Defect Length and Profile Influence on Frequency Domain Reflectometry

S. W. Glass, L. S. Fifield, A. M. Jones, T. S. Hartman

Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99352, Bill.Glass@pnnl.gov

INTRODUCTION

As nuclear power plants 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 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 SLR 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 unaged 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 the cable's system integrity.

One test that is gaining favor within the industry is frequency domain reflectometry (FDR). This is a low-voltage nondestructive test that can be applied at a cable end. Testing from the cable end is important because typical cable routing practice prevents local inspection all along the cable length. The FDR technique has been shown to locate cable insulation damage due to thermal, radiation, environmental, and mechanical damage [1][2]. Data interpretation, however, should consider a number of additional factors that can influence the FDR-based cable damage assessment. This paper addresses factors that can influence the FDR particularly focusing on defect length and defect profile.

FDR THEORY

FDR is based on the interaction of electromagnetic waves with conductors and dielectric materials as the waves 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, splices, faults in the conductors, or degradation in the cable polymer material. For the FDR measurement, two conductors in the cable system are treated as a transmission line through which a low-voltage, swept-frequency waveform is propagated (Fig. 1). 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. Because the applied signal is low-voltage, the test is nondestructive and poses no special safety concerns to operators.

FDR measurements have demonstrated sensitivity to a number of cable parameters—some of which are useful to evaluate cable health and some of which are associated with the test and environment and should be understood to be able to distinguish from the interesting cable health-related issues. Some of these parameters (not exhaustive) are shown in Table I and many of these parameters were explored in [3].

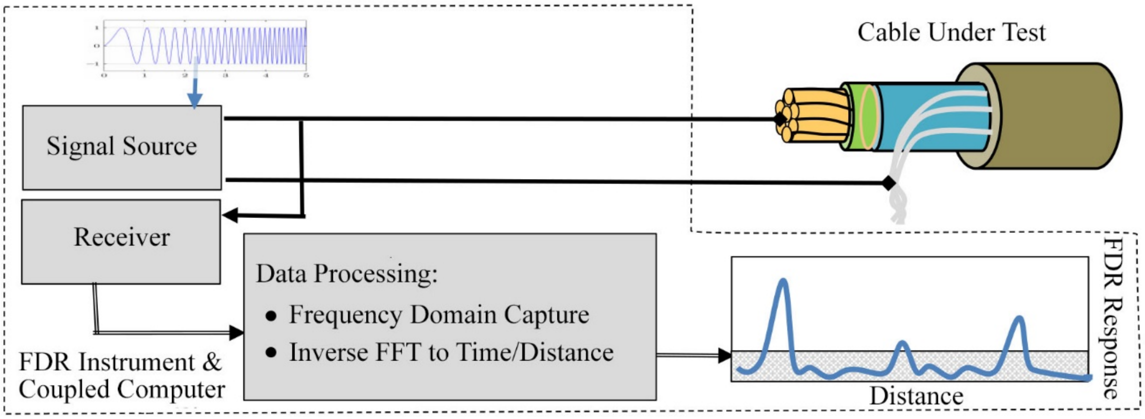

Fig. 1. FDR cable test connects to a signal and return line at one end of the cable. Signal analysis software displays FDR data as a function of distance from the cable test end.

TABLE I. Cable/Cable Health-Related and Cable Test/Environmental-Related FDR Influence Parameters

Cable/Cable Health-Related FDR Influence	Cable Test and Environment FDR Influence
Splices/terminations	Temperature
Insulation geometry (cuts, gouges, pinches, thickness)	Proximity of different conductivity surfaces
Insulation permittivity change (from thermal or radiation)	Design – shielded, semi-conductor shield, twist, …
Cable layout, bends/bend radius	Test frequency bandwidth
Cable signal transmission velocity	FDR normalization and presentation
Cable signal attenuation	Specific FDR instrument
Cable length	Termination impedance (load connected or not)
Damage profile	

To better understand how some of these parameters influence the FDR output, a physics-based finite element model was developed to allow parametric variations and simulation of the FDR test system. Where possible, the model was verified by a real cable test [3]. Two of the more interesting and practical parameters, defect length and defect profile, are discussed below.

