Spread Spectrum Techniques for Measurement of Dielectric Aging on Low Voltage Cables for Nuclear Power Plants

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ABSTRACT

Spread spectrum time domain reflectometry (SSTDR) is used to test dielectric aging of a cable type used in the nuclear power plant industry. A 16 AWG twisted pair shielded cable is thermally aged to the equivalence of 50 years in service, and SSTDR data is collected at 10-year intervals during the aging process. The SSTDR data shows that velocity of propagation and characteristic impedance decrease as the cable ages (increasing the electrical permittivity), making them suitable markers for monitoring aging and demonstrating the ability of SSTDR to determine this aging.

Index Terms — **cable insulation, transmission lines, reflectometry, dielectric aging ~~heating~~, dielectric losses**

1 INTRODUCTION

The fleet of nuclear plants operating in the United States (U.S.) were originally licensed for a 40-year life span, and many have subsequently been approved for a life extension to 60 years. Due to growth in demand for electric power, and the expected retirement of nuclear plants following 60 years of operation the Department of Energy (DOE) supported an additional 20 year extension, for a total operating life of 80 years [1]. The DOE Light Water Reactor Sustainability Program was established to support research to determine the aging effects on key passive components supporting existing equipment and whether they could perform reliably or require replacement within the proposed 80 years. These aging effects were addressed by the Nuclear Regulatory Commission regulations for obtaining license extensions [2]. Cables were to be inspected and tested at regular intervals to monitor their condition and the trend and rate of degradation. Cable degradation is a function of the material properties and the environment (e.g. ambient temperatures, level of radiation exposure, and moisture).

There are a number of test methods used today for evaluating the condition of cables. Some tests are destructive to the cable, while others test a small sample, enabling the cable to continue use after testing. Tests are visual, chemical, mechanical or electrical. Visual inspections which focus on the appearance of the cable in areas where it is accessible are typically used as an initial screening tool. First the room through which the cable is routed is observed to see if there are any indicators such as signs of overheating, water or oil on the floor, or high vibrations which could result in degradation. Where cables are visible, the cable is inspected for change in color, cracking and hardening of the insulation. Thermography may be used as part of the visual inspection to detect localized heating.

Mechanical tests evaluate hardness and tensile strength. Elongation at break (EAB) has long been used as a test metric for ~~merit of~~ cable aging, because the change in cable elasticity is useful to detect cable insulation and jacket degradation. One way a cable ages thermally or from ionizing radiation results in increased cross linking which causes increased hardness and a reduction in EAB [3]. EAB is a destructive test where a portion of the cable jacket is cut out in the shape of a dog bone, or a tubular sample is made by removing the conductor. The sample is placed in a set of clamps and pulled apart at a constant velocity until it breaks [4], [5]. An end of useful life can be identified based on the elongation at this breaking point[6].

Several chemical tests are performed, usually on a sample of the cable in a laboratory. One example is oxidation induction time (OIT) which is an important test for determining when antioxidant has been depleted. After this time the cable aging characteristics change due to the interaction of oxygen with the free radicals that have formed [4], [7]. Testing has also been performed to correlate OIT with measurements of EAB [8].

Electrical test methods are generally performed in the field and are not intended to be destructive tests unless the cable condition has deteriorated significantly. The tan-delta (tan δ)

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test is perhaps the most common method used on medium voltage cables. For this test the cable is de-energized and disconnected, and an AC voltage at very low frequency is applied between the conductor and shield. The angle δ, of the vector between the capacitive and resistive currents caused by the applied voltage is measured. The tangent of this measurement (tan δ) provides a ratio of the resistive loss current to the capacitive current. Increased tan δ) indicates increased resistive or leakage losses and provide an indication of cable health [7]. Another test method is insulation resistance (IR). IR measurements are typically taken from bulk resistance measurements at 500V DC with the cable de-energized and disconnected [9]. Details of cable test methods are outlined by EPRI [5].

Reflectometry methods such as time domain reflectometry (TDR), Frequency Domain Reflectometry (FDR) and Partial Discharge send a high frequency signal into a cable, where it reflects off impedance discontinuities and returns to the test end. The delay between the incident and reflected signals, and the magnitude of the reflection is a function of the dielectric properties of the cable insulation [10], which changes as the cable ages [9], [11]. There are many types of reflectometry, distinguished by their test signals and method of analysis [12]. At least two of these methods -- frequency domain reflectometry [13], [14] and time domain reflectometry [15] – have been used to evaluate cable insulation degradation. However, these methods have significant limitations if they are to be used to test energized systems, because existing signals on the cables may interfere with the reflectometer, or the reflectometry signal may interfere with the cable under test. Thus, the reflectometry signals have to be carefully chosen so they do not interfere with/from the system under test.

