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Inter-Digital Capacitive Sensor for Evaluating Cable Jacket and Insulation Aging

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Abstract. An inter-digital capacitive (IDC) sensor has previously been used to measure dielectric properties of cable insulation polymer material when placed in direct contact with the insulation. Often cable insulation is covered by a polymer jacket. The dielectric properties of many cable jacket and insulation polymers are known to change due to thermal and radiation exposure-related damage. These dielectric properties frequently track with other measures of cable aging, such as tensile elongation-at-break and indenter modulus that have been broadly established as cable insulation polymer assessment methods. The external jacket of a cable is likely to have a different permittivity from the underlying insulation, and frequently the jacket material exhibits more severe damage than the insulation material due to environmental exposure. Because the jacket serves primarily to guard the cable during installation, as long as the underlying insulation condition is acceptable, the jacket condition is relatively unimportant in service.

As part of a continuing program to develop and evaluate nondestructive examination methods that may be applied to cable condition assessment, a set of tools has been developed including (1) a parallel-plate sensor to directly measure the permittivity spectrum of flat sheet material and (2) an IDC and fixture to measure the effect of cable polymer dielectric property change on the sensor response. The IDC consists of two fork-like electrodes facing each other with the fork tines interspersed and separated by a small gap. The electrodes are printed on one side of a flexible substrate that can be conformed to the surface of a cylindrical cable, with tines parallel to the cable axis. The electrodes are connected to a broad-frequency-spectral impedance meter that senses the capacitance between the narrowly gapped electrode tines. This capacitance is known to vary as a function of the permittivity of any material in close proximity to the electrodes. By finite element modeling (FEM) and experimentation, this study investigates the effect of tine spacing and other design parameters associated with the IDC on the voltage (potential) distribution and electric field depth of penetration. The IDC measurement of an unshielded ethylene-propylene rubber (EPR)-insulated cable is shown to track with the degree of aging and quantities obtained by established methods. For jacketed cable systems, the IDC response is dominated by the jacket but, by analyzing measurements from IDC sensors with different depths-of-field penetration into the cable under test, the influence of the chlorinated polyethylene (CPE) cable jacket material degradation can be separated from an assessment of the cable insulation thereby enabling assessment of the insulation beneath/through the jacket.

BACKGROUND

Degradation of the cable jacket, electrical insulation, and other cable components of installed cables within nuclear power plants (NPPs) is known to occur as a function of age, temperature, radiation, and other environmental factors. With greater than 1000 km of power, control, instrumentation, and other cables typically found in an NPP, replacing all the cables would be a severe cost burden. Methods to nondestructively assess the level of aging and degradation in cable insulation and jacketing materials are therefore needed.

There are a number of non-destructive examination approaches to assess cable insulation condition and these approaches may generally be divided into bulk, distributed, and local tests [1]. Bulk and distributed tests are applied from the cable ends with bulk tests withstanding resistance, partial discharge, Tan-Delta, and dielectric spectroscopy providing an overall cable assessment. Distributed techniques such as time-domain and frequency-domain reflectometry also provide information on where the most likely location for damage may be. Usually these tests group the cable as (1) Good; (2) Further Study Required; or (3) Action Required.

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Acceptance criteria that define the threshold for degradation below which cables may continue to be used are a challenge, because it is impractical to subject each cable system to loss-of-coolant accident (LOCA) or seismic simulation events following 40+ years of service. The report *Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets* [2] develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers. The report describes 50 percent elongation-at-break (EAB) as a conservative practical end-of-life threshold for cables that may be stressed during maintenance or subjected to LOCA exposure. This however is a mechanical test and the more important material behavior is the electrical material. One way to assess insulation electrical behavior for some classes of cables is through the use of an IDC sensor.

NPP cable designs typically include a conductor to carry power, instrumentation or control signals, and an insulating cover layer to isolate the conductor (Fig. 1). They may include more than one insulated conductor within a bundle, a semiconductor screen, a shield over each conductor and/or over all conductors, binder tape, and a jacket. IDC studies have primarily focused on unjacketed and unshielded cables where the IDC could directly contact the insulation. This study particularly exploits the cable configuration where the insulation is covered by a jacket. The IDC however is not suitable for measuring any material behavior through a conducting or semiconducting shield. While the insulation provides electrical isolation, in jacketed cable configurations the jacket mainly serves to provide mechanical protection during installation and sometimes fire or moisture resistance depending on the cable construction. Installed cables with intact insulation may well be able to continue to provide safe operation with degraded jacket material. Generally, jacketing materials degrade more readily than insulation materials, thereby enabling their use as leading indicators for local stress effects prior to insulation degradation and failure.

