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Final Report

Joint Time-Frequency Domain Reflectometry for Diagnostics/Prognostics of Aging Electric Cables in Nuclear Power Plants

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GRA: David Coats, Jingjiang Wang
PI: Yong-June Shin
University of South Carolina
301 Main Street
Columbia, SC 29209
coats@email.sc.edu; wang66@email.sc.edu; shinjune@cec.sc.edu

Project Manager: Darrell Murdock
Mechanical & Electrical Engineering Branch
Division of Engineering, Office of Research
US Nuclear Regulatory Commission
Washington, DC 20555-0001
Darrell.Murdock@nrc.gov

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1. INTRODUCTION: Motivations for Nuclear Cable Monitoring

Due to the complexity of interconnected control, generation, and operational electronics of nuclear systems, the integrity of wiring in the electric power system of a nuclear power plant is vital to its safe operation. Electric power cables are subjected to various stresses including electrical stress from transmission of energy, mechanical stress from generation processes and rod instrumentation, chemical and liquid intrusion from coolant systems and generated steam, and especially thermal stresses from reactors and heat dissipation in electromechanical systems [1]. These thermal stresses in particular can accelerate the aging process of cable insulations in normal service conditions. Nuclear plants provide additional complications to the typical concept and science of component aging due to radioactive materials which may not be as thoroughly studied and delineated as conventional aging methods. Nuclear power plants are facing the technical challenges of detecting and locating faulty cables among miles of instrumentation, and are also experiencing premature failures much earlier than the life expectancy originally estimated, highlighting the need for non-destructive and non-intrusive test methods. In our research over the course of this NRC grant, we have developed a new perspective for cable aging and health management based on the aforementioned concerns and towards a joint time-frequency based metric of fault location, reflection coefficient based line and localized fault impedance, fault classification, and prognostic aging profile under various stresses.

As a summary of recent works in the diagnostics and prognostics of electric cables both nationally and internationally, the NRC and Brookhaven National Laboratory have worked on the diagnostics and prognostics of electric cables with the Broadband Impedance Spectroscopy (BIS) (developed by Boeing) [2] while internationally the OECD Halden Reactor Project in Norway has produced the specialized frequency domain interpretation method known as Line Resonance Analysis (LIRA) [3] and the Japanese Nuclear Energy Safety Organization (JNES) has developed advanced environmental qualification methods [8]. The purpose of these techniques is to detect and locate defects before they cause a component to fail. Although BIS and LIRA have different names, these two methods both monitor impedance of faults caused by insulation degradation using frequency-domain reflectometry (FDR), primarily due to the extreme challenges involved in accurately measuring fault impedance in the time domain. Joint time frequency domain reflectometry (JTFDR) fills a void in current non-destructive, non intrusive, in situ test methods by providing a customizable reference signal in which the user can select appropriate parameters of frequency bandwidth, center frequency, and time duration to provide resolution in both the time and frequency domains.

From this joint domain resolution attributes of the cable such as impedance and impedance mismatch of localized aging gradients can be monitored to assess the status of cable insulation in an effort to predict the remaining life of power cables. JTFDR captures the advantages of both TDR and FDR by using advanced digital signal processing while avoiding some of their limitations [4]-[6]. JTFDR has been proven to be able to accurately and sensitively detect both hard and incipient defects on coaxial cables [5]-[6]. The unique features of the time-frequency cross-correlation function employed by JTFDR also allow it to monitor the minor changes in cable insulation which indicate the health status of the cable with a high degree of sensitivity.

2. TECHNICAL APPROACH

2.1. Overview of accelerated aging procedure

The accelerated thermal aging tests in this report will apply higher stress levels than normal operation values to quickly induce age-related degradation of cables and enable the study of the aging process of cable in a relatively short time period. The cable samples will be aged for a specific time, which is usually used to verify the effectiveness of the monitoring techniques. The current system function diagram is shown in Figure 1 while the actual test equipment is shown in Figure 2.

The simulated service life of all four types of insulated power cables is set to between 90 and 120 years but compared on a basis of 90 years (or 150% of normal cable service life). The accelerated aging temperature and the aging time at the acceleration temperature are calculated using the Arrhenius model [7].

$$\frac{t_s}{t_a} = e^{\left[\frac{E_a}{B}\cdot\left(\frac{1}{T_s}-\frac{1}{T_a}\right)\right]} \tag{4}$$

While this method is typically provided in a larger context for a single chemical reaction, it is an adopted methodology for general assessment of complex or compound chemical and chemical decomposition processes. The length of all four types of cable samples is 10 m. Each cable sample, except the TR-XLPE insulated cable, also has a one meter long “hot spot” from 5 m to 6 m which corresponds to the part of the cable to be aged in the oven. The TR-XLPE insulated cable utilizes a 0.6 meter long “hot spot” from 5 meters to 5.6 meters to allow the thicker diameter and lower bend radius to fit within the heat chamber cavity. During the accelerated aging tests, JTFDR is employed to assess the various states of the “hot spot” during the aging process. All JTFDR measurements are acquired after allowing for cooling to ambient temperatures to avoid measuring cable geometry changes.