For the nuclear industry, being able to test energized cables without disconnection/reconnection could save time and reduce the potential for maintenance-induced damage. It could also potentially identify intermittent faults [16] and provide prognostic maintenance information by testing more often than the single snapshot of cable health taken only during a planned outage.

Spread spectrum time domain reflectometry (SSTDR) is designed for testing energized cables [17]. It sends a high frequency pseudo-noise (PN) code into the cable, where it reflects off impedance discontinuities and returns to the test end. There it is correlated with the initial PN code to produce a reflectometry signature that encodes the state of the cable [16]. The PN code can be made small enough that it is below the noise margin of the system under test, while still providing a useful test signal. SSTDR has been applied in the airline [16] and rail [18], [19] industries and is currently being evaluated for use in photovoltaic power plants [20].

This paper evaluates the ability of SSTDR to identify aging in 16 AWG twisted pair shielded cables, commonly used in nuclear power plants. Aging will be identified through changes in the *VOP* and impedance induced through artificial thermal aging the cable to a 50-year equivalent. Section 2 will outline the fundamentals of SSTDR and its operation. Section 3 will detail the aging test performed and the results. The paper will conclude with an outline of the proposed next phase of testing.

2 REFLECTOMETRY

Reflectometry measurements send a high frequency signal into the cable, where it reflects off impedance discontinuities, and returns to the test end. The time delay (Δt) between the incident and reflected signals can be used to tell the distance associated with reflections along the cable:

$$distance(m) = \Delta t(s) \cdot VOP(m/s) \tag{1}$$

where *VOP* is the velocity of propagation on the cable. The reflected voltage (V_r) for an incident voltage (V_i) moving from impedance Z_1 to Z_2 is found from the reflection coefficient:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{2}$$

There are two main reflections of interest. The first is the reflection between the SSTDR ($Z_{SSTDR} \approx 68\ \Omega = Z_1$ [20]) and transmission line ($Z_{TL} = Z_2$). The second is between the transmission line ($Z_{TL} = Z_1$) and a near-matched load at its end ($Z_{TL} \approx Z_{LOAD} = 65.7\ \Omega = Z_2$). As the dielectric constant (ε_r) of the insulation changes with age [9], [11], the impedance of the transmission line (Z_{TL}) changes, resulting in a change in both of reflections [10], as described below. In addition, the velocity of propagation will change, resulting in a change of apparent location of the peak associated with the reflection at the load [10].

The characteristic impedance of a lossless twin lead line depends on the dielectric constant of its insulation (ε_r) as:

$$Z_{TL} = \frac{\eta}{\pi\sqrt{\varepsilon_r}} arcosh\left(\frac{D}{d}\right) \tag{3}$$

where η (≈377 Ω) is the characteristic impedance of free space, D=3.06 mm is the separation of the wires, and d=1.54 mm is their diameter. The calculated impedance of a new cable at 40ºC is Z_{TL}=91 Ω, however our measurements found Z_{TL}=65.7 Ω by placing a potentiometer at the end of the cable and adjusting it until its reflection was no longer visible.

The reflection in (1) is for a lossless cable. If the cable insulation is a good dielectric but with some small conductivity σ, and permeability μ, the attenuation constant (in Np/m) is

$$\alpha = \frac{\sigma}{2}\sqrt{\frac{\mu}{\epsilon_r}} \tag{4}$$

Changes in conductivity and permittivity for radian frequency ω are also commonly measured as

$$\tan\delta = \frac{\sigma}{\omega\varepsilon_r} \quad . \tag{5}$$

The *VOP* is also a function of dielectric constant (ε_r):

$$VOP = \frac{\mathrm{c}}{\sqrt{\epsilon_\mathrm{r}}} \tag{6}$$

where c is the speed of light in free space. We calculated *VOP* = 0.579c and measured it to be 0.55c when the cable is new and at ambient temperature (40ºC).

As the cable ages, the dielectric constant (ε_r) increases [9], [11], [21], resulting in a decrease in the impedance of the transmission line (Z_{TL}), attenuation (α) and *VOP*. We will evaluate the reflection at the end of the cable as a function of aging. This approach has been applied using frequency domain reflectometry [13], [14] and time domain reflectometry [15]. We should also note that an increase in temperature will also change ε_r, [9], [11], [21] so tests evaluating aging should all be done at the same temperature.

