Applications of Joint Time-Frequency Domain Reflectometry for Health Assessment of Cable Insulation Integrity in Nuclear Power Plants

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ABSTRACT

Defective cables in the electric power systems of nuclear power plants can cause failure of essential components in control and instrumentation or power distribution subsystems, resulting in potential safety concerns. Due to this problem, a nondestructive and non-intrusive condition assessment technique is highly desirable to evaluate cable status and to predict the remaining useful life of a cable. The capability of joint time-frequency domain reflectometry (JTFDR) as such a condition assessment technique is studied in this paper. The health status of four popular insulation types utilized in nuclear power plants for control and distribution is monitored using JTFDR in thermal accelerated aging test including: Cross-linked polyethylene (XLPE), tree retardant cross-linked polyethylene (TR-XLPE), ethylene propylene rubber (EPR), and silicone rubber (SIR). The experimental results show that JTFDR can successfully monitor the aging process of all four insulation types. Further, the results from JTFDR are compared with the results from Elongation-at-Break (EAB). These results show that JTFDR technique is comparable with EAB, in some cases providing more linear characteristics with respect to aging time, and has great potential as a non-destructive and non-intrusive condition assessment technique.

Key Words: Joint Time-Frequency Domain Reflectometry (JTFDR), prognostics, XLPE cable, EPR cable, SIR cable

1 INTRODUCTION: MOTIVATIONS FOR NUCLEAR CABLE MONITORING

In nuclear power plants, miles of electric cables are used to perform numerous operational and safety related functions. The integrity of wiring in the electric power system of a nuclear power plant is vital to its safe operation, but electric power cables are subjected to various stresses including electrical, mechanical, chemical, and especially thermal stress [1]. These thermal stresses can accelerate the aging process of cable insulations in normal service conditions. Given these conditions with additional complications from radioactive materials, nuclear power plants are facing the technical challenges of detecting and locating faulty cables and are also experiencing premature failures much earlier than the life expectancy originally estimated. [2],[3],[4],[5].

In addition to safety concerns, recently reported data from 2008 and beyond reveal $300 billion in annual revenue for power utility compared to operating expenses of $267 billion and accentuate the continued emphasis of reduced operation and maintenance costs for increased net revenue [6]. Previous
trends have shown an increase in net generation and revenue while current economic factors have produced a new climate for the industry in which this is no longer the case. In this new power utility climate, annual net electric power generation, to which nuclear power contributes 19.6% of all kilowatt hours, has actually decreased for the first time since 2001 [6].

In order to prevent electrical outages and to save maintenance expenses, a prognostic technique is needed which can quantify the degradation of the insulation of a cable to predict the remaining life of the cable. Ideally, the technique should be non-destructive, non-intrusive, applicable to cable types and insulation materials commonly used. Furthermore, the ideal scenario is to be able to accurately monitor the health status of cable in real-time and continuously. In practice however, there are no condition monitoring techniques available that have all the above attributes. In this paper, the capability of joint time-frequency domain reflectometry (JTFDR) to monitor the status of cable insulation in an effort to predict the remaining life of power cables is studied. JTFDR captures the advantages of both TDR and FDR while avoiding some of their limitations by using advanced digital signal processing [7]. A distinct advantage of this reference signal is its configurability; the user can select appropriate parameters of the reference signal, including frequency bandwidth, center frequency, and time duration, by considering the frequency characteristics of the wire being tested. JTFDR has been proven to be able to accurately and sensitively detect both hard and incipient defects on coaxial cables [8]. 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.

This method has the highest potential to meet most of the desirable attributes discussed above. The fundamental theory of JTFDR will be introduced in section 1.1 of more detailed descriptions of experimental implementation in sections 1.2.1 - 1.2.3. In section 1.2, JTFDR will be applied to four popular insulations in nuclear power plants: Cross-linked polyethylene (XLPE), tree retardant Cross-linked polyethylene (TR-XLPE), ethylene propylene rubber (EPR), and silicone rubber (SIR) during thermal accelerated aging test to monitor their aging process. The cable samples representative of these insulation types cover a wide range of applications from control to medium voltage transmission. Overall conclusions of this paper are drawn in section 1.2.4.

### 1.1 Joint Time-Frequency Domain Reflectometry

JTFDR utilizes an incident signal that is localized in both the time and frequency domains simultaneously. This incident signal is composed of a Gaussian envelope applied to a linear chirp signal [7],[8],[9] as below:

\[
s(t) = (\alpha/\pi)^{1/4}e^{-\alpha(t-t_0)^2/2} + j\beta(t-t_0)^2 + j\omega_0(t-t_0)
\]  

(1)

where coefficient \( \alpha \) determines the time duration of the incident signal; coefficients \( \alpha \) and \( \beta \) determine the bandwidth of the incident signal; and \( \omega_0 \) is the center frequency. After obtaining the signals reflected by defects in the cable under test, JTFDR uses a predetermined kernel (the Wigner distribution is used in this paper) to find the time-frequency distributions of the incident signal and the reflected signal.