RESULTS

Defect Length Influence on FDR Response

To evaluate the influence of defect length on the FDR response, the shielded triad cable model was adjusted to include a range of defect lengths in the center of a 100 ft. cable. The defect sections were represented by a uniform 5% change in insulation dielectric constant. Relatively short defects ranged from 0.25 ft. to 2 ft. and longer defects ranged from 3 ft. to 10 ft. The similarly grouped FDR responses were divided into relatively short damage lengths up to approximately ½ wavelength of the maximum FDR frequency bandwidth and relatively long damage lengths of ≥ ½ wavelength of the FDR's highest frequency bandwidth. At 200 MHz, the electrical wavelength for the triad cable modeled is approximately 1 m (½ wavelength ~1.6 ft.).

The simulation results for these two groups are shown in Fig. 2. No stochastic noise representing the effects of fabrication tolerances was included in the simulation. For the relatively short defects, the reflection peak decreased in amplitude from the 2 ft. length maximum response by 5–10 dB. The maximum amplitude defect length is equivalent to the ½ maximum frequency bandwidth spatial resolution of the FDR spectrum.

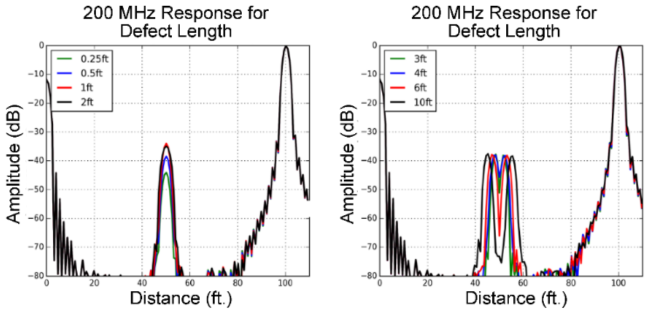

Fig. 2. 200 MHz ANSYS simulation results for 5% increase in insulation dielectric constant for (*left*) relatively short defect lengths (<1 wavelength at maximum frequency) and (*right*) relatively long defect lengths in shielded triad cable.

For the longer defects shown in Fig. 2, two distinct peaks were observed in the FDR response at the beginning and end of the defect segment. This is due to the defect length being greater than the spatial resolution of approximately 1.6 ft. for the 200 MHz FDR. The amplitudes of these peaks were approximately 3 dB lower than the maximum single peak.

In order to confirm the predicted response for relatively long defects, a set of cables was artificially aged for 1638 hrs. (corresponding to ~ 50% EAB or end of cable life) (Fig. 3 *left*). The shortest aged cable segment was 1.5 ft. and the longest was 10.5 ft. The 1.5 ft. damaged segment presented as a single peak (Fig. 3 *center*) while two distinct peaks were clearly visible with a 7.5 ft. (Fig. 3 *right*) and 10.5 ft. aged section when measured at 100 MHz and at 200 MHz.[a]

The significance of these observations is that the length of assumed uniform cable degradation should be considered during a peak amplitude calibration of FDR tests for assessing the degree of cable damage. Short defects will produce lower amplitude responses than defects that are on the order of a half-wavelength at the highest frequency of the FDR. Mechanical defects are typically quite short and this explains why they frequently produce small FDR peaks. Artificially aged cables passing through typical small ovens without any loops have damaged segment lengths near the maximum FDR peak response.

Defect Profile Influence on FDR Response

The previous paragraphs noted that longer defects with abrupt step changes in the insulation dielectric constant profile (equivalent to capacitance) produced significant responses at the beginning and end of the damaged area. In order to investigate defect scenarios where the change in cable electrical profile is of a more gradual nature, the model was adjusted for a tapered increase in the insulation dielectric constant along a defect compared to a uniform step changes. Simulation results for a linearly tapered defect profile along a 10 ft. section of a 100 ft. three-conductor shielded cable are shown in Fig. 4. The maximum change in the insulation dielectric constant is 5% in both cases. No stochastic noise representing the effects of cable fabrication tolerances was