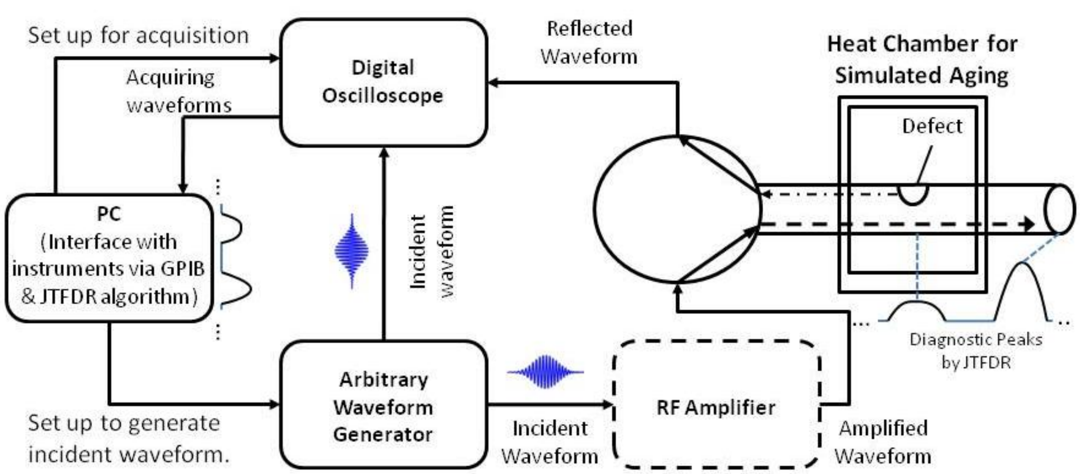

Figure 1. JTFDR System Function Diagram.

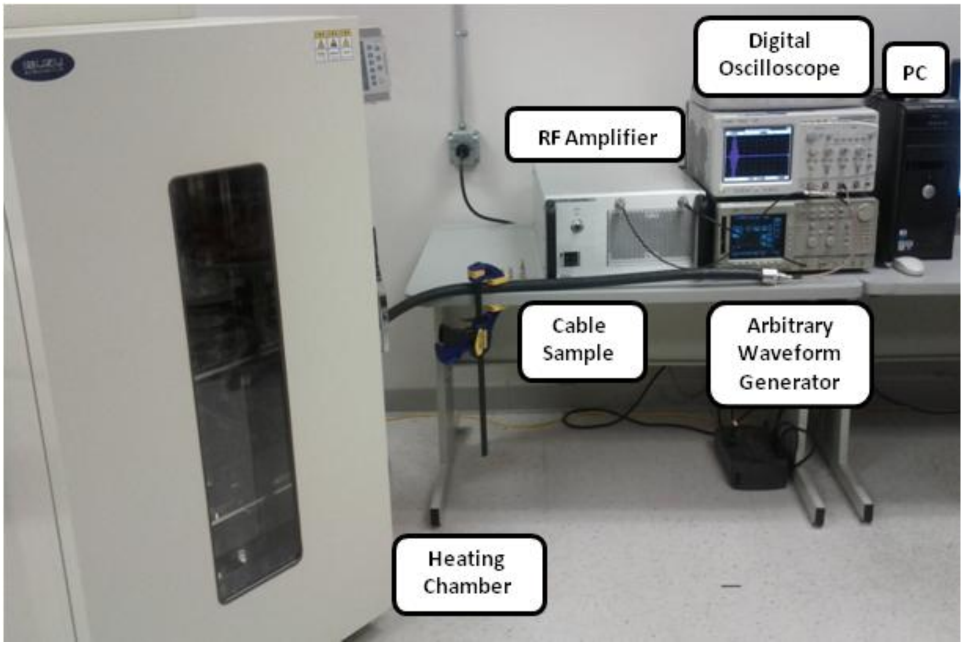

Figure 2. Existing JTFDR Workstation at Power IT LAB in University of South Carolina.