The Wigner distribution of the time signal, \( s(t) \), is obtained by the following transformation:

\[
W(t, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} s(t-\frac{1}{2}\tau) \cdot s(t+\frac{1}{2}\tau) e^{-j\tau \omega} d\tau
\]  

(2)

JTFDR computes the time-frequency cross-correlation between the incident signal and the reflected signal with the following equation:

\[
C_{sr}(t) = \frac{1}{E_sE_r(t)} \int_{t'=t-T_a}^{t'=t+T_a} \int W_s(t', \omega)W_r(t', \omega) d\omega dt'
\]  

(3)
where $W_r(t,\omega)$ is the Wigner distribution of the reflected signal; $W_s(t,\omega)$ is the Wigner distribution of incident signal; and $E_s$ and $E_r(t)$ are normalization factors. The peaks of the time-frequency cross-correlation are used to detect the defects and determine their locations. Changes or growth in the time-frequency cross-correlation indicate that the faulty condition of a wire or cable is degrading. This degradation indicator will be shown in detail in section 1.2.

### 1.2 Health Monitoring Tests with Accelerated Thermal Aging

#### 1.2.1 Overview of accelerated aging procedure

The accelerated thermal aging tests in this paper 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. Simulated accelerated aging takes place in a heat chamber shown in Fig. 1. The simulated service life of all four types of insulated power cables is set to be 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 [10].

$$t_a = t_s e^{\frac{E_a}{R_B} \left( \frac{1}{t_a} - \frac{1}{t_s} \right)} \quad (4)$$

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 5m to 5.6m 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. Four accelerated aging tests are performed in this paper: one for an XLPE insulated cable sample, one for a TR-XLPE insulated cable sample, one for an EPR insulated cable sample, and one for a SIR insulated cable sample.

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 are given for each in section 1.2.2.

1.2.2 Cable insulation materials

- Cross-linked polyethylene (XLPE) insulation

  The low voltage cable sample with XLPE insulation is from a Rockbestos Firewall III XHHW, 14AWG, dual conductor, 600 V cable, which is normally used for control and instrumentation in nuclear reactors where the cables suffer aging caused by heat and radiation. The insulation on each conductor is composed of XLPE and a neoprene jacket covers the bundle of insulated conductors. To simulate exposure to a service temperature of 50°C for a cumulative duration of 90 years, the cable needs to be heated in the chamber at 140°C for 24 hours.

- Tree-resistant cross-linked polyethylene (TR-XLPE) insulation

  The second XLPE cable sample is a medium voltage MV-90, 1/0 AWG, single conductor, 35kV cable, commonly used for both underground duct and direct buried transmission applications. Surrounding the single, stranded copper conductor are layers of extruded thermosetting semiconducting shield for the conductor, Voltalene TR-XLPE insulation, insulator shielding, separator tape for the return path, and an outer PVC jacket. To simulate exposure to a service temperature of 50°C for an overall duration of 90 years, the cable needs to be heated in the chamber at 140°C for 24 hours.

- Ethylene propylene rubber (EPR) insulation

  For accelerated aging tests, the EPR insulation cable sample used is from a Nexans MIL-DTL-24640 TXW-4, 600 V cable. This type of cable is normally used as a power cable in ship power systems and might be exposed to constant vibration, heat, and other age related stresses. It is well-known that EPR is a “better” insulator than the XLPE, but it is not easy to quantify it via monitoring of the insulation. To simulate exposure to a service temperature of 50°C for a total duration of 120 years, the cable needs to be heated in the chamber at 160°C for 48 hours. These values are determined by the Arrhenius equation with activation energy of 1.1 eV [2].

- Silicon rubber (SIR) insulation

  The SIR insulated cable sample used is from a Nexans LSTSGU-9: M24643/16-03UN cable. This type of cable is also normally used as a power cable in ship power systems and therefore might also be exposed to the same stresses as the EPR insulated cables: constant vibration, heat, and other age related stresses. To simulate exposure to a service temperature of 50°C for a duration of 120 years, the cable needs to be heated in the chamber at 120°C for 12 hours. These values are determined by the Arrhenius equation with activation energy of 2.1 eV [11].

1.2.3 Application of Joint Time-Frequency Domain Reflectometry method

An optimal reference such as the one seen in Fig. 2-(a) is developed for each insulation type under test according to previously determined algorithms [7]. This signal is injected into each 10 m cable sample following the outline of Fig. 1. The computer (PC) instructs the arbitrary waveform generator to produce the Gaussian-chirp incident signal based upon the input center frequency, bandwidth, and time duration. This incident signal propagates into the target cable via the circulator with an optional pre-distortion and RF amplifier stage for longer segments of cable. This signal is reflected at the fault location, and travels back to the circulator where it is then sampled by the digital oscilloscope.

The JTFDR method described in section 1.1 is then applied using the incident reference signal and reflected signal. Time-frequency cross-correlation peaks from the JTFDR method are seen in Fig. 2-(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.
Figure 2. (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.

1.2.4 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 Fig. 3-(a). Traditional elongation-at-break measurements are provided in Fig. 3-(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 [12]. 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 Fig.2, the results of EAB of all three types of insulation are plotted in one figure. Similar to the time-frequency cross-correlation peaks in Fig.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.

Figure 3. (a) Comparison of results of JTFDR for XLPE, TR-XLPE, EPR, and SIR. (b) Comparison of Elongation-at-break for XLPE, EPR, and SIR
2 CONCLUSIONS

In this paper, 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. 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 while maintaining a non-destructive and non-intrusive prognostic paradigm for monitoring cable status continuously. 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.

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4 REFERENCES