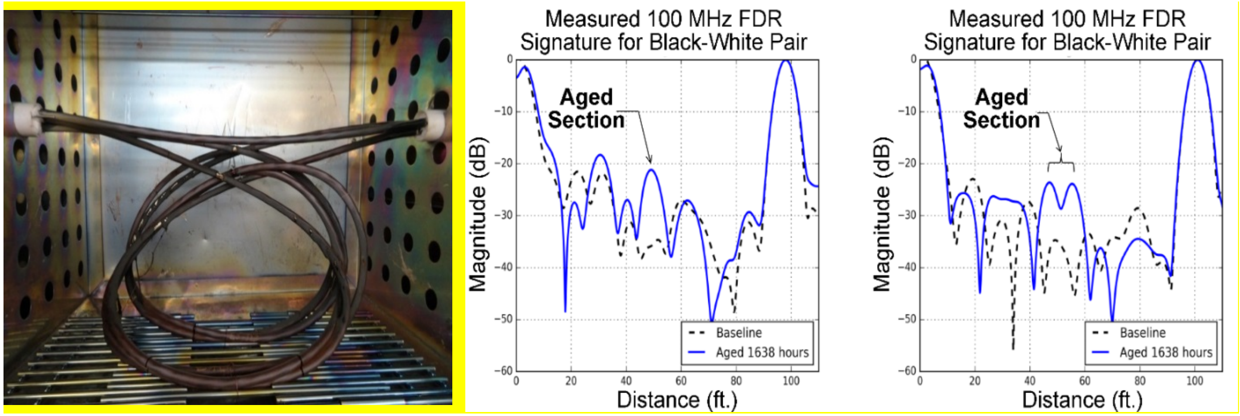

Fig. 3. 0, 1, and 3 loops of cable in the accelerated aging oven (*left*). FDR for 1.5 ft. thermally aged (*center*) and 7.5 ft. thermally damaged (*right*) shielded triad cable.

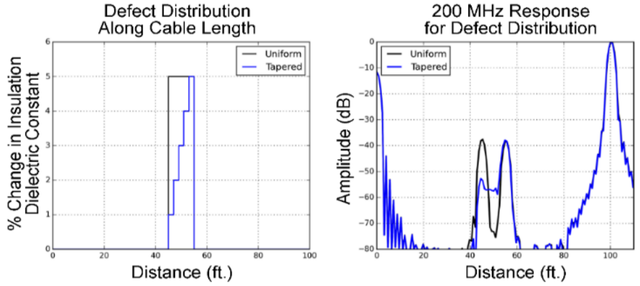

Fig. 4. A uniform 5% capacitance change from 45 ft. to 55 ft. (black) (*left)* versus a tapered change (blue) (*right*).

included in the simulation. The amplitude response at the beginning of the ramped segment is approximately 15 dB below the uniformly damaged segment since the gradual change in impedance along the cable smoothly transitions the electromagnetic wave between the undamaged and damaged segments. However, the amplitude response at the end of the ramped segment is equal to the uniformly damaged segment. This is due to the impedance change that occurs at this junction as the wave abruptly transitions back to the undamaged section. The two distinct peaks present in the FDR response for the uniform defect are separated by approximately three wavelengths along the cable.

Quantifying the effect of reflection peak variations under typical field conditions where a damage profile may be impossible to predict would be difficult. However, it can be understood that a non-uniform damage profile may exhibit an FDR response level different than a uniform damage profile.

CONCLUSIONS

Defect length and profile have an important influence on the FDR amplitude response. The maximum amplitude occurred for defect lengths on the order of ½ wavelength of the highest bandwidth frequency. This also corresponds to the FDR spatial resolution. For significantly shorter defects, the amplitude response is reduced. This is an explanation for the relatively small FDR amplitude responses for mechanical cable damage, because most mechanically damaged segments only extend for a short length.

For damage lengths longer than this half wavelength, two distinct peaks appear in the FDR response generally located at the start and stop of the damaged segment.

When the damage profile was tapered rather than occurring as a step condition change, the amplitude of the FDR peak was reduced. This was due to the gradual impedance change that reduces the reflection from the tapered portion of the defect segment. An in-plant analogous situation would be a cable routing where temperature increase is gradual as in a large room vs. a cable routing where the cable crosses a hot steam line or abruptly transitions from a cool room to a hotter room.

ENDNOTES

[a] Not shown in this report but these graphs are available in [3]: 100 MHz graphs with aged and baseline traces are clearer than 200 MHz traces without baseline.

REFERENCES

1. S. W. GLASS, A. M. JONES, L. S. FIFIELD, T. S. HARTMAN, "Bulk Electrical Cable Non Destructive Examination Methods for Nuclear Power Plant Cable Aging Management Programs," PNNL-25634, Pacific Northwest National Laboratory, Richland, WA (2016).
2. P. F. FANTONI, A. NORDLUND, "Wire System Aging Assessment and Condition Monitoring (WASCO)," Report NKS-130, Nordic Nuclear Safety Research, Roskilde, Denmark (2006).
3. S. W. GLASS, A. M. JONES, L. S. FIFIELD, T. S. HARTMAN, N. BOWLER, "Physics-Based Modeling of Cable Insulation Conditions for Frequency Domain Reflectometry (FDR)," PNNL-26493, Pacific Northwest National Laboratory, Richland, WA (2017).