Additional equipment has been purchased over the course of the NRC grant to validate JTFDR experimental methods for high voltage cables. An RF Amplifier (120W) was acquired to provide for longer distance test and tests of thicker cables. Very Low Frequency (VLC) high potential source or hipots was also acquired to perform tests such as partial discharge in various insulation types. Additional equipment purchased on future grants will allow for partial discharge testing of cables up to 65kV.

Figure 3. Newly acquired test equipment: Controller for Very Low Frequency (VLF) source, LC meter, and instrumentation (left) and VLF High Potential Test Source up to 65kV (right).

2.2. Cable insulation materials

The cable sample with XLPE insulation is from a Rockbestos Firewall III XHHW, 14AWG, dual-conductor, 600 V cable; the TR-XLPE insulated sample is from a Pirelli MV-90, 1/0 AWG, single conductor, 35kV cable; the EPR insulation cable sample used is from a Nexans MIL-DTL-24640 TXW-4, 600 V cable; the SIR insulated cable sample used is from a Nexans LSTSGU-9: M24643/16-03UN cable. Further details on each type of cable and the Arrhenius model parameters with accelerated aging specifications for each cable type are summarized in Table I.

This table includes the activation energy, a chemical property of materials used to indicate chemical breakdown of insulation materials, as well as the experimental temperature and duration to simulate 90-120 years of service at an operating temperature of 50˚C. The activation energy is used to calculate accelerated aging parameters as a variable in the Arrhenius equation.

Table I: Summary of Cable Information and Experimental Duration

Insulation Type	Manufacturer, Cable type	Activation Energy (eV)	Temperature (˚C)	Experimental Duration (Hr)
Cross-linked polyethylene (XLPE)	Rockbestos, Firewall III XHHW	1.33	140	24
Tree Resistant Cross-linked Polyethylene (TR-XLPE)	Pirelli, MV-90	1.33	140	24
Ethylene Propylene Rubber (EPR)	Nexans, MIL-DTL-24640 TXW-4	1.1	160	48
Silicon Rubber (SIR)	Nexans, LSTSGU-9: M24643/16-03UN	2.1	120	12

2.3. Application of Joint Time-Frequency Domain Reflectometry method

An optimal reference such as the one seen in Figure 4-(a) is developed for each insulation type under test according to previously determined algorithms. This signal is injected into each

10 m cable sample following the outline of Figure 1. The JTFDR method described in previous reports is then applied using the incident reference signal and reflected signal.

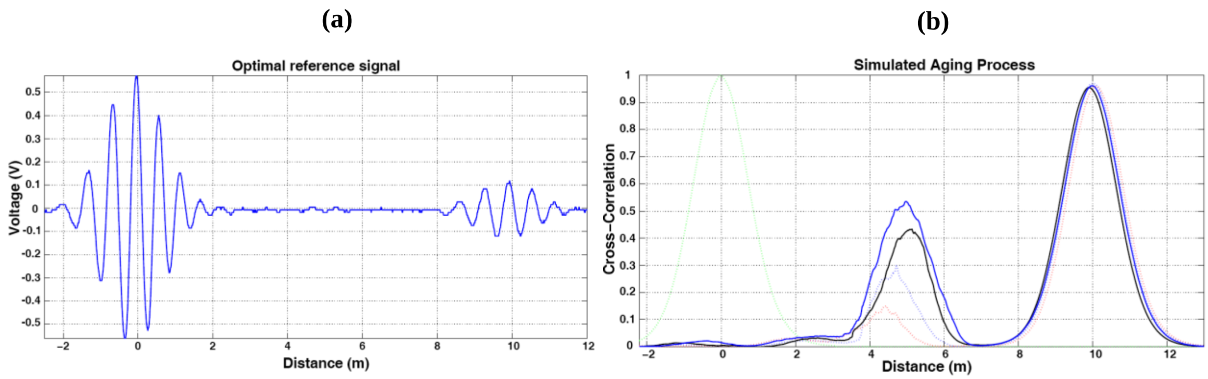

Figure 4. (a) Example optimal reference and reflected signal and (b) Time-frequency cross-correlation at various times during the aging test for MV-90, TR-XLPE insulated cable.

Time-frequency cross-correlation peaks from the JTFDR method are seen in Figure 4-(b) for medium voltage transmission cable (MV-90). General trend lines effective for prognostics can be established for assessment of insulation integrity based on the peak while time and frequency localization also provides effective diagnostics for low error fault location.