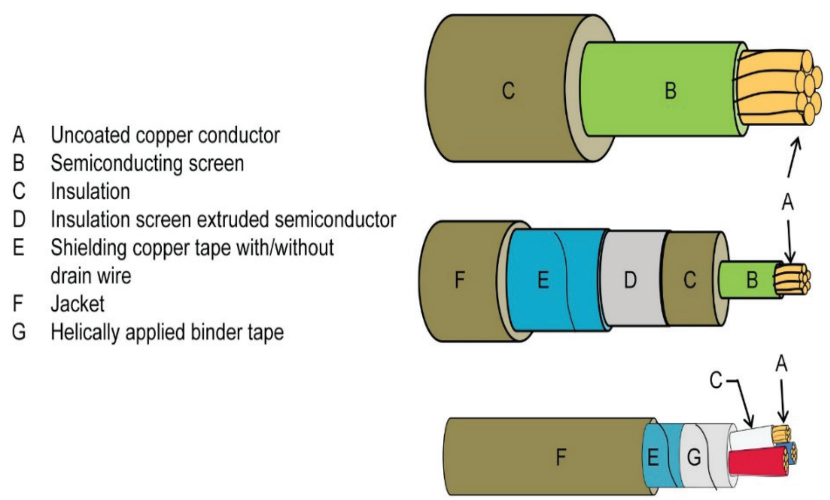


FIGURE 1. Configurations of typical cable designs used in NPPs. All components—particularly B, D, E, F, and G—are not always present in every construction [3].

PRINCIPLES OF CAPACITIVE TESTING

Capacitive sensors are used in the area of materials characterization known as dielectrometry [4, 5]. The output capacitance of a capacitive sensor placed in the vicinity of a test-material is sensitive to the dielectric properties of that material. Capacitance can be measured using a typical inductance-capacitance-resistance (LCR) meter, connected to a capacitive probe. Generally familiar is the parallel-plate capacitor configuration with a dielectric wafer sandwiched between charged (±Q) conductive plates (Fig. 2) whose complex capacitance $C^*[f]$ is given by

$$C^*(f) = \varepsilon^*(f) A/d \tag{1}$$

wherein $\varepsilon^* = \varepsilon' - j\varepsilon''$ [f/m] is the complex permittivity of the material that fills the space between the capacitor plates, A [m^2] is the area of one of the two identical capacitor electrodes, d [m] is the uniform separation between them, and f [Hz] is frequency. Parallel-plate electrodes are suitable for dielectrometry on flat specimens of uniform thickness that are somewhat thinner than the diameter of the electrodes and can be accessed on both sides. For other sample shapes, and in the case of samples that can be accessed from only one side, custom capacitive electrodes can be designed according to various considerations [6-8]. These design considerations usually involve a trade-off between signal amplitude and measurement sensitivity.

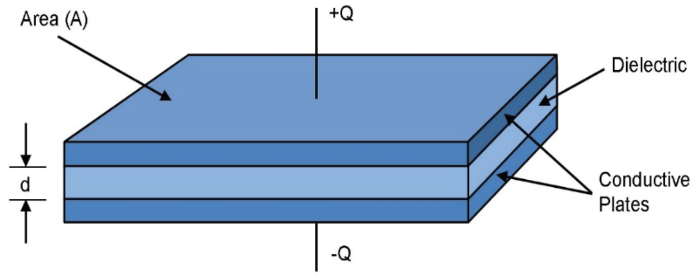


FIGURE 2. Parallel capacitor model with dielectric sandwiched between two conductive plates.

A typical LCR meter measures *C* as the real part and *D* as the loss factor of the complex capacitance, where

$$C^*(f) = C(f)\left[1 - jD(f)\right]. \tag{2}$$

Thus, for the parallel-plate geometry, $C = \varepsilon' A/d$ and $D = \varepsilon''/\varepsilon'$. A typical LCR meter covers the frequency range ~1 Hz to ~1 MHz, although specialized dielectric spectrometers can access to ~1 GHz.

