Diagnostics of Electric Cables in Nuclear Power Plants via Joint Time-Frequency Domain Reflectometry

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Abstract—Defective cables in the electric power systems of nuclear power plants can cause a component to fail, resulting in potential safety concerns. Due to this problem, a non-destructive, non-intrusive condition assessment technique is highly desirable. Joint time-frequency domain reflectometry (JTFDR) is proposed and verified to be effective for cross-linked polyethylene (XLPE) cable, which serves critical instrumentation and control operations in nuclear power plants. The experimental results demonstrate and verify the ability of JTFDR to effectively detect and locate incipient defects with high accuracy and to monitor the aging process of the cables to predict both future defects and the remaining service life of the cables.

I. INTRODUCTION

In nuclear power plants, miles of electric cables are used to perform numerous operational and safety related functions. The integrity of the wiring in the electric power system of a nuclear power plant is vital to its safe operation [1]. One of the most common types of insulation for cables used in nuclear plants is cross-linked polyethylene (XLPE) because of its excellent physical, chemical and electrical properties [2]. XLPE cables have been installed extensively since the 1970’s and are still in service. Unfortunately, a number of mechanisms can degrade the XLPE insulation such as thermal embrittlement, mechanical stress, and radiolytic degradation. The aging effects and failure rate of these old cables varies. Some cables are still in good condition, and to replace them all would be costly. Therefore, a diagnostic technique is needed which can detect and locate hard defects accurately before they lead to any kind of damage. Furthermore, the ideal scenario is for incipient defects to be detected before they evolve into hard defects. For this purpose, a non-destructive, non-intrusive prognostic technique is required which can monitor the status of the cable and predict the remaining life of the cable [3][4].

Thus far, all available techniques are destructive (such as Elongation at Break), need to be performed in a laboratory setting (such as Oxidation Induction Time), or cannot provide information about the remaining useful life of the cables (such as Partial Discharge) [6]. The current state-of-the-art technology for wiring diagnostics and prognostics are reflectometry-based techniques; they can be largely categorized as either time-domain analysis or frequency-domain analysis. Time-domain analysis typically employs time domain reflectometry (TDR); frequency-domain analysis commonly involves either frequency-domain reflectometry (FDR) or standing-wave reflectometry (SWR) [4]. These reflectometry techniques are based on the analysis of a reference signal and the signal(s) reflected by imperfections on the wire being tested. However, these classical techniques are limited by the fact that they analyze the reference and reflected signals in either the time domain or the frequency domain only.

In this paper, the authors propose a new signal processing-based reflectometry technique, joint time frequency domain reflectometry (JTFDR). This innovative technique captures the advantages of both TDR and FDR while avoiding some of their limitations by using advanced digital signal processing. In other words, JTFDR utilizes a reference signal that is localized in both the time and frequency domains simultaneously [7]. This reference signal is composed of a Gaussian envelope applied to a linear chirp signal. A distinct advantage of this reference signal is its configurability; the user can properly select the parameters of the reference signal, including frequency bandwidth, center frequency, and time duration, by considering the frequency characteristics of the wire being tested [7]. After obtaining the signals reflected by defects in the cable under test, JTFDR uses a predetermined kernel to find the time-frequency distributions of the reference signal and each reflection. JTFDR then computes the time-frequency cross-correlation between the reference signal and each reflected signal and uses the peaks of the correlation to detect the defects and determine their locations. JTFDR has been proven to be able to accurately and sensitively detect both hard and incipient defects on coaxial cables [7]. The unique features of the time-frequency cross-correlation function employed by JTFDR also allow it to sensitively monitor all minor imperfections. Changes or growth in the time frequency cross-correlation indicate that the faulty condition of a wire or cable is degrading.

In this paper, JTFDR is first applied to an XLPE cable with incipient defects to verify the efficacy and configurability of this technique. The experimental setup of the JTFDR is described in Section II. In Section III, we will discuss the experimental results of JTFDR and we will discuss how JTFDR can achieve scientific prognosis of an aging cable and can monitor a cable for signs of insulation degradation. Conclusion of the paper is provided in Section IV.
II. Experiment Setup

The JTFDR technique is applied to real-world cable and it is compared with the traditional diagnostic techniques with the experiment. The experimental setup and system functional diagram for the testing described above is pictured in Figs. 1(a) and 1(b).

![Figure 1. (a) Experimental JTFDR wiring test bed and (b) JTFDR System Functional Diagram.](image)

Fig. 1(a) shows the experimental JTFDR wiring test bed, which is composed of a signal generator (Tektronix Arbitrary Waveform Generator 610), a data acquisition device (Agilent Infiniium 54754A), and a control PC. The computer controls the arbitrary waveform generator to produce the time-frequency domain reference signal, which propagates into the target cable via the circulator. This reference signal is reflected at the fault location and travels back to the circulator. The circulator redirects the reflected signal to the digital oscilloscope. The computer program acquires both the reference and reflected signals from the oscilloscope, calculates the time-frequency distribution of the reference and reflected signals, and executes the time-frequency cross-correlation algorithm to detect, locate, and assess any defects on the cable.

Fig. 1(b) is the system schematic diagram that describes configuration of the experimental devices. The heat chamber (EC17 Environmental Chamber) in the schematic is used for accelerated thermal aging purpose.

III. Results

A. Incipient Defect Detection and Location

In this paper, the cable samples studied are Rockbestos Firewall XHHW, #14AWG, 2 conductors, 600V cables. This type of cable is normally used as a power or control cable and might be exposed to harsh environments. The cables have XLPE insulation on each conductor and an overall Neoprene jacket covering the bundle of insulated conductors.

