DEVELOPMENT AND IMPLEMENTATION OF AN IN-SITU CABLE CONDITION MONITORING METHOD FOR NUCLEAR POWER PLANTS

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ABSTRACT

The sustainability of the existing fleet of nuclear power reactors depends on utilities' ability to manage the aging of key components that cannot easily or economically be replaced or upgraded. Cables, metals, and concrete structures are among the major and key components that the industry and government are working on to ensure the long term reliability and safety of nuclear plants. To ensure that these key components continue to meet their performance requirements, new testing and condition monitoring technologies must be developed that are capable of identifying and quantifying degradation in these materials. The work presented in this paper focuses on the development and implementation of an in-situ condition monitoring method for nuclear power plant cables. This cable condition monitoring method is based on the frequency domain reflectometry (FDR) technique, which is a non-destructive in-situ electrical test that uses the principle of transmission line theory to locate and quantify impedance changes in a cable circuit. Through extensive research, development, and validation, the FDR test technique has been adapted as a cable condition monitoring method that trends with increasing cable degradation. In addition, the FDR data has been correlated to the industry standard elongation at break (EAB) test to quantify the degree of localized degradation in nuclear plant cable insulation material caused by long term exposure to high temperatures and radiation. By correlating FDR to EAB, the aging condition of cables routed through harsh environments can be better understood in relation to its ability to perform its intended function.

Key Words: cable insulation, degradation, condition monitoring, aging management, reflectometry

1 INTRODUCTION

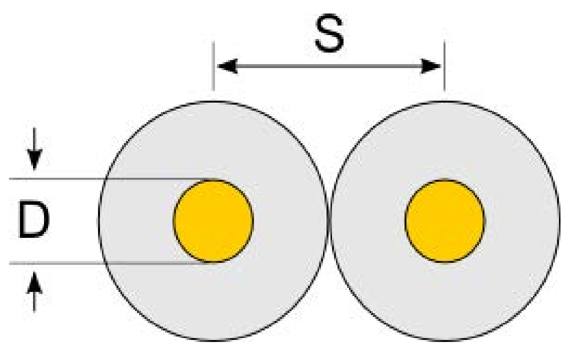
Most of the current fleet of U.S. nuclear power plants have been granted life extensions to operate for an additional 20 years, and federal regulators are now considering the possibility of extending operating licenses to 80 years or more. To ensure the long term operational safety and reliability of these reactors, nuclear power plant personnel must manage aging assets that were originally qualified for 40 years of operation [1]. One of the primary aging asset management concerns for nuclear power plants centers around the long term health and performance of cables [2,3]. Many of the cables installed in nuclear facilities experience prolonged exposure to harsh environmental conditions, including high temperatures and radiation, which can result in age related degradation of the cables' jacket and/or insulation materials. Unfortunately, wholesale replacement of cables is costly and simply not practical. Thus, aging assessment and condition monitoring (CM) techniques must be used to determine the long term health and operability of plant cables.

In response to this industry need for cable condition monitoring technologies, several U.S. and international agencies, companies, and laboratories have worked to develop electrical, mechanical, and thermal/chemical tests capable of monitoring the condition of degraded cables. In fact, over the last five (5) years Analysis and Measurement Services (AMS) Corporation has conducted research and development work to identify, develop, and test cable condition monitoring technologies for nuclear plant applications. These research efforts include collaborating with 17 U.S. and international organizations under a Coordinated Research Project (CRP) sponsored by the International Atomic Energy Agency (IAEA) to develop and test CM techniques that could be used for cables installed in nuclear power plants. This research primarily focused on evaluating and validating CM technologies capable of assessing the condition of cable insulation materials, which degrade overtime when exposed to environmental stressors (e.g. heat, radiation, moisture, etc.). In addition to the CRP, AMS has also conducted an extensive amount of research on cable CM techniques under several Department of Energy (DOE) funded Small Business Innovation Research (SBIR) projects.