PARALLEL-PLATE CAPACITOR MEASUREMENT SETUP

A parallel-plate capacitor offers a low-uncertainty approach to obtaining dielectric spectra if flat specimens with uniform thickness are available. As a rule of thumb, uncertainties due to fringing field effects (non-uniform electric fields at the edges of the electrodes) are controlled by maintaining a ratio of greater than ten between the electrode diameter and the sample thickness. Many electrode setups also employ guard electrodes to maintain the uniformity of the electric field between the sensing electrodes. Uniformity of the electric field between the electrode plates allows Eq. (1) to be employed in the conversion from measured capacitance to the material property, permittivity.

An Agilent E4980A precision LCR meter, or another similar electrometer, was employed in measuring capacitance (C^*) and inferring permittivity (ε^*) for both flat plate and cylindrical IDCs reported in this study.

Capacitive Sensors for Cylindrical Surfaces

Although flat-plate capacitive sensors are easily related to material properties like permittivity, it has long been recognized that co-planer rectangular or concentric inter-digital dielectrometry can also be sensitive to changes in material properties with one-sided access [9]. Motivated by the need to inspect wire insulation in air- and spacecraft, a capacitive sensor whose two electrodes conform to the cylindrical surface of the insulated wire was developed [10]. By means of a semi-analytical model developed through a Green's function analysis of the electric field distribution in the wire due to a point charge on its surface, with a method-of-moments calculation to determine the charge distribution upon the curved electrodes, the permittivity of the wire insulation was inferred from measured capacitance. In an accelerated aging experiment, differences between wire insulation thermally exposed at various temperatures were observed. Again, recognizing the advantages of inter-digital electrodes for increasing the measured capacitance and the sensing area of the sensor, a clamp fixture with an IDC sensor was developed for in situ evaluation of wire insulation [6]. It was demonstrated that the sensor was capable of detecting differences between aircraft wires exposed to various types of aviation fluids [6].

The IDC sensor was applied to nuclear-related wires and cables beginning in 2014. EPR-insulated wires of various colors that had been exposed to thermal- and radiation-induced oxidative aging were tested and very good correlations were observed between measured *C* and *D* at 1 kHz and 1 MHz, EAB, and indenter modulus measurements [11, 12]. These encouraging results provided significant momentum for continuing development of IDC sensing for monitoring polymer components (jacket and insulation) in NPP cables. Correlation magnitudes of around 0.85 were found between measured *C* at 1 kHz and EAB in thermally aged EPR and cross-linked polyolefin cable jacket materials. The idea of measuring insulation permittivity beneath a jacket was also explored using COMSOL FEM with the artificial assumption that the jacket permittivity did not change [13].

Target Cable Design to Assess Insulation Condition through the Jacket

A relatively large-diameter cable was selected to facilitate the design of the IDC sensors and enable flat-plate measurements of aged samples using flattened jacket stripped from the actual cable. This EPR cable insulation material was known to have a measurable change in permittivity with accelerated aging. Moreover, the manufacturer had provided flat samples of the insulation material on which flat-plate capacitance, inferred permittivity, dissipation factor, EAB, and other measurements could be made. The details of the cable are shown in Table 1.

TABLE 1. Design parameters for Okoguard® - Okolon® TS-CPE Type MV-90 2.4kV unshielded cable

Service	Total Diameter (mm)	Conductor		Insulation		Jacket	
		Diameter (mm)	Material	Thickness (mm)	Material	Thickness (mm)	Material
Type MV-90 2.4kV Nonshielded Power Cable (90°C, wet or dry) – manufactured by Okonite	22.4	12.0	Coated, stranded copper	3.2	Okoguard® (EPR-based) Nominal Permittivity =3.1	2.0	CPE: Nominal Permittivity = 3.5

IDC Electrode Design

The cable test IDC consists of two fork-like electrodes facing each other with the fork tines interspersed and separated by a small gap (g). The electrodes are printed on one side of a flexible substrate that can be conformed to the surface of a cylindrical cable, with tines parallel to the cable axis (Fig. 3). The same types of electrodes were used to test both jacketed and unjacketed cable. Initial efforts used circuit-board printing technology to make the electrodes in copper but later measurements used additively manufactured silver electrodes.