There are many types of reflectometry, distinguished by their test signals and method of analysis [12]. Most types cannot be used on energized cables, because existing signals on the cables may interfere with the reflectometer, or the reflectometry signal may interfere with the cable under test. In addition, existing signals or noise on the cable may interfere with the reflectometer. For example, time domain reflectometry (TDR) sends a pulse or stepped voltages onto the cable, and measures its reflections as a function of time [22], [23]. This is a broad-band signal, easily interfering with or interfered by many electrical signals. In order to use TDR on energized cables, the electrical system under test must be immune to the TDR pulses, and the TDR must be immune to the signals on the system under test. Similarly, frequency domain reflectometry (FDR) sends a sequential set of sinusoidal signals into the cable, and measures the magnitude and phase of their reflections [13], [14]. If FDR is to be used on a live system, its frequencies must be chosen so that they can be added on top of the existing signals on the wires, without causing interference. In addition, the existing signals and noise on the cable must be out of the frequency band of the FDR, in order to prevent interference with the reflectometer.

Spread spectrum time domain reflectometry (SSTDR) is designed for testing energized systems [17], [24]. It sends a high frequency pseudo-noise (PN) code into the cable, where it reflects off impedance discontinuities and returns to the test end. There it is correlated with the initial PN code to produce a reflectometry signature that encodes the state of the cable [16]. The PN code is a long set (typically 1000+) of bits, which appear to the system as random noise, but are actually fully reproducible. The magnitude of the PN code signal can be made very small, well below the noise margin of the system, yet it can still be picked up and detected via correlation with the original PN code. This is similar to spread spectrum communication systems such as code division multiple access (CDMA) systems, where the energy of the test signal is spread across a broad spectrum, so the interference with existing signals at any individual frequency is minimal. This allows SSTDR to be used on energized cables without interference from/to the cable under test.

3 CABLE THERMAL TESTING

A 16 AWG twisted pair shielded cable, commonly used in nuclear power plants, was artificially thermally aged to a 50-year equivalent. This thermal stress leads to changes in chemical and/or mechanical properties resulting in changes to the electrical characteristics of the cable insulation. The dielectric constant (ε_r) of the ethylene propylene diene rubber ~~di-monomer~~ (EPDM) cable insulation increases with age [9], [11], [21], resulting in a decrease in the *VOP* and impedance [25]. We tested a two-conductor twisted and shielded pair (TSP) with a conductor size of #16 AWG. The conductor insulation is an EPDM, ε_r = 3.866 [26]) with a Hypalon™ jacket. The EPDM was 0.51mm thick while the Hypalon™ had a thickness 0.25 mm. The entire cable was covered with a jacket of black Hypalon, thickness of 1.14 mm.

A 16.8 m (55 ft.) length of new cable was inspected for faults and damage. One end was connected to the SSTDR with the other end terminated with a potentiometer, which was varied until a minimum reflection from the load was seen. The value of this potentiometer estimates the impedance of the cable to be Z_{TL} = 65.7 Ω. A load resistor of this value was left in place during the thermal aging tests, representative of a well-matched load connected to the cable. Although SSTDR could be used on an energized cable, for these tests, the cable was not energized.

For these tests, we will ~~used~~ use an S100 SSTDR from Livewire Innovation [27]. This device transmits a square-wave modulated PN code at 24 MHz, receives the reflected signal, and correlates them to create the reflection signature to evaluate [16]. This reflection signature is shaped like a *sinc* function multiplied by a *triangle* function, and can be evaluated as any other pulsed reflectometry system. Although our cables are not energized in these tests, we choose the SSTDR method so they could be in the future. The impedance of the SSTDR is $Z_{SSTDR} \approx 68\ \Omega$ [20].

The cable was then wrapped around a cylindrical metal mandrel approximately 46 times the diameter of the cable. It is recommended [28] that the mandrel be at least 40 times the cable diameter. The cable wrapped around the mandrel was placed in the oven, with about 4.6 m (15 ft.) coming out of an unsealed portal ~~in~~ the oven to be connected to the SSTDR, which is outside of the oven.