As a result of the work performed under these projects, AMS developed a nondestructive in situ electrical cable CM system that is capable of identifying, locating, and quantifying degradation in insulation materials. This test technology is based on the Frequency Domain Reflectometry (FDR) technique, which was adapted for this CM system to test cables in nuclear power plants. This paper summarizes the work performed to: 1) develop a FDR system for condition monitoring of nuclear plant cables and 2) demonstrate this technology in an operating nuclear power plant.

1.1 Frequency Domain Reflectometry Test Information

The FDR technique is a non-destructive in-situ electrical test that uses the principle of transmission line theory to locate and quantify impedance changes in a cable circuit. These impedance changes can result from connections, faults in the conductors, or degradation in the cable insulation polymer material itself. For a cable, its characteristic impedance is a relationship between the physical dimensions of the cable and the permittivity of its dielectric, which is a measure of resistance encountered when forming an electric field in a medium. Fig. 1 shows the relationship between cable characteristic impedance (Z_0) and insulation permittivity for a two-conductor cable. When an insulation polymer degrades, its electrical permittivity changes resulting in changes to the cable's characteristic impedance.



$$Z_0 = \frac{120}{\sqrt{\varepsilon_r}} * ln\left(\frac{2S}{D}\right) \quad (1)$$

D = diameter of cable conductors
S = separation between conductors
ε_r = permittivity

Figure 1. Relationship between cable impedance and permittivity.

Since the permittivity of a cable insulation polymer changes when the material degrades, the FDR technique is well suited to identify, locate, and quantify insulation degradation caused by exposure to environmental stressors.

The FDR test is performed with one end of the cable under test connected to a signal source which sends a sweep of sine waves of constant amplitude and varying frequency through the cable. The waves travel the length of the cable and a portion of them are reflected back from the locations where the impedance deviates from the cable's characteristic impedance. The reflected signal is separated, measured, and then converted to a ratio with the outgoing or incident signal. This signal ratio is established for each individual frequency within the measured spectrum. The time domain impulse response of the cable is generated from using an inverse fast Fourier transform (IFFT) and AMS data analysis algorithms. Once in the time domain, the impulse response is further enhanced by integrating over time to generate a step response. Finally, the distance-to-fault is calculated using the velocity of propagation (Vp) for the cable under test, and a gating window is applied to remove unwanted reflections and isolate localized impedance changes from the bulk cable data for analysis.

Fig. 2 shows FDR data converted to the time domain step response for a cross-liked polyethylene (XLPE) insulated cable that has a localized region of thermal degradation or "hot spot." As shown in the figure, changes in the characteristic impedance of the cable result in changes to the FDR reflection coefficient, Rho. As the insulation material for the cable degrades, the ΔRho at the "hot spot" increases. This increase in ΔRho is caused by changes in the electrical permittivity of the insulation material, which changes as the material ages along with other mechanical, chemical, and electrical properties of the polymer. As a result, this change in ΔRho can be correlated with industry standard tests, such as elongation at break (EAB). By correlating FDR results to EAB, the aging condition of cables routed through harsh environments can be better understood in relation to its ability to perform its intended function.