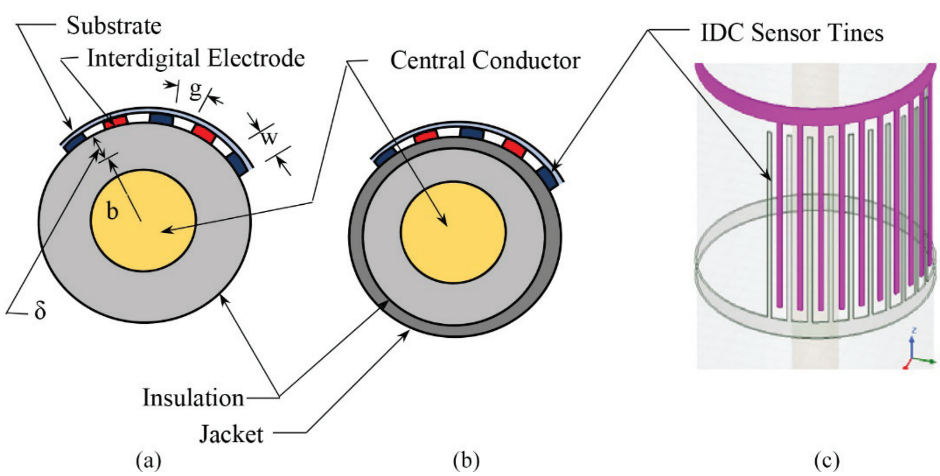


FIGURE 3. (a) Unjacketed cable cross section with IDC, (b) jacketed cross section, (c) orthogonal view of IDC

In a relatively lossy material, the penetration depth of the dynamic electromagnetic field, commonly known as the skin depth, is defined as the depth at which the field magnitude falls to 1/*e* (about 37%) of its surface value. In a low-loss (dielectric) material, a different definition is needed, following earlier precedent [7], to describe sensing depth for an IDC electrode situated on the curved surface of a cylindrical dielectric medium with a coaxial conductive core. In this case, penetration depth δ is given by

$$\delta = b - a_{10} \tag{3}$$

where b is the radius from the cylinder axis to the exterior surface of the dielectric layer and a_{10} is the radius of a conductor that generates a 10% increase in capacitance compared with that for the case in which there is no conductor. This approach was used with a FEM of the IDC to assess the variation in capacitance and effective field penetration depth of an inter-digital sensor as a function of the parameter g, the gap length between neighboring digits, and the number of digits. The parameter g has the strongest influence on δ of all the sensor parameters. Qualitatively the concept of increasing field depth with increasing g is shown in Fig. 4. Quantitatively this is better represented in Fig. 5 where, for the range of g examined, the penetration depth δ is nominally linearly related.

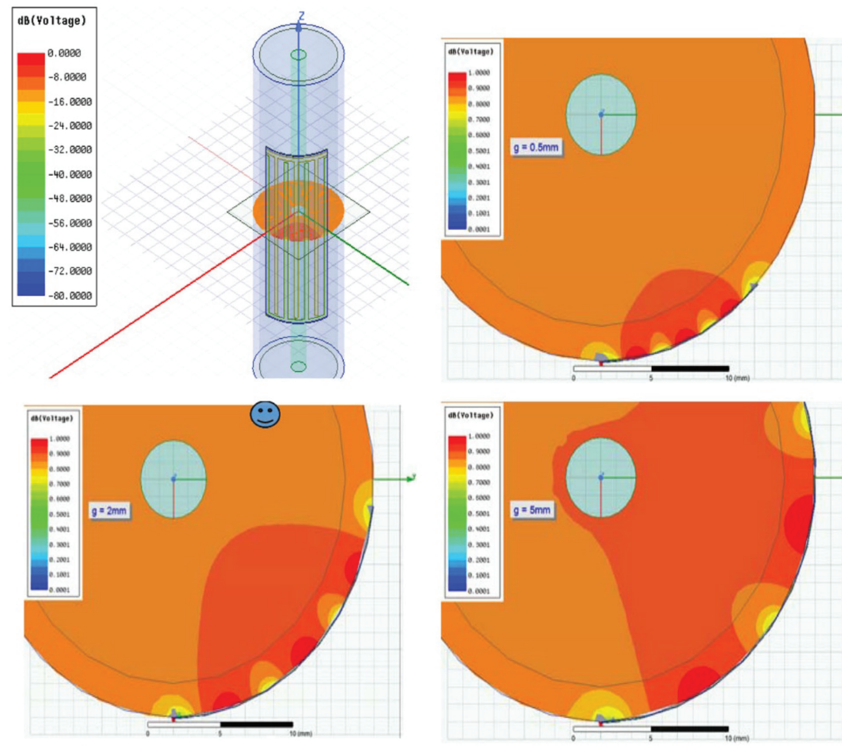
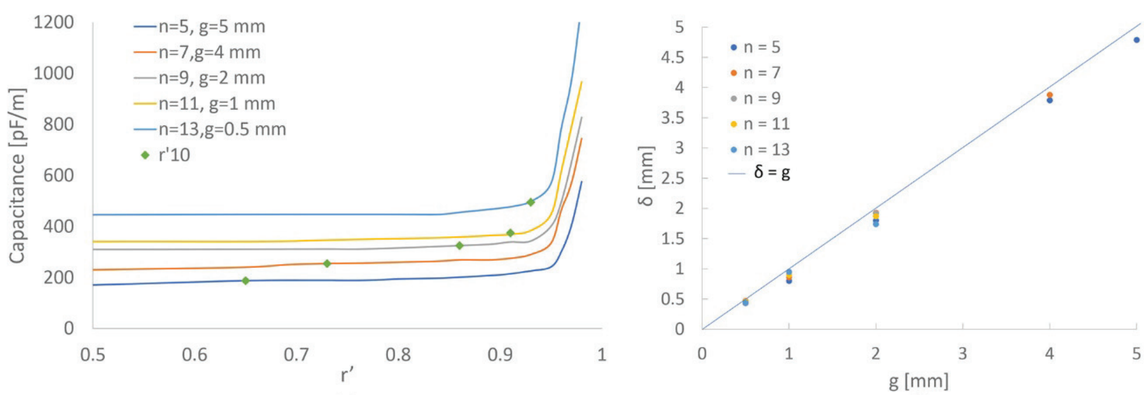