The cable remained connected to the SSTDR throughout the test (from start to an equivalent of 50 years). At 10-year aging intervals, SSTDR data was collected. The load end of the cable was also passed through an unsealed portal in the oven and connected to the resistive load (so the resistive load itself was not subject to aging). A baseline SSTDR reflectometry measurement, shown in Figure 1, was taken at ambient temperature. The large reflection at the start (0 m) is the reflection between the SSTDR and the cable. The shape of the pulse is the classic SSTDR shape (a *sinc*-like function centered at 0 m) [16]. The data is normalized to the measured reflection for an open circuit at the load and ambient temperature. The reflection at the end of the cable (16.8 m) is very small, because the load is nearly matched.

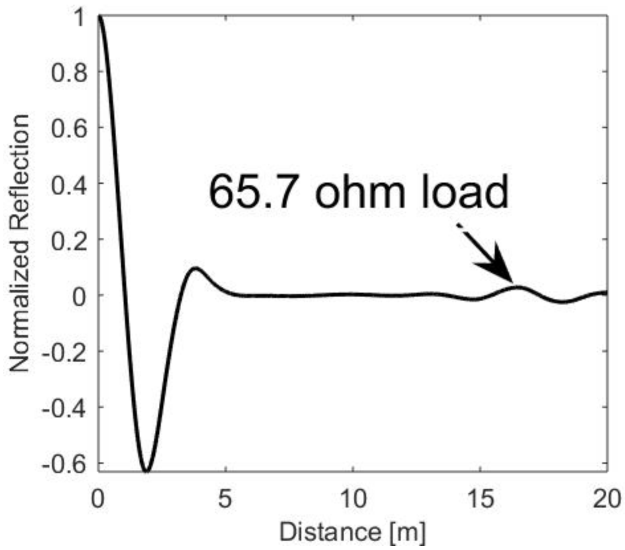

Figure 1. Baseline SSTDR reflection with cable wrapped on the mandrel and load impedance closely matching characteristic impedance.

The mandrel with the cable on it was placed in an oven, and heated to 150°C for 40 days, corresponding to an accelerated age of 50 years. The aging time was calculated using the Arrhenius methodology [29] based on a normal operating temperature. In this case, we assumed an ambient temperature of 40ºC, and a 90ºC rise reflecting a cable carrying rated current. The activation energy used for EPDM was 1.4 eV [30].

SSTDR reflection data was collected at 8-day intervals, representing 10-year periods of accelerated aging. Measurements of aged cable (taken at 150°C) are visually indistinguishable from the baseline (taken at ambient temperature) (Figure 1). To identify these differences, the baseline (Figure 1) was subtracted from SSTDR reflections taken at each 8-day interval and compared in Figure 2.

In Figure 2 the first reflection at 0 m is caused by the impedance difference between the SSTDR and cable. It can also be caused by any other change in impedance between the SSTDR and mandrel, such as moving the wires around between tests. Because of this uncertainty, which is clearly seen in these tests, we will not use this first reflection in our evaluation. The largest change in the reflection in Figure 2 is at the load (16.8 m), which we zoom in on in Figure 3. The load resistor (Z_{LOAD} = 65.7 Ω) is chosen to be as near a match as possible to the impedance of the unaged cable ($Z_{TL} \approx 65.7$ Ω), so any change in the impedance of the cable would increase the magnitude of the reflection seen at the load. The insulation dielectric constant (ε_r) increases with age [9], [11], [21], which decreases the impedance of the cable (1), corrupting the impedance match and increasing the magnitude of the reflection. In addition, the attenuation (4) decreases, further increasing the magnitude of the reflection with age, as seen in Figure 3. The peak values as a function of age are shown in Figure 4. The normalized reflection increases more quickly in the early stages of aging and slows down later, indicating a change in the aging process. In addition to the increase in magnitude of the reflection coefficient, the *VOP* should also increase according to (2), causing a shift in the apparent location of the reflection. This shift and its dependence on age is not as clear from Figure 3, in part because of change in the shape (width) of the pulse.

The changes in reflection magnitude seen in Figure 2 at other locations along the line are caused by small changes in the multiple reflections between the source and load. These add to the confirmation that an aging change exists. These are different than changes that would be seen from localized damage, which would produce a more localized difference in reflection.

