and globally aged cables of the same design is given in Table 9.4. The outer jackets of these cables were cracked and quite fragile, clearly showing damage. 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 9.4. Selected Extracted Parameters from Commercial FDR Systems for Globally Aged Cables

	LIRA Velocity Factor		AMS Velocity Factor		LIRA Delta G		Lira Capacitance		AMS Capacitance	
Cable	Value	% Change	Value	% Change	Value	% Change	pF/ft.	% Change	pF/ft.	% Change
ES-B	0.60		0.60		25.5		30.3		30.7	
ES-TG1	0.57	−5	0.57	-5	40.3	+58	30.9	+2	33.1	+7
EU-B	0.63		0.63		14.9		17.3		18.2	
EU-TG1	0.63	0	0.63	0	17.4	+17	16.3	−6	17.6	−3

The AMS CHAR system can display the integrated impulse response, which results in a step response reflection coefficient plot format similar to a TDR system. This type of time-domain plot displays regions of concern along the cable as local discontinuities in the reflection coefficient value. The plot format can be helpful in quickly assessing the condition of the cable. Examples are shown in Figures 9.38–9.40. Figure 9.38 shows the change in reflection coefficient produced by local thermal aging at 72.2 ft. for

EPRI cable EIL4. Figure 9.39 shows the reflection coefficient discontinuities at the documented 19.7 ft. location and undocumented 36 ft. location for EPRI cable EDC3. The overall positive slope of the reflection coefficient versus distance is due to the frequency-dependent characteristic impedance of the cable. Figure 9.40 shows the discontinuity produced by local thermal aging at 26.25 ft. for EPRI cable XRL1.

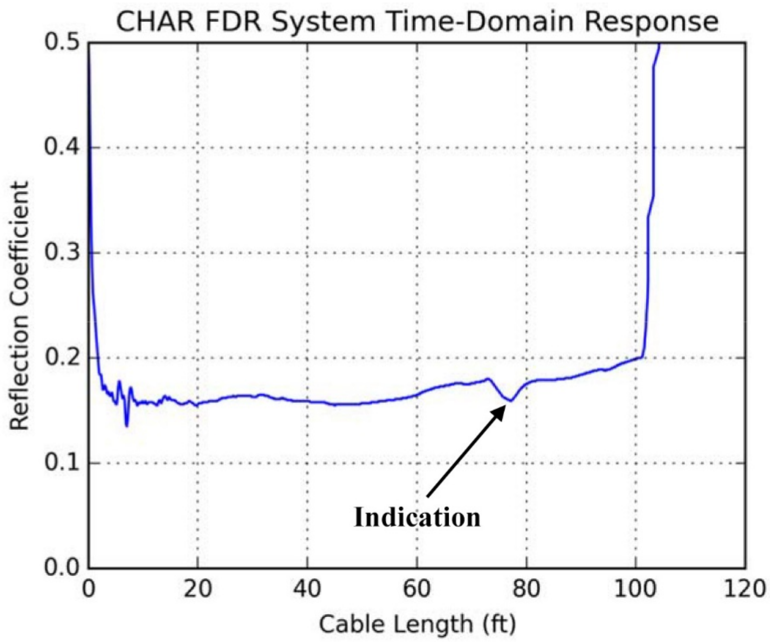


Figure 9.38. Step response reflection coefficient from AMS CHAR system for EPRI cable EIL4 (3.5 ft. thermally aged section at 72 ft.).

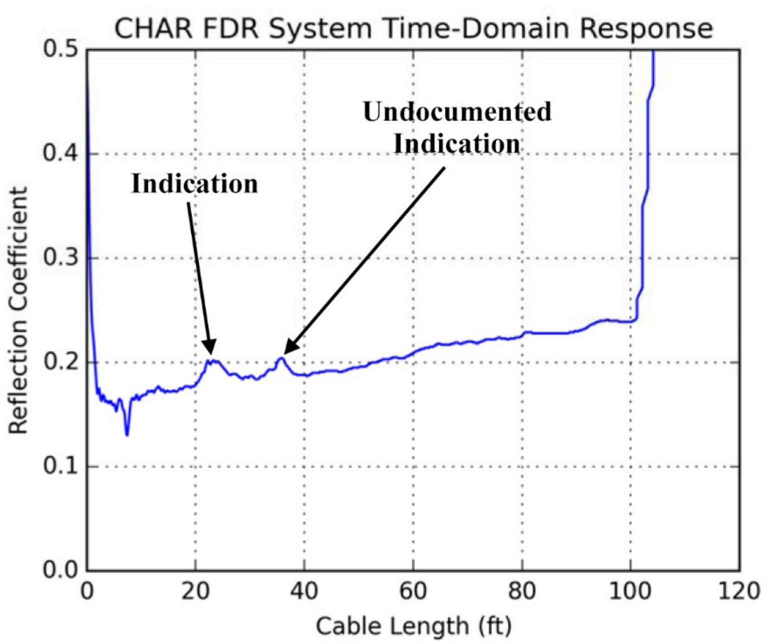


Figure 9.39. Step response reflection coefficient from AMS CHAR system for EPRI cable EDC3 (cut part-way to both conductors at 19.7 ft.) represented by peak at 23 ft. plus undocumented peak at 35 ft.