2.4. Results of health monitoring tests

In order to compare the performance of all four types of insulation, the results of the time-frequency cross-correlation local peaks for XLPE, TR-XLPE, EPR, and SIR are plotted in one figure as shown in Figure 5-(a). Traditional elongation-at-break measurements are provided in Figure 5-(b) for comparison and were reported for XLPE, EPR, and SIR materials, though not necessarily the same cable brand as those tested in our study, by the Japan Nuclear Energy Safety Organization [8].

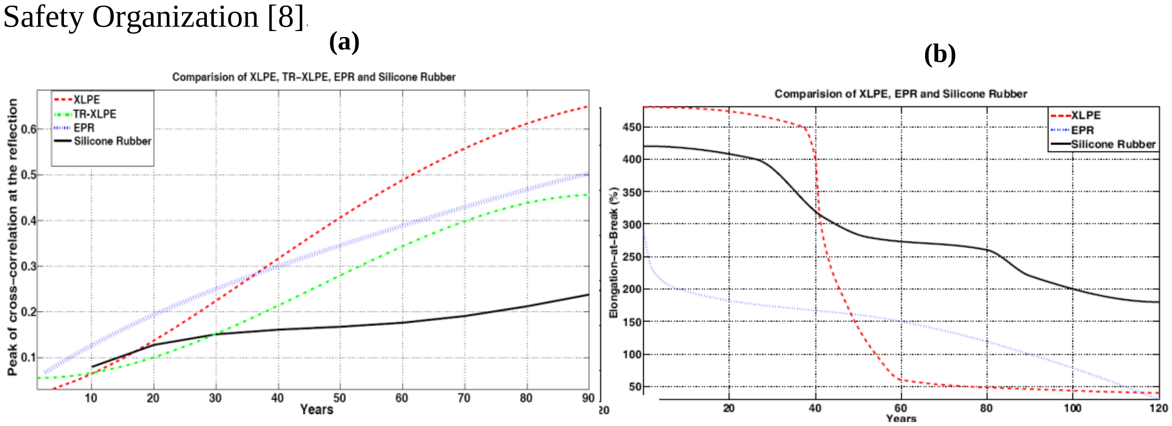

Figure 5. (a) Comparison of results of JTFDR for XLPE, TR-XLPE, EPR, and SIR. (b) Comparison of Elongation-at-break for XLPE, EPR, and SIR

It can be observed in the figure that the XLPE curve has the greatest change and the SIR curve has the smallest change in the local peak value corresponding to the "hot spot" over the period of testing. Additional observation indicates that the TR-XLPE curve shows less overall change compared to XLPE cable without tree-resistant additive. SIR has the best thermal stability and is suited for extremely severe and demanding service applications. Further, it can be observed that the XLPE insulation has better performance than EPR and SIR during the first 20 years of their service life, but as the aging process goes on, the XLPE shows higher peak values than SIR around 20 years and then shows higher peak values than both SIR and EPR after 40 years. These low starting trends extend to 30 years for the tree-resistant XLPE case. Also, in Figure 5, the results of EAB of all three types of insulation are plotted in one figure. Similar to the time-frequency cross-correlation peaks in Figure 1, the XLPE curve also has greatest change for the EAB metric over the duration of the test, and the SIR curve has the smallest change.

The results of EAB show that XLPE has better performance during the first 40 years of service life, but that it degrades faster than EPR and SIR. The XLPE curve drops to a lower value than SIR after 40 years and then dips to a value lower than EPR after 50 years. The EAB metric also demonstrates that the SIR insulation is more resistant to thermal damage than the EPR insulation throughout the duration of testing.

2.5. Results of simulated defects

For simulated fault tests, the cable under test is coaxial cable RG-58 whose characteristic impedance is 50Ω, while the cable sample used to perform the first type of experiment is 10 meters long. Defects are then simulated in the cable samples such as abrasion damage, water tree, and corrosion. Abrasion damage simulates fraying that could happen over cable lifetime in harsh environments that does not completely sever connection and is shown in Figure 6. Two instances of abrasion were simulated in these tests: a 1 cm long abraded and a 3 cm long abraded segment, spanning half of the cables' outside circumference in which both cable jacket and grounding have been eroded.

