46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-6787

CAPACITANCE MEASUREMENTS FOR NONDESTRUCTIVE TESTING OF AGED NUCLEAR POWER PLANT CABLE

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ABSTRACT

In this work, distributed measurements of capacitance on a nuclear power plant (NPP) cable are examined for their effectiveness as a method of nondestructive evaluation. Many U.S. NPPs are approximately 40 years old and undergoing a costly process of license renewal, motivating inspection of cables, concrete, and other materials whose integrity are critical to the safe functioning of the plant. In particular, a shielded, tri-core instrumentation cable insulated with flame-resistant ethylene propylene rubber (FR-EPR) and jacketed with chlorinated polyethylene (CPE) was studied. A half-meter section of a 28.5-meter-long cable was thermally aged at 140 °C in an air-circulating oven for 1,600 h. Open-circuit capacitance measurements were made by connecting an Agilent LCR meter to the cable sample by means of a two-point probe test fixture, by which one conductor was maintained at positive potential (1 V) whereas the other two conductors and the cable shield were maintained at 0 V. Portions of cable were cut from the end of the cable and the capacitance remeasured after each portion was removed, developing a dataset from which the minimum value of damage ratio at which the damage is detectable via this method, approximately 12 %, could be inferred. This method is promising for practical application in NPPs since it offers the potential to detect unacceptable levels of aging in insulation polymers at locations along the cable that are remote from the cable end and are perhaps inaccessible. It is also capable of providing an estimate of the extent of the damage. The method offers the additional advantage of being applied via an existing cable connector or exposed cable terminal ends, which are typically accessible, unlike most of the cable length which is likely to be in cable trays or conduits thereby restricting direct access.

Keywords: cable aging, capacitance, polymer aging

NOMENCLATURE

C	capacitance
D	dissipation factor
R	damage ratio (%)

1. INTRODUCTION

In the last few decades, the assessment of the condition of instrumentation, power, and control cables has become important due to their critical role in performing safety-related functions in structures such as aircraft and nuclear power plants (NPPs). The drive to operate existing NPPs beyond their initial design life of 40 years, to 60 or even 80 years, requires assurance that cables will function safely for a period greater than their initial design life, motivating the development of reliable tests to monitor cable degradation.

Depending on their location in an NPP, cables may be exposed to mechanical stresses, elevated temperature, radiation, humidity and environmental stresses which can lead to their degradation. Of all the materials involved in cable construction, the polymeric jacket and insulation materials are the elements most affected by these stressors during their service life. It is therefore crucial to develop condition monitoring techniques to assure continued safe operation under the normal operating condition and under Design Basis Events (DBEs). Tensile elongation-at-break (EaB) of polymer-based insulation is used as a standard metric for remaining useful life of a cable, with end of life commonly defined as the point at which EaB is 50% of the value of the pristine insulation material. Similarly, an surface indenter modulus measurement is a mechanical test that relies upon the change in stiffness of the polymer as a function of age. The first of these is destructive, however, and the second relies upon direct access to the cable surface, so there is interest in complementing these methods with non-destructive techniques that can be applied to accessible parts of the cable system. Dielectric spectroscopy (DS) is one method that potentially

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addresses this need. Bulk impedance methods such as DS are influenced by the damage profile of a cable. Cable damage may be evenly distributed over its full length or (more likely) may be localized to a small length segment associated with proximity to local water exposure, local high temperature or radiation, or mechanical damage [1].

In this work, dielectric spectroscopy is performed on a three-conductor (triad) cable with a thermally-aged segment. During the experiment, the cable length is shortened by physically removing end sections from the cable, measuring the distributed properties capacitance (C) and dissipation factor (D) each time a section is removed. An increase in C and D is expected as the length of the aged section becomes a larger fraction of the total cable length, i.e. with increasing damage ratio R where

$$R = \text{(length of aged section) / (total length)} \qquad (1)$$

The goal of this work is to assess the feasibility of detecting a thermally aged cable section by measuring its electrical properties from the cable end-connector. The research question can be stated as follows: At what value of damage ratio is a thermally-aged cable section detectable by measurements of distributed capacitance and/or dissipation factor?

2. MATERIALS AND METHODS

2.1 Sample preparation

FR-EPR-insulated, CPE-jacketed, shielded triad instrumentation cable was selected for study, Figure 1. A central portion of the cable, 49 cm long and located 1,467 cm from end ‘A’ of the cable, was aged at 140 °C in an air-circulating oven for 1,600 h, Figure 2.

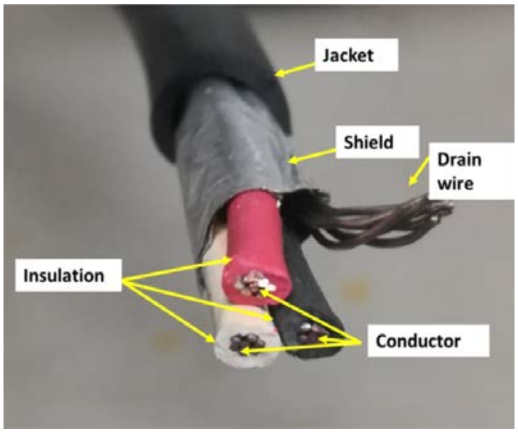

FIGURE 1: FLAME-RESISTANT EPR/CPE SHIELDED TRIAD INSTRUMENTATION CABLE (GENERAL CABLE)

FIGURE 2: CABLE PLACED IN AIR-CIRCULATING OVEN FOR AGING

Varying lengths of cable were cut from the original sample, first from end ‘B’ and then from end ‘A,’ to develop a set of samples with increasing damage ratio R, where R varied from 1.71 to 100 %. In particular, 12 samples were obtained with R = 1.71, 1.95, 2.24, 2.65, 3.23, 4.26, 6.25, 11.7, 32.88, 50, 75.4, and 100 %.