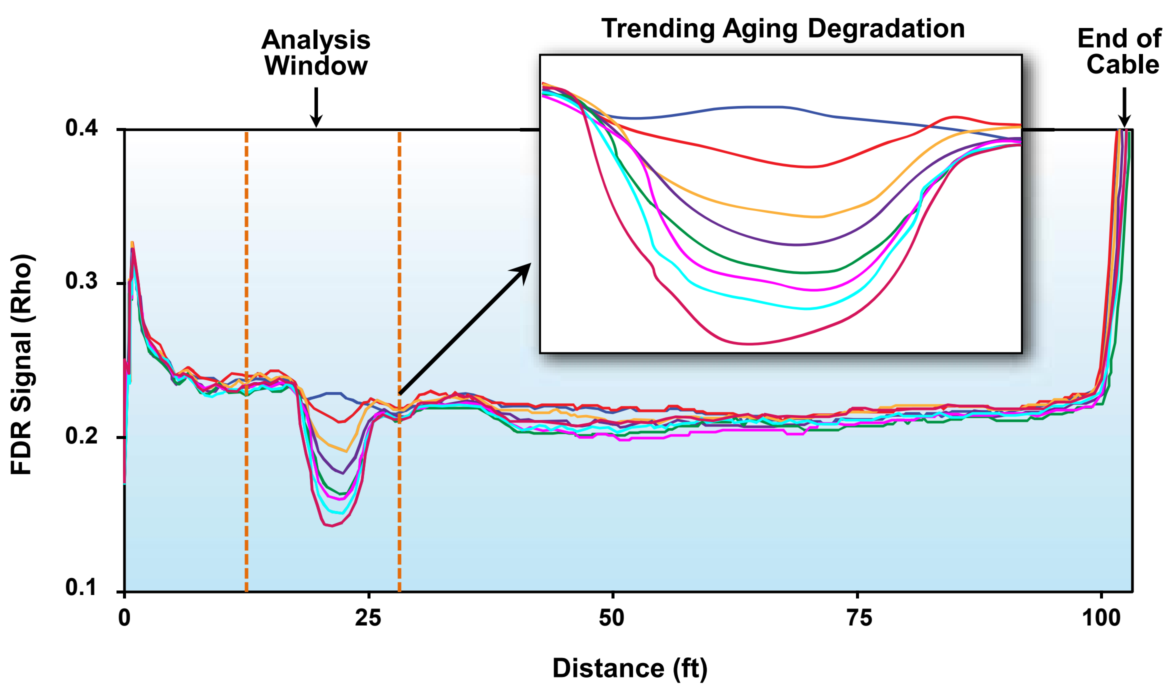


Figure 2. FDR data that shows thermal degradation or 'hot spot' for XLPE insulation.

1.2 FDR and EAB Correlations

To develop the FDR and EAB correlations, extensive accelerated thermal aging research was performed and used to generate a cable aging database for a variety of nuclear power plant cable insulation polymers. These experiments included the most widely used cable polymer types in the nuclear industry, Ethylene Propylene Rubber (EPR) and cross-linked polyethylene (XLPE). The tests were performed by inducing thermal "hot spots" in the cables under test, periodically conducting FDR measurements as the insulation materials degraded, and correlating the results with EAB data from tubular insulation samples that were removed from the cable.

The "end of life" for these cables was established based industry guidelines for EAB testing. A cable with an EAB of more than 50% is considered by the nuclear industry to be able to perform its function not only during normal operation, but also in accident and post-accident conditions. In contrast, a cable with an EAB of 50 percent or less may not be able to function after subjected to adverse conditions [4].

Using these industry guidelines for EAB measurements, the FDR and EAB data correlations for XLPE and EPR cable insulation types are categorized based on the percent of their aged life so as to define general acceptance criteria that can be used when performing in-plant testing. These FDR aging categories for cable insulation are divided as shown in Table I. Each category represents an "% Aged" estimation for the cable under test as it relates to the EAB "end-of-life" condition (50% EAB). For example, FDR measurements that fall into "Category 1" show minimal change from the unaged cable insulation indicating that little to no degradation has occurred. FDR measurements that fall into "Category 2" have been aged between 33% and 66% of the remaining useful life. FDR measurements that fall into "Category 3" have been aged between 66% and 99% of the remaining useful life and cable data that falls into "Category 4" would be expected to be at or near an EAB measurement of 50%.

Table I. Acceptance criteria for FDR testing of nuclear power plant cables

FDR Category	% Aged	Comments
1	0 – 33	Little to no indication of age related degradation
2	33 – 66	Initial indication that age related degradation has occurred
3	66 – 99	Cable insulation has significant aging but is expected to function normally
4	>99	Cable insulation is at or near its end-of-life condition as defined by 50% EAB

Using these acceptance criteria, the aged condition of a degraded cable section can be quantified in situ using the FDR system. This allows nuclear plant personnel to: 1) identify and locate degraded cable sections and 2) determine if the cable section should be repaired or replaced based on the severity of the degradation. For the current generation of reactors, the ability to locate, identify, and quantify degradation in cable insulation materials is very important to cable aging management programs. Using the FDR cable CM technology, nuclear plants can identify damaged or degraded cables and replace or repair them before they cause significant operation issues. In addition, utilities can avoid unnecessary cable replacement costs if the FDR test determines that the cables are still in good condition.