FIGURE 4. Finite element simulation of field penetration depth as a function of tine gap width.



(a) (b)

FIGURE 5. (a) Finite element-simulated IDC capacitance of Okoguard EPR material with center conductor radius varied and with varying numbers of IDC tines and gaps. (b) Linear relationship between tine gap g (mm) and penetration depth δ (mm) defined by 10% increase in observed capacitance as the center conductor radius increases from r = 0 (no center conductor).

IDC TO CHARACTERIZE THE BEHAVIOR OF INSULATION BENEATH JACKET

The feasibility of using a narrow gap and wide gap IDC sensor to characterize insulation beneath a jacket was investigated using a finite element IDC simulation of the Okoguard cable described in Table 1. During field measurements, only the jacket on the outside of the cable is accessible for measurement. Using the FEM simulation, however, the model can estimate what the measurement would be on the insulation if the jacket were not present. The simulation permittivity of both the jacket and the insulation was varied by ±20% from the nominal values and then the IDC sensor capacitance was calculated and used to estimate what the capacitance measurement would be if the sensor could be placed directly onto the insulation (Fig. 6). The simulated regression shows inferred (Cvirt) capacitance values based on the simulated measurements using both wide and narrow gap IDCs to correlate well with a simulated measurement that would be made directly on the insulation. This is evident based on the small deviation from the 45° regression line.

FIGURE 6. EPR/TS-CPE cable samples aged at 140°C for up to 35 d in 7 d increments. After aging, part of the jacket was removed.