2.2 Capacitance measurement

C and D measurements were performed using an Agilent E4980A Precision LCR Meter with 16095A probe test fixture. An open-short calibration procedure was conducted prior to sample measurement. A potential of 1 V was applied to the cable sample between the black-insulated conductor (Figure 1) and the other two conductors (white- and red-insulated) plus the shield. A frequency sweep of the applied voltage from 20 Hz to 2 MHz was employed. Measurement uncertainties were found to be acceptable over a frequency range of 100 Hz to 100 kHz . Eight sets of measurements were recorded for each sample, each set being recorded using a moving average with factor of eight. C was normalized by the length of the sample.

3. RESULTS AND DISCUSSION

Specific C, obtained by dividing measured C by the length of the sample, and measured D are plotted in Figure 3 as a function of damage ratio R. From Figure 3 it can be seen that for R less than approximately 10 % the data are scattered and there is no clearly observable trend in C or D. In fact, as R increases from 1.71 to 11.7 the specific capacitance increases by only ~ 1 %.

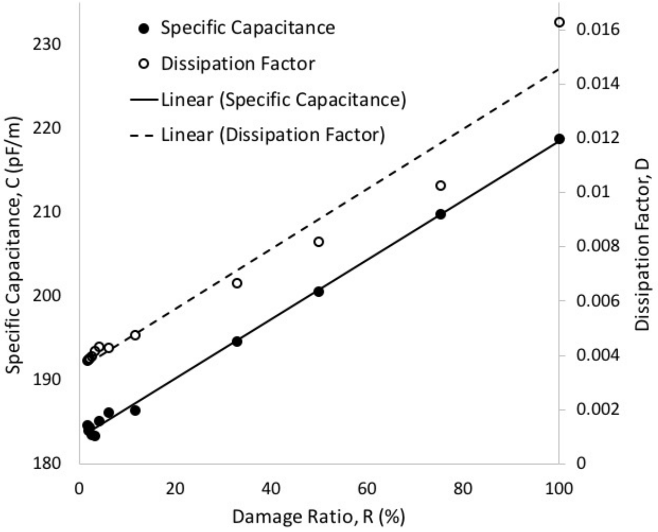

FIGURE 3: SPECIFIC CAPACITANCE AND DISSIPATION FACTOR MEASURED ON FR-EPR/CPE INSTRUMENTATION CABLE AT 1.09 KHZ PLOTTED VERSUS DAMAGE

Considering the slopes of the two best fit lines to the data shown in Figure 3, it can be inferred that there is a more dramatic change in dissipation factor for R less than approximately 10 % than there is in specific capacitance. In fact, as R increases from 1.71 to 11.7, the specific capacitance increases by ~ 24 %, indicating that D is a more sensitive parameter than the specific capacitance as an indicator of the presence of a damaged section in the cable. This conclusion is also supported by considering larger values of R. As R increases from 10 to 33 %, C is observed to increase by ~ 5% whereas D increases by ~ 40 %.

A simple analysis of the results can be conducted in the following way. If C_0 and D_0 represent values measured for R = 0, i.e. on a pristine (unaged) sample, and C_{100} and D_{100} represent values measured for R = 100, i.e. on a fully aged sample then, in general,

$$C_R = \frac{(C_{100} - C_0)}{100} R + C_0 \tag{2}$$

and

$$D_R = \frac{(D_{100} - D_0)}{100} R + D_0 \tag{3}$$

Such trends are observed in the data presented in Figure 3, where best linear fits are made to the data with C_0 = 183 pF/m, C_{100} = 219 pF/m, $D_0 = 3.95 \times 10^{-3}$, and $D_{100} = 14.7 \times 10^{-3}$. One may measure C_R and D_R at the cable termination point. If R is estimated by inspection or by understanding the segment length exposed to harsh environments, and C_0 and D_0 are estimated based on pristine cable measurements, the C_{100} and D_{100} damaged segment value (that is the values associated with the damage segment) may be estimated.

4. CONCLUSION

This work has shown that a thermally-aged section of FR-EPR/CPE cable is observable via measurements of distributed capacitance and dissipation factor when the aged cable section comprises greater than 10 % of the full cable length, for 1,600 h of aging at 140 °C. This work also shows that capacitance increases linearly as the damage ratio increases, for this cable aged in this way.

Advantages of measuring distributed capacitance and dissipation factor as a method of cable polymer evaluation include: i) its ability to detect thermal damage in a cable that may be hidden from maintenance operator view, ii) its potential to indicate the extent of the damage by taking measurements of electrical properties from more accessible sites than the aged section itself, and iii) it is non-destructive.

ACKNOWLEDGEMENTS

This work was conducted at Iowa State University and Pacific Northwest National Laboratory (PNNL) with funding from the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability (LWRS) Program Materials Research Pathway and in partnership with the University of Bologna, Italy. PNNL is operated for the United States Department of Energy by Battelle Memorial Institute under contract DE-AC05-76RL01830.

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