2 APPLICATION OF FDR SYSTEM IN NUCLEAR POWER PLANT

Commercial testing of the FDR system was conducted at the Oyster Creek Generating Station during a refueling outage in the fall of 2016. These tests were performed to assess the aged condition of low voltage control cables routed through harsh environments in the plant.

The control cables tested as part of this commercial work were for the turbine controls, feedwater pumps and condensate pumps. These cables included five (5) conductor, seven (7) conductor, nine (9) conductor, and twelve (12) conductor cables. Depending on the number of conductors in the cable, multiple combinations were tested and their FDR data was averaged to determine the aging category for the cable (i.e. a 12 conductor cable was tested using 12 conductor combinations). All of these cables were manufactured with GE Vulkene insulation, which is a type of XLPE insulation polymer.

The turbine control cables were tested from the control room to the turbine front standard in open circuit configuration with the leads at both ends lifted from the terminal blocks as shown in Fig. 3. Additionally, the feedwater and condensate pump cables were tested from the control room to the 4160V switchgear passing through the condenser bay in open circuit configuration as shown in Fig. 4. During plant operation, the turbine control cables are exposed to elevated temperatures (up to approximately 130ºF) and some levels of radiation along their path from the control room to the turbine front standard. Similarly, the feedwater and condensate pump cables are exposed to elevated temperatures (up to approximately 150ºF) and radiation in the condenser bay. Using the FDR test system, these cable sections were evaluated to determine the aged condition of the cables' XLPE insulation.

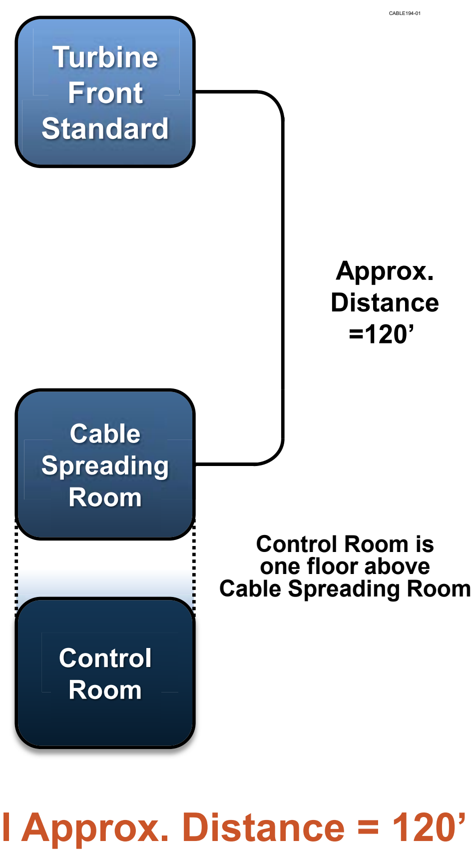


Figure 3. Cable routing diagram for the turbine control cables from the turbine front standard to the control room.