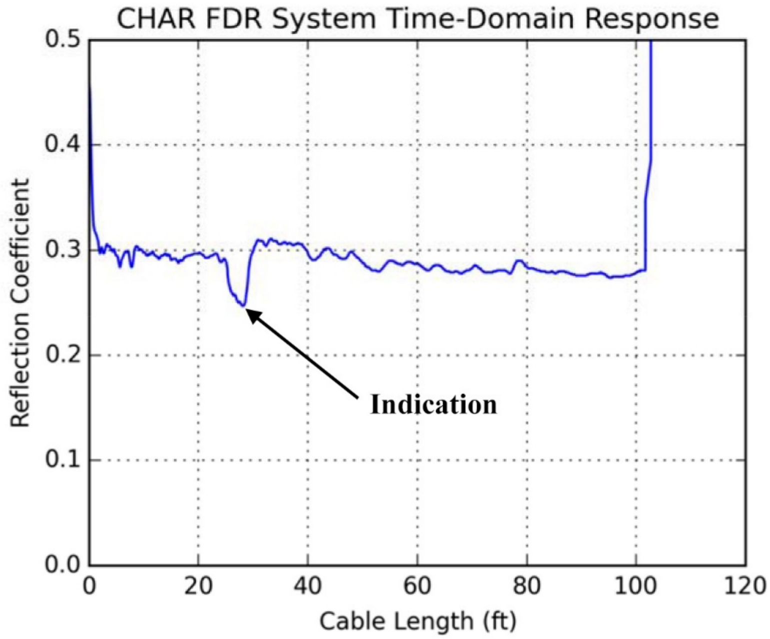


Figure 9.40. Step response reflection coefficient from AMS CHAR system for EPRI cable XRL1 (3.5 ft. thermally aged section at 26.25 ft.).

In summary, the aggregate data from each system plus the comparison of three FDR measurement systems showed the following:

- Major reflections corresponding to mechanical and thermally induced degradations were identified in the cable signature plots at similar levels after appropriate amplitude normalization. To avoid extraneous peaks in the data, all cables were routed to prevent reflections from excessive bends.
- Shielded cable is less noisy and less susceptible to metal proximity and other external influences than unshielded cable.
- Data for 100 MHz bandwidth acquisitions produced similar but not identical signal responses among the three systems. This provided confirmation that the FDR method provides similar results for different hardware systems when settings are equivalent. However, differences were observed that indicate that the same FDR instrument should be used to maintain a consistent database of measurements when comparing signatures of a given cable as a function of time. This will produce the best results when trending is used to detect subtle changes in the FDR response.
- Results of higher bandwidth acquisitions showed the ability to improve defect detection along the cable length in multiple cases. The use of bandwidths of at least 300 MHz provided good results for these relatively short cables. Higher bandwidths also enable a greater portion of the cable to be inspected by reducing the length of the termination shadow (“blind zone”) associated with the response from the far end of the cable.
- A reference level is helpful when attempting to interpret FDR data sets to detect localized defects. Compensating for the signal attenuation along the cable by removing the downward slope also improves ease of analysis of the signature plots, particularly for higher bandwidth acquisitions. For the LIRA system, the dynamic normalization sets the reference level for interpreting local peaks using a calculation of stochastic noise and also compensates for cable loss. For the AMS CHAR system, the step response reflection coefficient effectively sets a reference level for interpreting local impedance discontinuities and provides a familiar TDR-like presentation of the FDR data. In general, a sufficient signal-to-noise ratio is needed to differentiate responses due to local degradations from random or additional reflections along the cable length.

- Commercially available systems offer the ability to extract electrical parameters that can be monitored in addition to the signature plots which can be analyzed to identify local defects. In this study, the extracted cable capacitance for multiple cables was similar from two commercial systems. Other quantities include characteristic impedance, velocity factor, resistance, inductance, and attenuation.
- For globally aged cables, the reduced velocity factor along the cable or insulation loss-based indicators such as LIRA Delta-G can potentially be used to assess cable condition. Examples are shown in Figures 9.18, 9.19, and 9.25. However, the FDR system user must input key parameters (physical length or velocity ratio) for a cable measurement and be trained on a given assessment technique to properly interpret the results. Additionally, a baseline measurement (or series of measurements) of the cable is generally necessary to provide a reference for accurate assessment of global degradation.

