FREQUENCY DOMAIN REFLECTOMETRY TECHNOLOGY FOR CABLE AGING MANAGEMENT

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INTRODUCTION

The aging of polymer materials that are used for the insulation and jacket material of the cables found in nuclear power plants has been an area of emphasis in recent years with respect to the potential impact on plant safety and reliability in the face of plant life extension. In response, the U.S. Nuclear Regulatory Commission issued Regulatory Guide 1.218 entitled, “Condition Monitoring Techniques for Electric Cables Used in Nuclear Power Plants.” This guidance recommends performing cable condition monitoring to ensure that cable aging does not pose a threat to plant safety during normal operation or in post-accident situations.

For over 20 years, AMS Corporation, through its CHAR Services division, has provided cable testing services to the nuclear power industry to assess the health of low voltage cable circuits including conductors, connectors, and end devices. AMS has used the “CHAR” Cable Condition Monitoring system for this work (Figure 1), an all-inclusive test unit that performs a host of electrical measurements including Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), Reverse TDR (RTDR), Dynamic TDR (DTDR), Insulation Resistance (IR), Impedance (LCR), Current-Voltage (IV), DC Resistance, and Waveform measurements. These techniques are almost always used together to provide a full assessment of cable health and to verify the integrity of the circuit from the cabinet where the tests are performed to the end device in the field. Example CHAR system applications include nuclear instrumentation, resistance temperature detectors, radiation monitors, pressurizer heaters, rod control and rod position indication cables, motors, and a variety of other low voltage and Instrumentation and Control (I&C) cable circuits.

Figure 1. CHAR Cable Condition Monitoring System

This white paper is focused on the development and adaptations made by AMS to add the FDR measurement technique to the integrated CHAR test system to enable enhanced evaluation of low voltage cables for supporting cable aging management programs in nuclear power plants. In conjunction with the other tests found in the CHAR system, the work has shown that adding the FDR test method provides improved measurement sensitivity to cable insulation material degradation that results from environmental stressors such as heat, moisture, and radiation.

TRADITIONAL CABLE AGING MANAGEMENT TECHNOLOGIES

Commonly used methods for determining the effective age and/or condition of cable insulation material include walkdowns, visual/tactile inspections, and the elongation at break (EAB) and indenter modulus (IM) tests. The EAB test is a destructive laboratory method that requires a sample of the cable insulation material while the indenter modulus test is a localized mechanical evaluation that can be performed in-situ. As defined by the Electric Power Research Institute (EPRI) and others, 50% EAB is the classically defined end-of-life condition for nuclear plant cable insulation material. Additional laboratory tests such as oxidation induction time (OIT), density, and thermo-gravimetric analysis (TGA) can also provide valuable insight into the condition of the polymer material. In fact, AMS provides all the testing mentioned above through use of our IPAM4 cable indenter as originally developed by EPRI and our Cable Forensics laboratory located at the AMS Headquarters.

While traditional test methods play an important role in any cable aging management program, they often need to be performed in a laboratory environment with a sample of cable material, or if performed on-site, exclude cables that are routed through conduit, direct buried, or are otherwise inaccessible for inspection or hands-on testing. To address this need, an in-situ electrical test entitled Frequency Domain Reflectometry (FDR) was adapted by AMS as described in this white paper to identify, locate, and assess aging degradation in nuclear power plant cables. As with the other electrical measurements made by the CHAR system, the test is performed from one end of the cable with the end device connected and helps provide an indication of cable health along the entire length of the circuit.

FDR TECHNOLOGY

FDR is a technique historically used by the mobile phone industry to locate power losses in high frequency antennas. To perform an FDR test, one end of a cable is connected to a signal source which sends a sequence of sine waves of constant amplitude and varying frequency through the cable, as shown in Figure 2. The waves travel the length of the cable and a portion of them are reflected back from the locations where the impedance is different from the rest of the cable. The reflected signal is separated, measured, and then correlated with the outgoing or incident signal. This correlation is established for each individual frequency within the measured spectrum. The frequency domain data is then converted to the time domain using an inverse Fast Fourier Transform (FFT). Once in the time domain, the distance-to-fault is calculated using the velocity of propagation (Vp) for the cable under test. The FDR test can be adjusted to specific frequency ranges to compensate for bandwidth attenuation from losses that result from the distributed impedance along the length of the cable.

This single-ended measurement can be performed during all plant operating modes from a remote location with the end device connected. The cables under test are de-energized and the leads are lifted at the control room cabinets or junction box panel. The FDR test