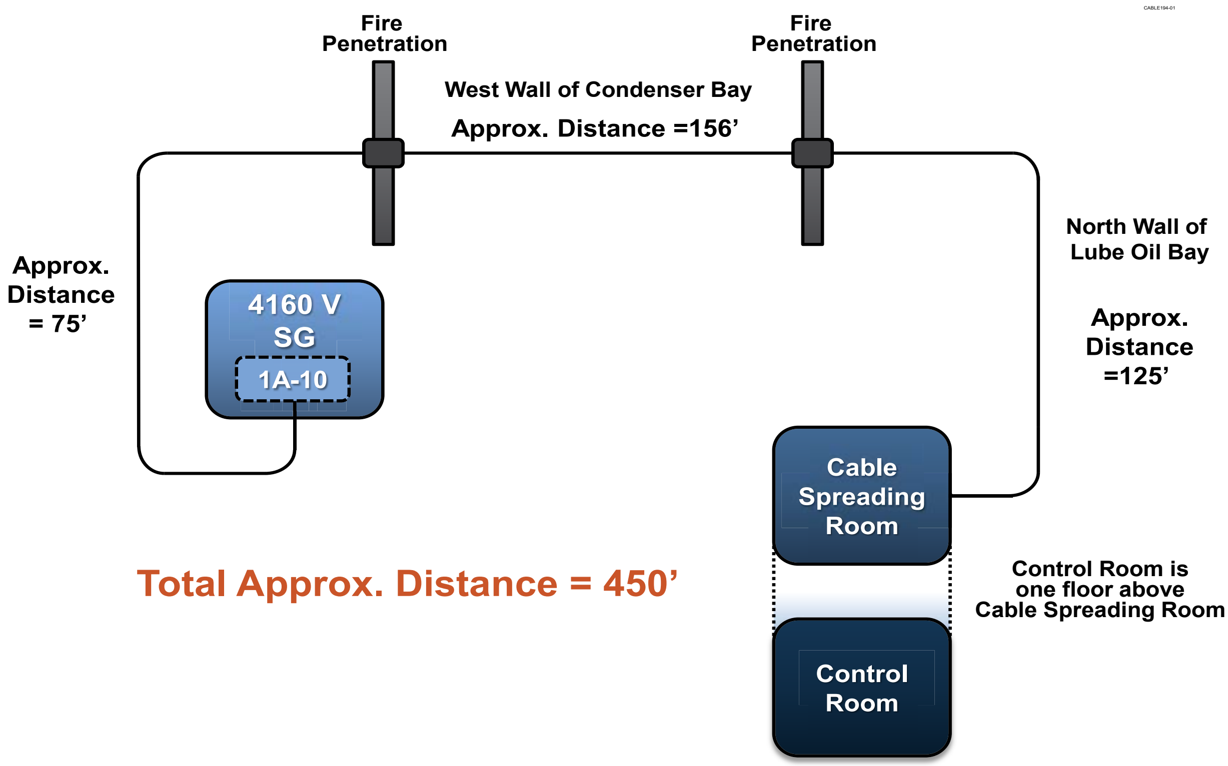


Figure 4. Cable routing diagram for the feedwater and condensate pump cables from the 4160v switchgear room to the control room.

To perform the FDR testing and analysis, the portions of the cables located in the control room were used as the healthy reference for comparison to the sections that were routed through the condenser bay and other harsh environments with elevated temperatures and radiation levels. This is done because the cable sections that have not been exposed to environmental stressors such as elevated temperatures and radiation are expected to degrade at a much slower rate than the cable sections exposed to environmental stresses. As a result, the difference in characteristic impedance or reflection coefficient (Rho) between these cable sections can be used to determine the degradation level of the XLPE insulation in the cables that were tested.

Fig. 5 shows the FDR data for a pair of conductors of one of the turbine control cable tested at Oyster Creek. The top plot is FDR data for the entire cable length with Rho as the y-axis and distance as the x-axis. The bottom plot of this figure shows a portion of the FDR trace that has a gating function applied to separate the section of cable routed though the harsh environment. The ΔRho value in this gated region is 0.084, which corresponds to a Category 2 ranking for XLPE insulation polymers. This indicates that the cable insulation in this region shows initial signs of age related degradation, but has not significantly degraded while it has been installed in the harsh environment.

As mentioned previously, multiple combinations of conductor pairs were tested to determine the average ΔRho and FDR categories for each cable. The average ΔRho values and the FDR categories for each turbine control cable tested are listed in Table II. None of these cables received a Category 4 ranking, and only one of the ten cables tested was ranked as a Category 3. The feedwater and condensate pump cables were in FDR Category 1, which indicates that they have experienced little to no age related insulation degradation.