Table 9.5. Advantages and Disadvantages of FDR Testing

Advantages	• Inspection of entire cable length from single-ended access • Low voltage safe, nondestructive 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

10. CONCLUSION

Although there is no single test for CM of NPP cables, a powerful set of tests exist and practical programs are being implemented to evaluate cable condition and justify continued NPP safe operation. The strategy generally includes: 1) trending of CM results within a structured database of select cables, 2) applying bulk electrical tests, 3) locating suspected weak points for focused local measurements, and 4) evaluating signs of cable degradation or damage so repair or replacement can be planned and cost-effectively managed. Bulk electrical tests such as the monitored VLF withstand tests using the tan δ indicator to alert the test engineer of increased leakage current indicative of cable degradation are widely used particularly for medium-voltage cables. This test may also be used for low-voltage cables and even unshielded cables but this is less common. Such tests are considered to be nondestructive with the caveat that if the current starts to increase or the tip-up value begins to significantly change, the test may be aborted before the test is complete. Partial discharge tests can also indicate locations of the cable degradation; however, access to the full cable length is necessary to completely inspect and locate the weakest segment of the cable. Bulk electrical tests such as FDR are particularly appealing because they include information about the location of questionable regions of the cable. Comparisons against baseline data also strengthen most test efficacies. Knowledge gaps highlighted from this work are:

- Need for a better physics-based understanding to associate peaks in the FDR, TDR, and other distributed electrical test responses to better justify the tests and support more specific acceptance guidelines. One example is a specific understanding of the length of the damage as an absolute value or as a percent of the overall tested cable length.
- Dielectric spectroscopy and/or VLF tan δ specific guidelines for low-voltage and unshielded cable tests similar to the guidelines already established for medium-voltage shielded cable.
- FDR responses identify locations of the most severe cable degradation but specific guidelines for dispositioning the cable as good, bad, subject to further investigation, or projections of remaining useful life are not available.
- New methods such as spread spectrum time domain reflectometry, nonlinear time domain reflectometry, and joint time-frequency domain reflectometry were not specifically evaluated within this report except to note that literature references indicated promise and potential for improved cable testing. These methods should be considered as/if near-field deployable instrumentation becomes available.

Work continues to refine tests and simplify analysis (as for FDR tests), to evolve existing and new approaches, and to refine the guidelines to aid in final disposition of a broader set of cable conditions.

11. APPLICABLE AND RELATED STANDARDS

- AEIC CS5, S*pecifications for Polyethylene and Cross-Linked-Polyethylene-Insulated Shielded Power Cables rated 5000–35000 V*
- AEIC CS6, *Specifications for Ethylene-Propylene-Rubber-Insulated Shielded Power Cables Rated 5–46 kV* (AEIC CS6 was replaced by AEIC CS8)
- IEC 60034-27–2007, *Rotating Electrical Machines – Part 27: Off-line Partial Discharge Measurements on the Stator Winding Insulation of Rotating Electrical Machines*
- IEC 60060-2–2010, *High-voltage Test Techniques – Part 2: Measuring Systems*
- IEC 60270–2015, *High-Voltage Test Techniques – Partial Discharge Measurements*
- IEC 60664-4–2005, *Insulation Coordination for Equipment within Low-voltage Systems – Part 4: Consideration of High-frequency Voltage Stress*
- IEC 61934–2011, *Electrical Insulating Materials and Systems – Electrical Measurement of Partial Discharge (PD) Under Short Rise Time and Repetitive Voltage Impulses*
- IEC/IEEE 62582-2–2016, *Nuclear Power Plants – Instrumentation and Control Important to Safety – Electrical Equipment Condition Monitoring Methods – Part 2: Indenter Modulus*
- IEEE Std 383–1974, *IEEE Standard for Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stati*ons
- IEEE Std 383–2015, *Qualifying Electric Cables and Splices for Nuclear Facilities*
- IEEE Std 400.2–2013, *Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)*
- IEEE Std 400–2012, *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std 436–1991 (R2007), *Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers*
- IEEE Std 525–2007, *Guide for the Design and Installation of Cable Systems in Substations*
- IEEE Std 1434–2014, *Guide for the Measurement of Partial Discharges in AC Electric Machinery*
- NEMA WC3/ICEA S-19-81, *Rubber Insulated Wire & Cable for the Transmission & Distribution of Electrical Energy*
- NEMA WC7/ICEA S-66-524, *Cross-Linked Polyethylene Insulated Wire & Cable for Transmission & Distribution of Electrical Energy*
- NEMA WC8/ICEA S-68-516, *Ethylene-Propylene Insulated Wire & Cable for the Transmission & Distribution of Electrical Energy*

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