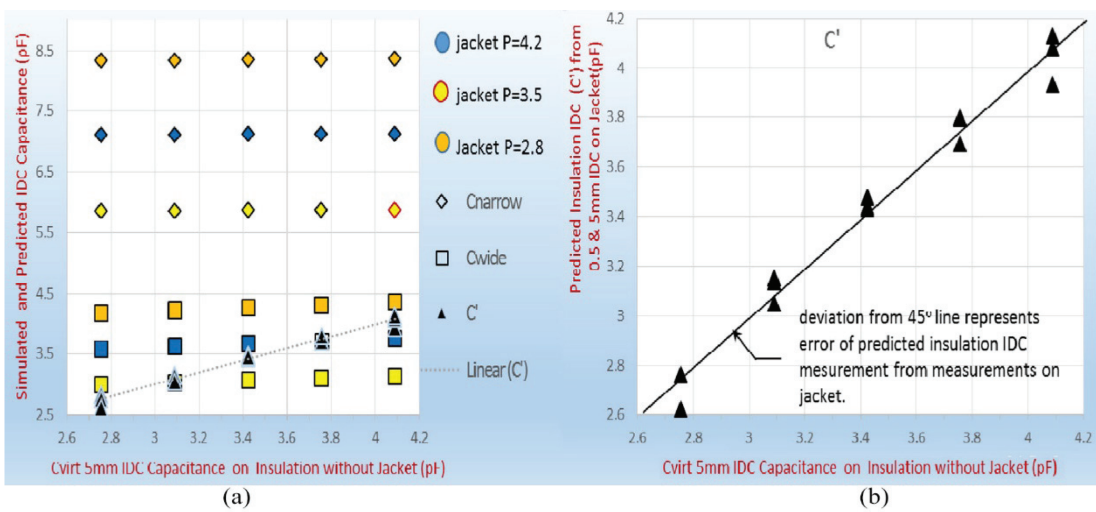


FIGURE 7. (a) Simulated IDC measurement on jacket surface for 5 and 0.5 mm gap (plus) C' for five different values of Ci where Ci is the virtual capacitance that would be measured on the insulation if there were no jacket present. (b) Expanded C' estimates of Ci based on two-variable regression using inputs from jacket measurement simulations.

A set of the Okoguard cables were thermally aged for 7, 14, 21, 28, 35, and 41 days (Fig. 7) to produce a range of age-related permittivity that was reflected in the range of measured IDC capacitance and dissipation factor (Fig. 8). The cables were aged with their jackets in place but the jackets were removed on half of each sample to allow direct measurement on the underlying insulation analogous to the FEM simulation exercise previously discussed. Parallel-plate measurements and mechanical measurements were also made on flat EPR insulation and CPE jacket witness samples as well as IDC measurements. Measurements included real and imaginary capacitance (that can be directly related to permittivity), dissipation factor, mechanical measurements (Fig. 9), and are summarized in Fig. 10. These measurements are more fully discussed elsewhere [14]. As previously shown with similar materials, the IDC measurements do correlate with end-of-life mechanical measurements.

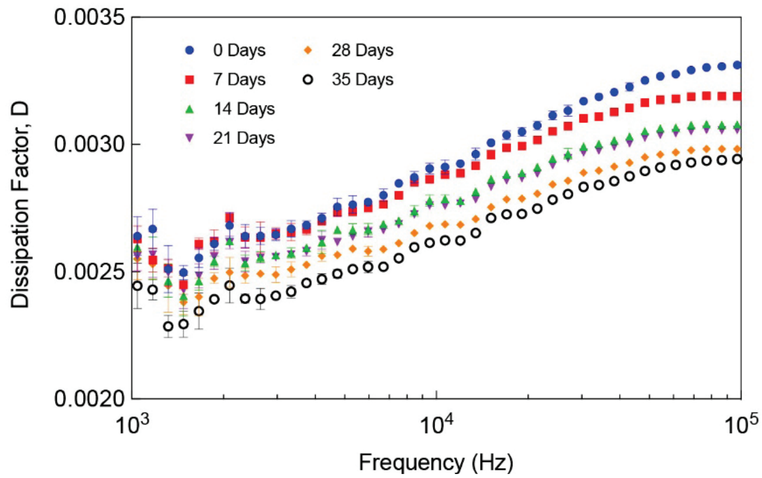


FIGURE 8. Pink EPR witness sample dissipation factor (D) vs. log frequency aged at 140°C for 35 days.

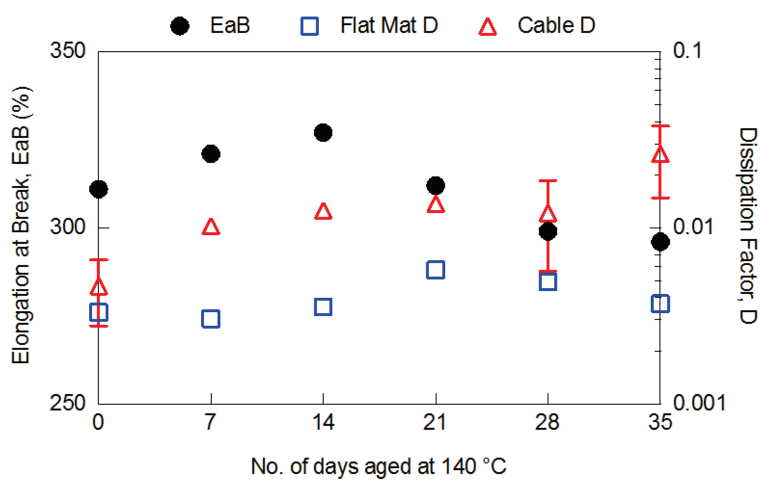


FIGURE 9. Pink EPR EAB and dissipation factor (D) vs. No. of days aged at 140°C for 35 days.

