Diagnostics of control and instrumentation cables in nuclear power plant via time-frequency domain reflectometry with optimal reference signal

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ABSTRACT

Among various types of cable diagnostic techniques in physical, chemical and electrical dimensions, time-frequency domain reflectometry (TFDR) is characterized by providing benefits of both time domain reflectometry (TDR) and frequency domain reflectometry (FDR) and is also non-destructive which such that the cable is not destroyed under test. This paper introduces an algorithm which optimizes parameters (center frequency, bandwidth and time duration) of the reference signal for TFDR diagnosis. The usefulness of the algorithm is verified by adapting it to the cable fault detection experiment.

KEYWORDS

Cable diagnostics, Fault detection, Reflectometry, Control and Instrumentation (C&I) cable, Cable insulation.

1. INTRODUCTION

The insulation of the cable enables shielding to work effectively by keeping the center conductor from external stimulus. The dielectric strength of insulation can be defined as the limiting voltage stress under which the dielectric can no longer maintain its integrity [1]. If the insulation is damaged, the electric field cannot be equally maintained at every point and the excess current flow passes through the insulation which leads to insulation failure. There are many causes of insulation failure including physical aging [2], electrical trees [3], moisture ingress [4] and failure in cable joints.

Control and instrumentation (C&I) cables in nuclear power plants, which are considered one of the most crucial components in reactor's safety, are used to measure critical parameters such as temperature for monitoring and controlling the reactor operations. Since these cables are exposed to severe environmental aging factors such as thermal and radioactive sources that aggravate their aging, it is not easy to determine and estimate the remaining life of these cables. Also, nuclear power plants are over thirty years old and the C&I cables in the plants are now faced with decisions to maintain, repair, refurbish, or replace their cable systems [5]. Therefore, it is important to develop and apply a cable diagnostic technique that enables us to assess the health condition of the cables in aging nuclear power plants.

Varieties of existing diagnostic methods of cable integrity can be categorized as chemical, mechanical, or electrical. Chemical and mechanical diagnostic methods including determination of oxidation induction time (OIT) [6], Gas-in-oil analysis [7], Fourier transform infrared spectroscopy (FTIR) [8], Dynamic mechanical analysis (DMA) [8], and Elongation at break [9]. Partial discharge (PD) test [10] and Very low frequency (VLF) test [11] are also used as well. However, these methods still have quite a few problems. Some need expensive testing equipment and dedicated testing procedures; some can only give vague data that cannot be interpreted properly, and most of them are destructive to the cable [12]. Therefore, we focused on a non-destructive and non-invasive diagnostic technique, reflectometry methodology, which is capable of assessing the cable's condition, estimating its remaining life, and locating defects before any failure occurs.

Reflectometry method is a non-invasive technique that allows the analysis of the properties of a cable. It is based on the reflection of signals at the impedance discontinuity point. Signals propagate into a medium and when it encounters a discontinuity, part of its energy is reflected back to injection point. Reflectometry is classified by both the time and frequency domain. Time domain reflectometry (TDR) is a measurement technique used to determine the characteristics of the cable by observing reflected signals in the time domain while the frequency domain reflectometry (FDR) is analyzed in the frequency domain. Since these methods analyze the signal in only one domain, it is vulnerable to be influenced by noise and sometimes has low resolution and accuracy.

The time-frequency domain reflectometry analyzes the reflected signal in time- and frequency- domain simultaneously. One important characteristics of the TFDR is that the results of diagnosis depend on the reference signal. TFDR uses the Gaussian envelope linear chirp signal as a reference signal. Since the reference signal has the bandwidth and the time duration together, the reference signal can reduce the influence of the noise. Also, it has high accuracy because TFDR uses the matching function (cross-correlation between signals) to detect the location, whereas other reflectometry detects the location by distinguishing the difference in the magnitude. The results, however, are derived from the cross-correlation between the reference signal and the reflected signal. Thus, it is necessary to design the optimal reference signal which is less distorted and less overlapped along the cable.

Therefore, we propose designing the optimal parameters of the reference signal on each cable for TFDR to achieve the best diagnostic result. This algorithm is based on the limits relationship between parameters of the reference signal. Section 2 introduces TFDR briefly covering the fundamental theory and then discussing theoretical background for optimizing the reference. The optimization procedure is described in Section 3. To verify the usefulness of the algorithm, Section 4 presents the TFDR experimental setup and results of applying the optimization procedure to C&I cables with different insulation respectively. Finally, the experimental results lead to the conclusion in Section 5 that the optimal parameters algorithm is practical to gain the optimal reference signal for TFDR.