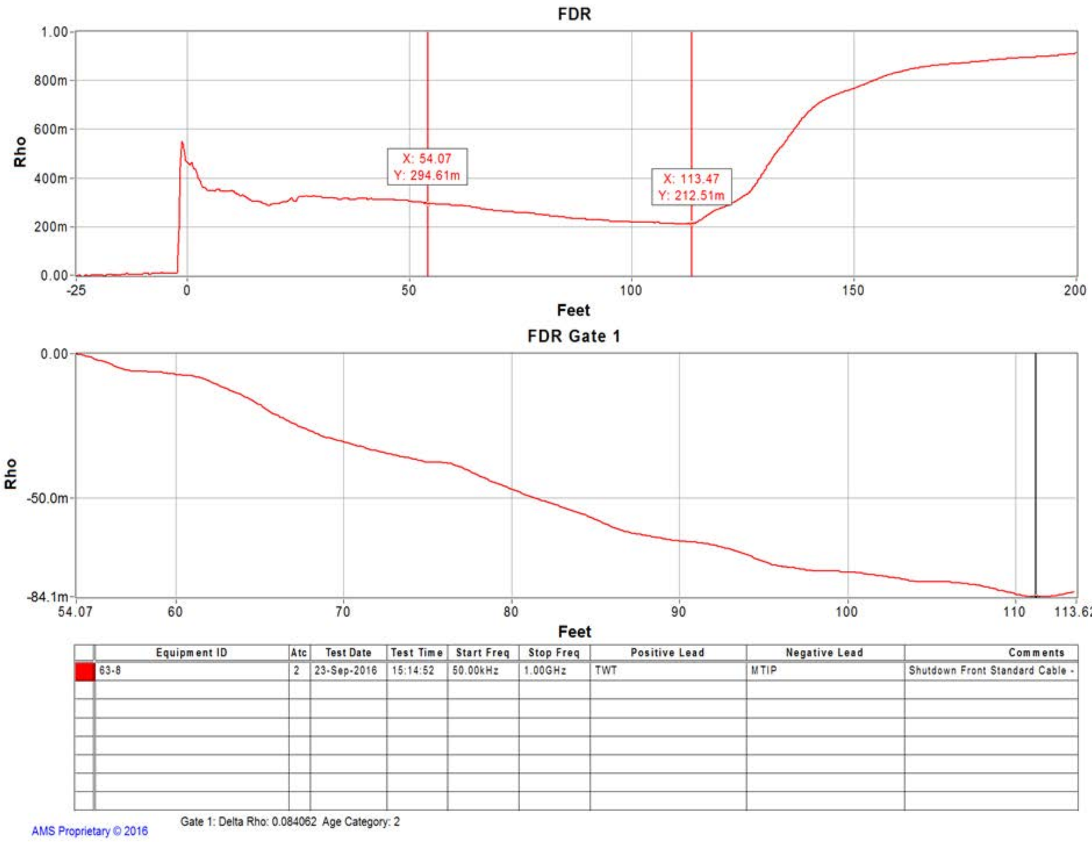


Figure 5. The FDR analysis of the turbine control cable conductor pair.

Table II. Turbine control cables average delta Rho and FDR categories

Cable ID	Average Delta Rho	FDR Category
1	0.046	1
2	0.104	3
3	0.070	1
4	0.092	2
5	0.070	1
6	0.081	2
7	0.051	1
8	0.045	1
9	0.061	1
10	0.075	2

In summary, the FDR data revealed some age related degradation for one of the turbine control cables and no significant aging for the remaining cables that were tested. Thus, all of these cables are expected to function normally both during normal operation and a design basis event. Based on these test results and visual inspections of the cables conducted by the plant, Oyster Creek personnel decided not to replace the control cables that were tested, saving the plant $3.7 million in cable replacement costs, new conduit installation, and scaffold building. In addition, performing joint electrical testing using the FDR system and visual inspections allowed for additional security in regards to continued plant operation. Overall, the FDR test system was instrumental in determining whether these control cables installed at Oyster Creek can continue to safely and reliably perform their intended function.

3 CONCLUSIONS

Through extensive research and development efforts, a nondestructive in situ cable CM technique has been developed and demonstrated in an operating nuclear power plant. This CM technique was developed by adapting the FDR test to nuclear power plant cables and correlating FDR and EAB data for the most common polymer types used in the industry. Based on these correlations, general aging acceptance criteria were developed that can be used to perform aging assessments for cables exposed to harsh environments (e.g. high temperatures, radiation, etc.). These aging criteria were integrated into the FDR system and used to determine the aged condition of control cables installed at Oyster Creek Generating Station.

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5 REFERENCES

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