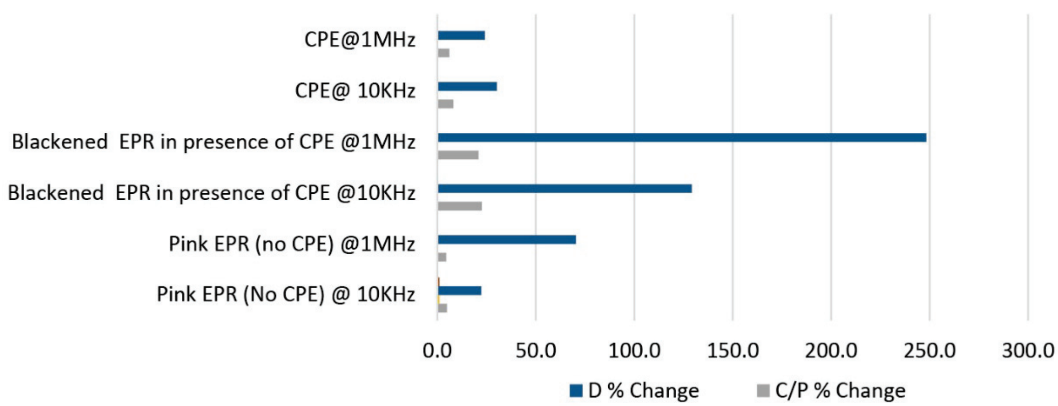


FIGURE 10. Percent change of dissipation factor (D) and relative permittivity and similarly capacitance (C/P) for EPR insulation and CPE jacket material.

The IDC measurements on the jacket with both wide and narrow gap electrodes were coupled with the narrow gap IDC measurements directly on the insulation to assess the possibility of measuring age-related behavior on the insulation similarly to the way this was assessed using the finite-element simulation. A two-variable regression analysis was performed and the result is shown in Fig. 11. As expected, the correlation and deviation from the ideal 45° line was not as good as with the finite element analysis, but the trend and possibility to predict the insulation behavior through the jacket is demonstrated.

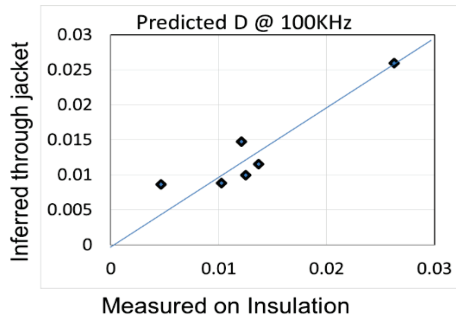


FIGURE 11. Measured IDC dissipation factor (D) directly on insulation after cutting away jacket (x) vs. inferred insulation D from narrow and wide gap IDC sensors measuring on the jacket surface (y).

CONCLUSIONS

- A substantial body of work suggests feasibility to measure cable jacket and insulation conditions using various forms of IDC sensors. Specific measures used in this work are:
  - Capacitance and inferred permittivity at relatively low and relatively high frequency (10 kHz and 1 MHz)
  - Dissipation factor at relatively low and high frequency (10 kHz and 1 MHz).
- The sensitivity to insulation degradation was good for inferred permittivity, but the most sensitive indicator for the samples examined was the dissipation factor provided that measurement frequency is selected judiciously.
- FEM models predict sensor behavior and can be used to optimize sensor configurations. In particular, IDC gap width is generally proportional to the field depth and corresponding measurement region for the IDC sensor. This is can be exploited to characterize insulation damage as a function of depth from the measurement surface or through a polymer jacket.
- Material permittivity and corresponding IDC measurements of capacitance and dissipation factor do correlate with age-related material degradation on the EPR insulation samples and CPE jacket samples examined. These measurements could be developed as a viable field test for local cable condition assessments as an alternate or complementary local measurement such as visual inspection, indenter modulus, or Fourier transform infrared/Fourier transform near-infrared spectroscopy.
- The IDC measurement can assess the condition of underlying insulation through an outer jacket material. This ability to assess material condition through the jacket is not possible with other local measurement techniques such as visual inspection, indenter modulus, or Fourier transform infrared/Fourier transform near-infrared spectroscopy.

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