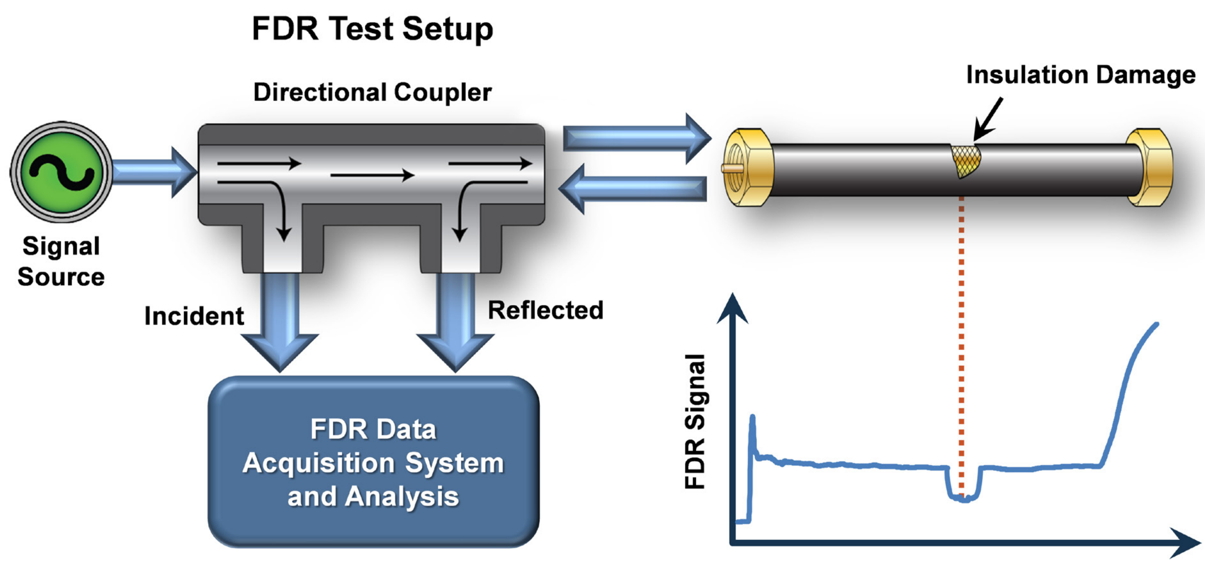

Figure 2. FDR Technique as Applied to Cable Testing

is performed from the field side leads and the test is administered using voltages that are negligible as compared to the rated operating voltage of the circuit under test (i.e. less than 2 volts).

Due to the nature of the FDR test as compared to other reflectometry methods, it has demonstrated increased sensitivity for detecting subtle impedance changes that occur with insulation hardening that results from accelerated polymer aging. The user-adjustable parameters allow fine-tuning of the test signal to optimize the sensitivity of the test and allow detection of other types of localized degradation such as corrosion, loose or damaged connectors, cuts and gouges, and moisture intrusion. When used in conjunction with TDR, IR, and Impedance measurements as found in the CHAR system, FDR can be a powerful tool for tracking and trending the baseline aged condition of the cable under test using non-destructive single-ended electrical measurements.

CORRELATION OF FDR TO ELONGATION AT BREAK

AMS has performed extensive thermal aging experiments to develop a database for a variety of cable polymers used in nuclear power plants in the U.S. and worldwide (Figure 3). This database continues to be developed, and as of this writing, AMS is performing accelerated thermal aging of Okonite EPR, Boston Insulated Wire (BIW) EPR, and Rockbestos XLPE cables. AMS is also performing radiation studies of Okonite EPR and Rockbestos XLPE cables. The results of these tests have shown that FDR data is capable of identifying and locating thermal hot spots in a cable caused by radiate heating (Figure 4a).

AMS work has also shown that FDR test data will trend with increasing cable degradation and can be correlated to the industry standard EAB test to help better evaluate the degree of localized thermal aging in cable insulation material (Figure 4b). By correlating FDR to EAB, the aging condition of cables routed through harsh environments can be better understood

Figure 3. Cable Thermal Aging Experiments in AMS Laboratory

in relation to the cable manufacturer's specifications for polymer aging. This information previously required physical access to the location of concern or sacrificial samples to be tested in a laboratory environment. FDR provides a practical, cost-effective solution to establish and

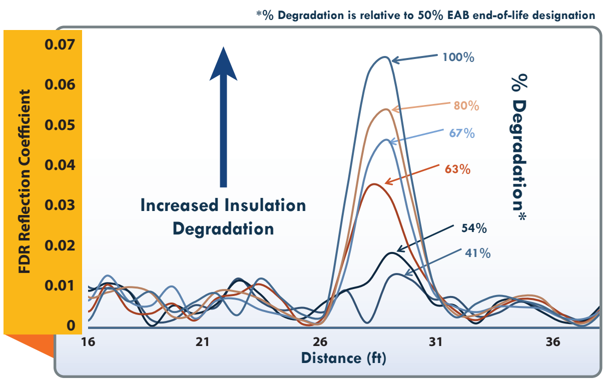

Figure 4a. FDR Signature Showing Location of Hotspot

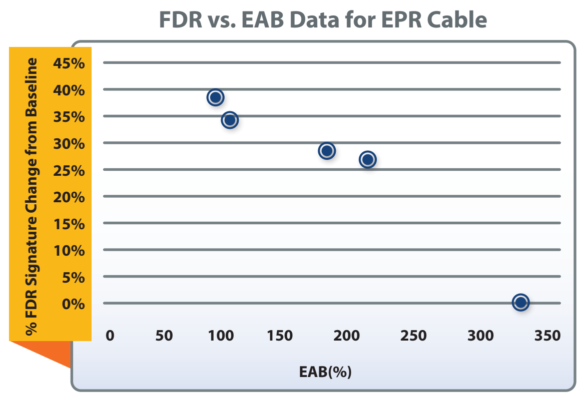

Figure 4b. FDR vs. EAB Correlation

trend the aged condition of critical cables of concern throughout the plant license extension period. The data can be used in conjunction with the other electrical measurements made by the integrated CHAR test system as well as traditional cable aging management methods to inform maintenance activities and to help provide justification for continued use of installed plant cables to 60 years and beyond.

CONCLUSION

Extensive research and development has shown that the FDR test can fill a critical gap in nuclear power plant cable aging management programs by providing a practical means for identifying localized cable polymer aging that may compromise circuit reliability. Cable circuit walkdowns, visual/tactile examinations, as well as laboratory and indenter testing are also important components of aging management. These methods can be further enhanced through non-destructive electrical testing such as FDR to provide improved insight into cables that are inaccessible and may be subjected to localized environmental stressors.