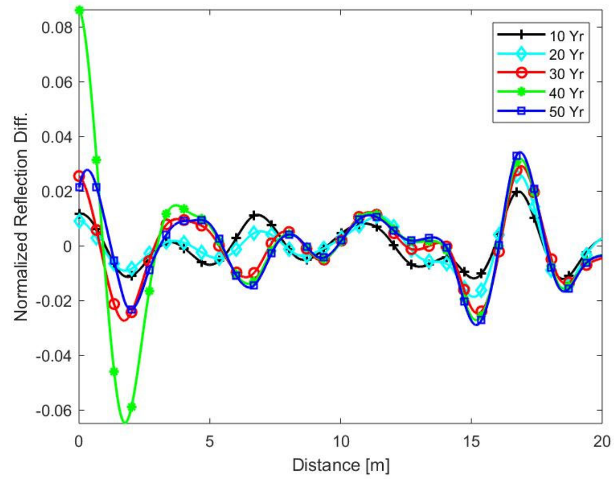

Figure 2. Difference from baseline SSTDR reflections for 10- through 50-year accelerated ages.

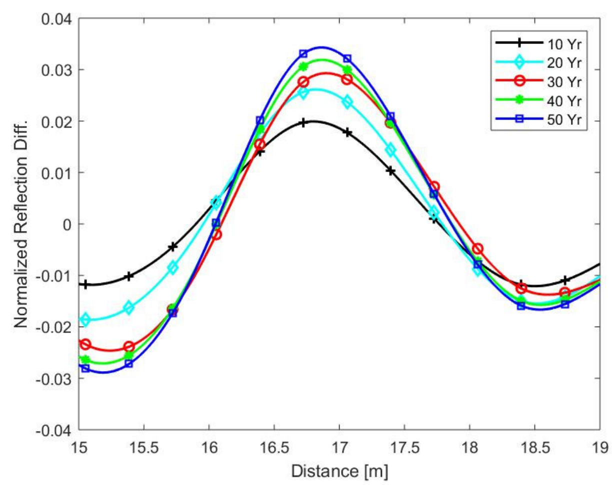

Figure 3. Difference from baseline SSTDR reflections for 10- through 50-year accelerated ages, zoomed in to the load at 16.8m.

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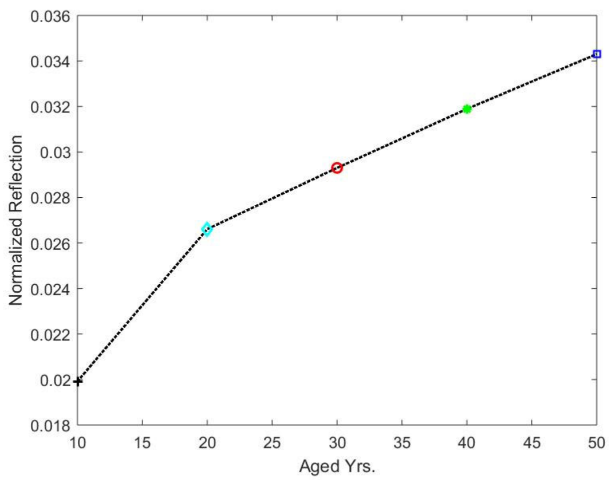

Figure 4. Difference from baseline of reflection coefficient at the load (magnitude of the peaks in Figure 3) as a function of aging time.

3 CONCLUSION

The objective of the study was to determine if SSTDR could detect aging in a #16 AWG cable of the type used in nuclear power plant. The end of the cable was nearly-matched with a resistor when the cable was new (unaged), resulting in a very small reflection at this load. The cable was then artificially aged in an oven, to ages representing 10 to 50 years. The reflection at the end of the cable increased as the cable aged, consistent with an increase in the dielectric constant of the insulation. This also indicates an increase in the tan δ value as the cable aged. These results indicated that SSTDR does show measurable changes associated with aging of this cable.

The advantage of SSTDR for cable testing in power plants is that it could be used to monitor the energized cable continuously during normal plant operation, providing closer monitoring than is possible today. Cables routed through nuclear plants pass through numerous rooms where environmental conditions vary, and therefore aging of the cable may vary based on its routing. The path of the cable will include bends, in some cases routing close to local adverse environments such as hot piping. In addition, it is likely that portions of the cable will not be accessible. This makes reflectometry an ideal test method, since it can test the entire cable including non-accessible areas and indicate where along the cable degradation may be occurring. Future work should consider these types of localized aging scenarios. A second phase of SSTDR test evaluation is under development. This next phase will study energized cables in configurations that reflect actual plant cable configurations.

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DISCLOSURE

Dr. C.M. Furse is a co-founder of Livewire Innovation LLC. which is commercializing SSTDR technology, and therefore has a financial conflict of interest with this company.

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