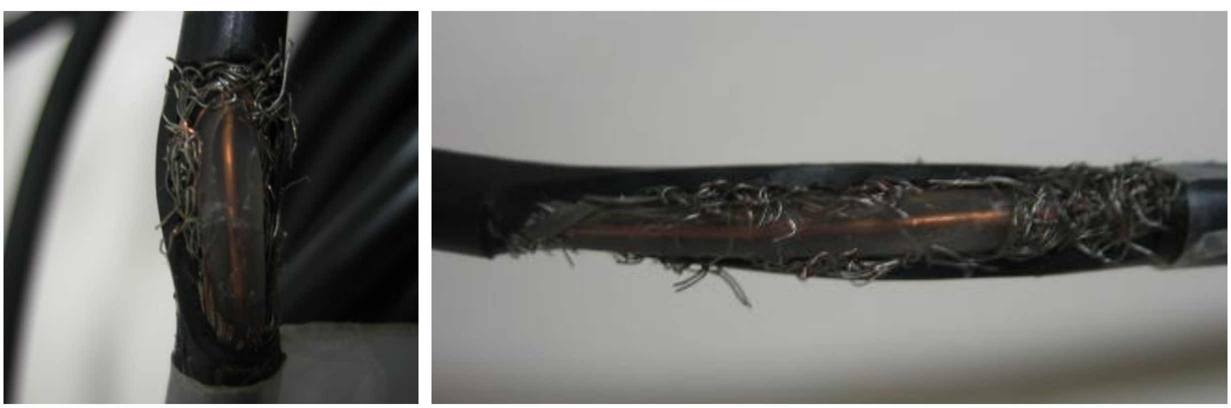

Figure 6. RG-58 cable with 1-3 cm sections of outer jacket removed around half of the cable circumference.

Also under consideration are segments simulating water damage and corrosion. These segments are shown in Figure 7.

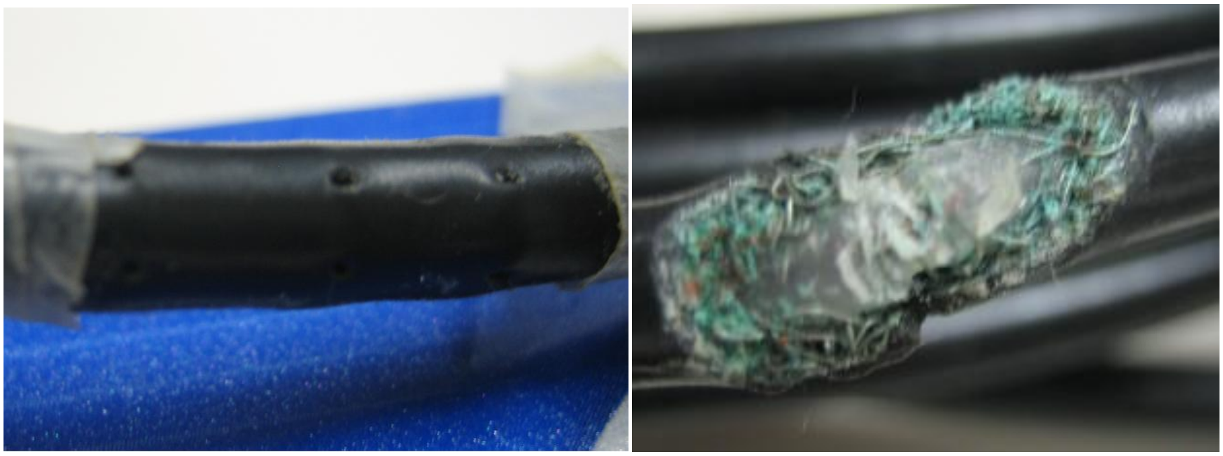

Figure 7. RG-58 cable with (a) injected water intrusion simulating early water-tree effects (b) 1 cm frayed and corroded segment extending around half of the cable circumference.

Tab. II shows the results of the first type of experiment, the results are similar to the simulation with some loss of fidelity due to noise and the error in the distance location of the defect. For pure resistance cases such as the 10 Ω and 197.2 Ω faulted cases, there are additional, minor series inductances due to complicating factors. One of the reasons for these additional inductances is that because JTFDR uses very high frequency signals, minor inductive reactive defects in the resistor are amplified. This idea is verified with a LCR meter, it does show some minor inductances in the nH scale. For pure capacitance, the results are acceptable. For the series connected 10 - and 103 pF Zd, The resulted Xc is -j3.2 which is close to the combined results of the capacitance (-5.2j) and the inductance of the resistor (j).

Table II: Experiment results for attached impedance

	Open	Short	10 Ω	197.2 Ω	103 pF	10Ω & 103pF
Theoretical	∞	0	10	197.2	-j5.2	10-j5.2
Z_d	-1.2e4-j7e3	0.2+j1.1	12+j	184+j5.53	0.77-j4.1	11.8-j3.2

Table III: Experiment results for simulated defects

	Abraded Segment (1 cm damaged)	Water damage	Corrosion
Z_d	42.7+j0.8	5.0+4.0j	39.5+j2.2

Tab. III shows the experimental results of some types of defects like 1cm insulation removal used to simulate abrasion damage, water damage, and corrosion damage. Figure 6 - Figure 7 shows the images of those defects. The corrosion of cable samples is simulated by putting the 1 cm abraded section into water with salt and corrosive chemicals for 24 hours.