The incident signal of JTFDR can be configured to maximize the capability of the technique for the cable under test based on the physical properties of the cable. For this reason, the transfer function of a 10m sample of the cable was found and the bode plot is shown in Fig. 2. If the center frequency of the JTFDR incident signal is chosen to be too high, the reflection will be too weak to be detected by the oscilloscope due to the high attenuation. If the center frequency is chosen to be too low, JTFDR will not have enough resolution to locate the defects accurately. Also, the phase of the frequency response at the corresponding center frequency should be linear; this will affect the impedance measurement of the defect. Such quantitative information will be helpful to identify the type of defect in future research. For these reasons, the incident signal for this experiment is chosen to have a 125 MHz center frequency and a 50 MHz bandwidth as shown in Fig. 2.

![Figure 2. Bode plot of Rockbestos Firewall XHHW.](image)

A defect corresponding to the removal of 0.25 in. of outer insulation around half the circumference of the cable is created at 5.5 m. For a comparison of the reflectometry techniques, TDR is first applied to the cable, and then JTFDR is applied to the same cable. The results of these tests are given in Figs. 3(a-c) below.
Figure 3(a) shows the waveforms of the incident and reflected waveforms in the time domain, in which it is difficult to observe the reflections from the defect. Fig. 3(c) reveals that TDR is of little use on the cable. Although the beginning and end of the cable are readily observable, it is difficult to distinguish the reflection of the incipient defect from other false reflections. However, the plot of the corresponding joint time-frequency cross-correlation function of the waveforms [Fig. 3(b)] shows an obvious peak which corresponds to the defect. According to calculations from Fig. 3(b), the defect is located at 5.43 m. The experimental results above show that JTFDR can accurately detect and locate incipient defects on XLPE cables, which is a difficult job for TDR as shown in Fig. 3(b).

B. Accelerated Thermal Aging Testing

Conducting life tests on cables under normal operation conditions is not practical because it is too time consuming; therefore accelerated aging tests are necessary. Accelerated aging tests will apply higher stress levels than normal operating values to more quickly induce age-related degradation of the cables. For XLPE insulation, the higher temperature will hasten the chemical reaction rate and enhance the degree of other thermally activated processes. At temperatures greater than 90°C, the crystalline regions melt and further oxidation occurs. The AC and impulse breakdown values are also reduced by 6 and 19% respectively from those at room temperature, with further respective reductions of 18 and 48% at 115°C [8].

The same Rockbestos Firewall in cable type that was used in the previous diagnostic test will be used for the accelerated aging test. The length of the sample is again 10 m, and the segment to be tested is located from 5 m to 6 m; thus, the length of the “hot spot” is 1 m. The same incident waveform is applied to the cable sample.

To simulate exposure to a service temperature of 50°C for duration of 60 years, the aging duration was determined using the well known Arrhenius equation. This equation describes the relationship between the reaction rate and the temperature of a chemical reaction. The equation has been verified to be effective for many materials. The modified Arrhenius equation for accelerated thermal aging is stated below:

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

(1)

Where:
- $T_s$ is the service temperature.
- $T_a$ is the accelerating aging temperature.
- $t_s$ is the aging time at service temperature.
- $t_a$ is the aging time at acceleration temp.
- $E_a$ is the activation energy (1.33 eV).
- $B$ is the Boltzmann’s constant (given below).

$$B = \left(8.617 \times 10^{-5} eV/K\right)$$

(2)

Before the cable is put into the chamber, which is preheated to 140 °C, the waveforms are acquired and processed to obtain the time-frequency cross-correlation baseline for future comparison. The intended hot spot of the sample is then put into the chamber for 15 hours. To monitor the aging process, the waveforms are acquired and processed after each hour to obtain an updated time-frequency cross-correlation plot.

To demonstrate the capability of JTFDR to monitor the severity of a defect over time, Fig. 4 shows the result of the aging test at 140°C (50°C higher than the maximum operating temperature of the cable under test). It presents the time-frequency cross-correlation function after one, ten, and 15 hours of thermal aging. The peaks of the time-frequency cross-correlation function at the origin and at the open-end of the cable show a peak value of one. These values at the beginning and end of the cable do not change with thermal aging; however, the time-frequency cross correlation exhibits reflections from the hot spot located at 5 m to 6 m away from the beginning of the cable. Notably, the time-frequency cross-correlation peak value increases from less than 0.1 after one hour up to 0.3 after 15 hours.
This experiment demonstrates that JTFDR can successfully monitor the aging process of a cable under duress. The peak of the time-frequency cross-correlation function provides information about the state of a wire under test, and this information can be monitored over time. With this capability, JTFDR can predict a hard defect before it reaches its most dangerous state. This technique also can be used to predict the remaining life of the cable, but that requires setting up a data base which records the corresponding correlation peak values for different aging states of the cable. We are continuing our research activities in order to extend the JTFDR diagnostic capability for the prognostics.

IV. Conclusion

In this paper, the innovative JTFDR is proposed and verified to be a robust, accurate, and sensitive diagnostic technique. It captures the advantages of both TDR and FDR and features a unique incident signal configurable to its application.

This research has also demonstrated that if a data base of correlation values of aging states of different cable types can be set up for JTFDR, it could be a promising prognostic technique which can monitor the aging process and provide a measurement for the aging states of the cable.

The testing in this paper is limited to XLPE cable to allow a full range of testing to be performed within the budget and schedule allocated for this study. Future research is desirable to investigate the effectiveness of JTFDR on other types of cables used in nuclear power plants such as ethylene propylene rubber (EPR).

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