Diagnostics and Prognostics of Electric Cables in Ship Power Systems via Joint Time-Frequency Domain Reflectometry

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Abstract – The integrity of the wiring in the electric power system of a ship is vital to its safe operation. To ensure the wiring integrity, it must be tested to determine if any incipient defects exist. Due to this problem, a non-destructive, non-intrusive condition assessment technique is highly desirable. Joint time-frequency domain reflectometry (JTFDR) is proposed and the theory behind JTFDR is also discussed. The experimental results demonstrate and verify the ability of JTFDR to be effective for polytetrafluoroethylene (PTFE) coaxial cable, which has been widely adopted for military applications in ship power systems. It is shown that JTFDR has the ability to detect and locate incipient defects with high accuracy and monitor the aging process of the cables to predict both future defects and the remaining service life of the cables.

Keywords – Joint Time-Frequency Domain Reflectometry (JTFDR), Diagnostics, Prognostics, PTFE

I. INTRODUCTION

The safe operation of the ship power system depends largely on the integrity of the wiring system. The typical electric ship power system contains miles of wiring. Some of which is difficult to reach and most of which is exposed to constant vibration, routine maintenance operations, heat and other age-related disturbances [1]. Therefore, a diagnostic technique is needed which can detect and locate these defects accurately before they lead to any kind of damage. However, the ideal scenario is for these incipient defects to be detected before they evolve into hard defects. In order to both prevent hard defects and save cost on periodically changing cables, 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 [2],[3].

The current state-of-the-art technology for wiring diagnostics can be largely categorized as 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 any 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.

Thus far, all available techniques are destructive, need to be performed in a laboratory setting, or cannot provide information about the remaining useful life of the cables [5]. Ideally, a technique would exist that could eliminate the disadvantages and undesired effects of these techniques for diagnostics, while also providing prognostic information. However, presently there is no single, feasible technical solution that can achieve both diagnostics and prognostics for all the types of cables and environments in ship power systems. JTFDR is proposed as a comprehensive solution.

In this paper, JTFDR is first applied to a M17/95-RG180 military grade cable protected by PTFE insulation with incipient defects to verify the efficacy and configurability of this technique. The theory of JTFDR is discussed in Section II. The experimental setup of JTFDR is described in Section III. In Section IV, we will discuss the experimental results of JTFDR, how JTFDR can achieve scientific prognosis of an aging cable, and how JTFDR can monitor a cable for signs of insulation degradation. Conclusions are provided in Section V.

II. JOINT TIME-FREQUENCY DOMAIN REFLECTOMETRY

In this paper, a new signal processing-based reflectometry technique, joint time-frequency domain reflectometry (JTFDR) is proposed. This innovative technique captures the advantages of both TDR and FDR while avoiding some of their limitations by using advanced digital signal processing. JTFDR utilizes a reference signal that is localized in both the time and frequency domains simultaneously. This reference signal is composed of a Gaussian envelope applied to a linear chirp signal as below:

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

where coefficient \( \alpha \) determines the time duration of the reference signal; coefficients \( \alpha \) and \( \beta \) determine the bandwidth of the reference signal; and \( \omega_0 \) is the center frequency. A reference signal is created in MATLAB and displayed in Fig. 1. The real-world reference signal used in the experiment can be...
observed from the oscilloscope and is shown in Fig. 3(a). 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 (the Wigner kernel is used in this paper) to find the time-frequency distributions of the reference signal and the reflection. The Wigner distribution of the time signal, \( s(t) \), is obtained by the following transformation:

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

(2)

JTFDR then computes the time-frequency cross-correlation between the reference signal and the reflected signal(s) with the following equation:

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

(3)

where \( W_r(t, \omega) \) is the distribution of the reflected signal; \( W_s(t, \omega) \) is the distribution of reference signal; and \( E_s \) and \( E_r \) are normalization factors.

The peaks of the time-frequency cross-correlation are used 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.