The water damage is simulated by injecting water into the cable insulation with a syringe. For serious abrasions, some part of the insulator is taken off which is equivalent to a decrease in the outer radius of the insulator. This will cause the inductance per meter of the cable to decrease and capacitance per meter to increase. The main effect will be the decrease of the characteristic impedance. This is coincident with the result which shows 42.7 Ω for 1 cm abraded scenario. For water damage, the water injected into the cable provides a conductive bridge between inner conductor and outer conductor, and is close to short circuit conditions, thus the result of this test reports a small resistance. For the simulated corrosion, the result has no big difference with the 1 cm without corrosion. This could be attributed to the fact that the corrosion is tested in dry status; the corrosion does not notably change characteristic impedance.

2.6. Tests of Experimental Surface Launcher for XLPE Cable

We have explored preliminary options of portable implementations of the JTFDR reference through use of a signal launching antenna. This signal launcher injects surface wave variants of reflectometry signals into the insulation material of cable samples. We used the signal launcher to inject (1) a TDR pulse and (2) a JTFDR reference pulse into 5 and 10 meter samples of cable. The utilization of a signal launcher for JTFDR is still under investigation, however, a short example of time-frequency analysis of the TDR implementation is presented in Figure 8. The time domain plot is presented in red with a peak visible around 180 ms for initial connections and another around 600 ms for the end cable reflection. A time-frequency scalogram is presented showing a clearer view of end reflections and a limiting of false peaks.

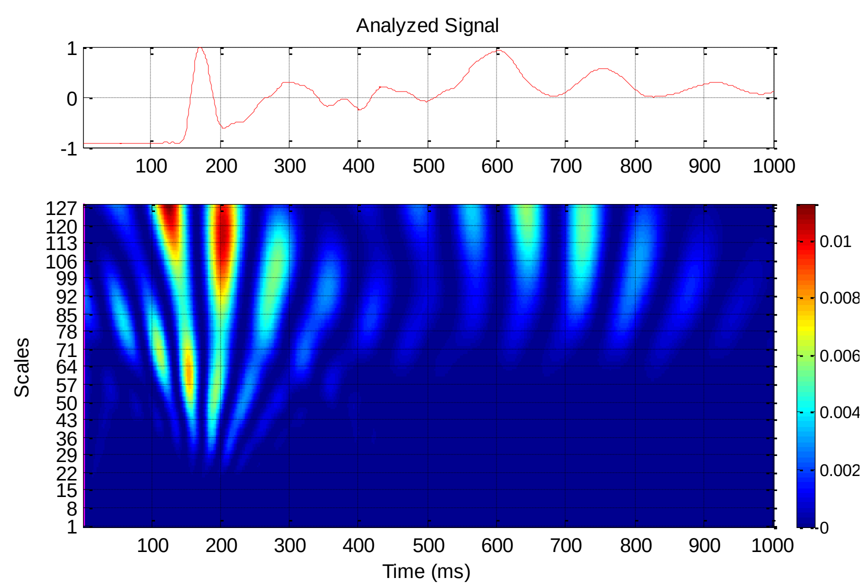

Figure 8. Time Domain Reflectometry implemented through use of a surface wave signal launcher in the time domain and time-frequency domain (via wavelet analysis).

2.7. Approximations of Life Faction for EPR, XLPE, and SIR Insulation Materials

Using previously gathered accelerated aging test data, the generic condition-based qualification presented by the NRC and shown in Figure 9 has been implemented for our accelerated aging samples.

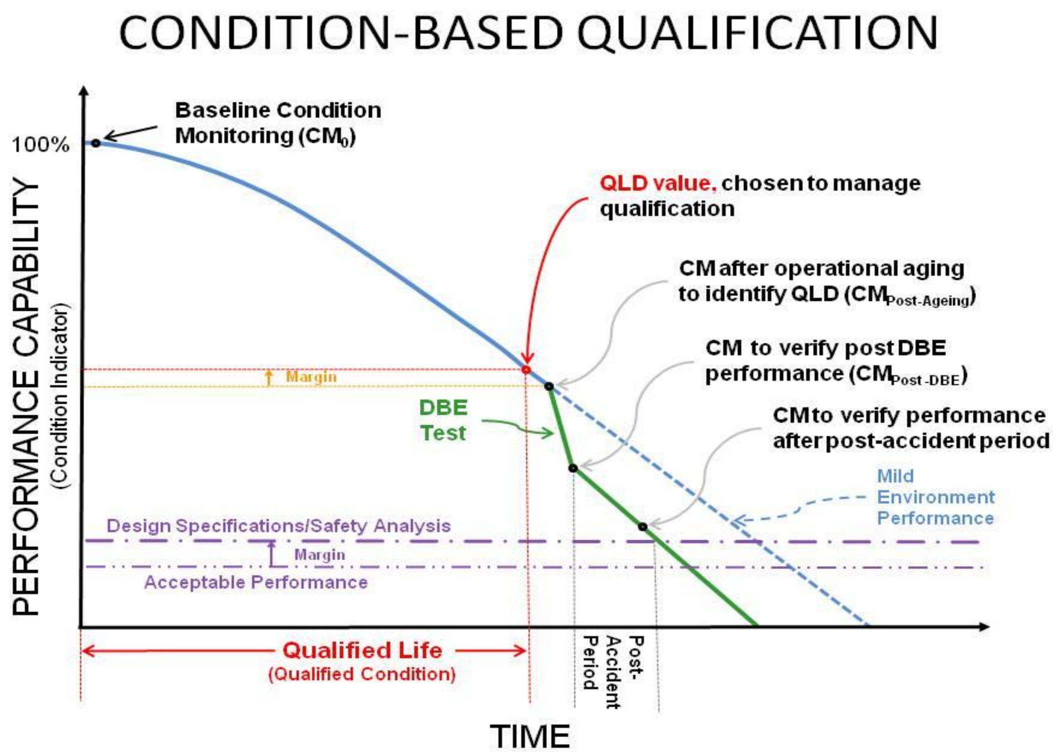

Figure 9. Condition-Based Qualification Presented by the NRC.

A preliminary life fraction indicator is suggested as shown in Figure 10 based on the cross correlation peaks from the incident and reflected signals. These have been shown to grow over simulated cable aging lifespan and further testing of additional cable samples should help in solidifying remaining useful life indicators for effective cable qualification and environmental tests. In the proposed cable life estimate or performance capability indicator, a key area of interest would be in the 30 to 60 year span indicating the close proximity of NPP commission and qualification periods and the typical extended life span of cable in lower stress utility environments.

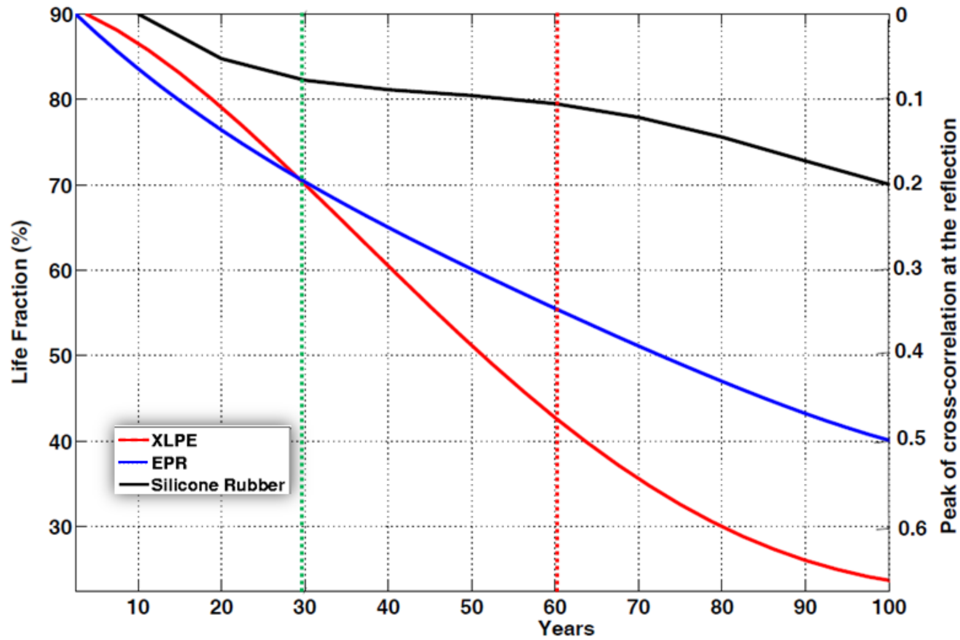

Figure 10. Preliminary Condition-Based Qualification estimates for XLPE, EPR, and SIR based on peaks.