III. EXPERIMENTAL SETUP

The experimental JTFDR wiring test bed is composed of a signal generator (Tektronix Arbitrary Waveform Generator 610), a data acquisition device (Agilent Infinium 54754A), and a control PC. The computer controls the arbitrary waveform generator (AWG) to produce the Gaussian-envelope chirp signal, which propagates into the target cable via the circulator or T-connector. 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 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.

An EC17 Environmental Chamber is used for accelerated thermal aging for prognostics verification.

IV. RESULTS

A. Diagnostics - Incipient Defect Detection and Location

In this paper, the cable samples studied are M17/95-RG180, with PTFE insulation. This type of cable is traditional military (MIL) specification coaxial cable that was developed 50-60 years ago. It was originally created to support WWII military applications and continues to be used today. Its solid dielectric provides superior crush resistance and its excellent mechanical properties make it well suited for tactical applications. However, these tactical applications increase the chance of defects.

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 10 m sample of the cable was found and the Bode plot is shown in Fig. 2. There is a trade off between frequency-based signal attenuation and location resolution in choosing the center frequency of the incident signal: the higher the center frequency, the greater the attenuation but also the higher the resolution, and vice versa. Because the cable sample is relatively short (only 10 m long), the resolution is more important than attenuation for detection and location purposes. Also, the phase of the frequency response at the corresponding center frequency should be linear or else errors could be introduced in the detection and location process. The linearity of the phase of the frequency response can also 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 425 MHz center frequency and a 100 MHz bandwidth as shown in Fig. 2.

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. The correlation function is normalized between 0 and 1 so that the detection of the defects can be quantified within bounded values; i.e., the function indicates the probability of reflection from potential defects. 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 PTFE cables, which is shown to be a difficult job for TDR.

B. Prognostics - 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 conditions to more quickly induce age-related degradation of the cables.

The same M17/95-RG180 cable type that was used in the previous diagnostic test will be used for the accelerated aging test. The length of the new 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 as before is applied to the cable sample. To simulate exposure to a service temperature of 50°C for a duration of 60 years, the accelerated 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:

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

(4)

where:

- \( T_s \) is the service temperature;
- \( T_a \) is the accelerated aging temperature;
- \( t_s \) is the aging time at service temperature;
- \( t_a \) is the aging time at acceleration temperature;
- \( E_a \) is the activation energy; and
- \( B \) is the Boltzmann’s constant (given below).

\[ B = (8.617 \times 10^{-5} \text{eV/K}) \]  

(5)

Before the cable is put into the chamber, which is preheated to 250°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, the results of the aging test at 250°C (50°C higher than the maximum operating temperature of the cable under test) are shown in Fig. 4. It presents the time-frequency cross-correlation function before the aging, after 5 hours (20 simulated years), and after 15 hours (60 simulated years) of thermal aging. The peak of the time-frequency cross-correlation function at the origin is the result of the auto-correlation of the incident signal with itself so it represents the beginning of the cable. The peak at 10 m is the result of the cross-correlation between the incident signal and the reflections from the open-end, so it represents the end of the cable. Both of them show a peak value close to 1. 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 at this location increases from around 0.1 before testing up to 0.5 after 15 hours.

The other peak, located at around 2.5 m, is caused by the undesirable leakage due to the non-ideal circulator. We are investigating methods for removing this minor abnormality. Because the peak of the cross-correlation corresponding to this non-defect is typically much smaller than the peak from true defects, we ignore it by setting a threshold greater than the cross-correlation peak of the non-defect, but still low enough to detect any real defects.

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 under test.

V. 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 JTFDR is a promising prognostic technique which can monitor the aging process. The peak of the time-frequency cross-correlation function provides information about the state of a cable 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 and predict the remaining life of the cable.

The testing in this paper is limited to a certain type of coaxial 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 ship power systems; TXW-4 and MIL-C-27500 are our next targets.

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