3. CONCLUSIONS

To further safety conditions and profitability of nuclear power plants, JTFDR is proposed as a non-destructive and non-intrusive condition assessment technique. It is applied to four popular insulations in power system cables: XLPE, TR-XLPE, EPR, and SIR to monitor the health status of cables in thermal accelerated aging test. The experimental results show that JTFDR can successfully monitor the aging process of all four insulations, and SIR is more resistant to the thermal stress than EPR and XLPE insulations. Tree-resistant XLPE samples are shown to improve upon the life and performance of general XLPE samples. When results from JTFDR are compared with the results from the classical EAB method, the previous conclusion that SIR is more resistant to thermal stress is potentially more obvious using the JTFDR method than EAB tests. Changes in effective cable aging follow a more predictable curve using JTFDR, which may provide additional versatility in prognostics. Additional results show that JTFDR methods can also be used to categorized faults based on reflectometry-based impedance measurements and may provide added benefit over traditional methods beyond simple fault location algorithms. The results show that under similar conditions the JTFDR technique is comparable with EAB and promises to be an accurate and advantageous cable status monitoring technique in both locating and categorizing faults while also maintaining a non-destructive and non- intrusive prognostic paradigm for monitoring cable status continuously.

JTFDR is further developed to provide potential paths toward in-situ monitoring via localized sensors and predictions of remaining performance capability. We have acquired additional test equipment to expand JTFDR capabilities to medium and high voltage cable. Through further partnership with the IAEA and NRC, we hope to acquire additional cable samples and research capabilities such as environmental testing and assessment of cable properties such as activation energy.

Based on this research, the PI published the following publication and presentation:

- J. Wang, "Theory and Application of Joint Time-Frequency Analysis on Health Monitoring of Electric Cable and Pipeline," Ph. D dissertation, University of South Carolina, 2010.

- Jingjiang Wang, David Coats, Yong-June Shin, and Roger Dougal, "Health Monitoring of Power Cable via Joint Time-Frequency Domain Reflectometry," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 3, pp.1047-1053, Mar. 2011.

- Jingjiang Wang, Philip Crapse Stone, Yong-June Shin, and Roger Dougal, "Diagnostics and Prognostics of XLPE and EPR Cables via Joint Time-Frequency Domain Reflectometry," *IET Signal Processing, Special Issue on Time-Frequency Approach to Radar Detection, Imaging, and Classification*, Vol. 4, No. 4, pp. 395-405, 2010.

- Yong-June Shin and David Coats, "Cable Diagnostics Research Activities at University of South Carolina," IAEA Coordinated Research Program (CRP) Informal Meeting, Knoxville, TN, August 2011.

- Jingjiang Wang, David Coats, Yong-June Shin, Thomas Koshy, "Applications of Joint Time-Frequency Domain Reflectometry for Health Assessment of Cable Insulation Integrity in Nuclear Power Plants," International Symposium on the Ageing Management and Maintenance of Nuclear Power Plants (ISaG), Tokyo University, Tokyo, Japan, May 2010.

- David Coats, Jingjiang Wang, Yong-June Shin, Thomas Koshy, "Applications of Joint Time-Frequency Domain Reflectometry for Health Assessment of Cable Insulation Integrity in Nuclear Power Plants," *Proceedings of the 7th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies* (NPIC&HMIT 2010), November, 2010.
- "Diagnostics and Prognostics of Electric Power Cables in Aging Nuclear Power Plants," Korea Institute of Nuclear Safety (KINS), Taejon, Korea, June 30, 2010.

4. FUTURE WORK

To further explore the merit of JTFDR, the next step of this research is to perform the "time to breakdown" accelerated aging test to predict the remaining lifetime of the cables, however, this will require significant upgrades to experimental equipment. Time to breakdown tests are used to predict the remaining life of a cable by testing the performance of sample equipment in accelerated aging conditions until breakdown.

As steps toward this larger goal, we will (1) expand the scope or current time-specific aging tests such as those presented in Table I and (2) begin designing experimental procedure for time to breakdown testing to include partial discharge verification methods.

One concern from previous research is the variations possible from different cable manufacturers. In future work, we aim to obtain low-voltage cross-linked polyethylene (XLPE) and PVC insulated cable from manufacturer Nexans to retain consistency with current Nexans samples (EPR and SIR insulated samples shown in Table I). Additionally, we would like to perform similar (24 - 48 hour) accelerated aging tests on low-, medium-, and high-voltage cable samples for a particular insulation type (most likely XLPE from which samples have already been obtained). Once these shorter 24 – 48 hour time-specific tests have been completed, longer periods of accelerated aging will be considered up to 120 hour accelerated aging tests, paving the way to time to breakdown tests.

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