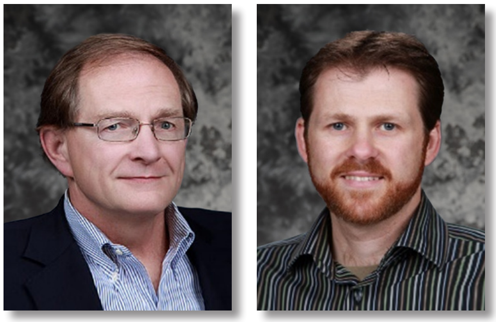
Interdigital Capacitance Sensor for Cable Insulation Test and Monitoring: A Nondestructive Method to Assess Aging and Degradation



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Degradation of installed electrical cable within nuclear power plants is known to occur as a function of age and operating environment. With more than 1,000 km of power, control, and instrumentation cables typically found in a plant, complete replacement could be a severe cost burden. Methods are therefore needed to nondestructively assess aging and degradation of cable materials to assess their performance.

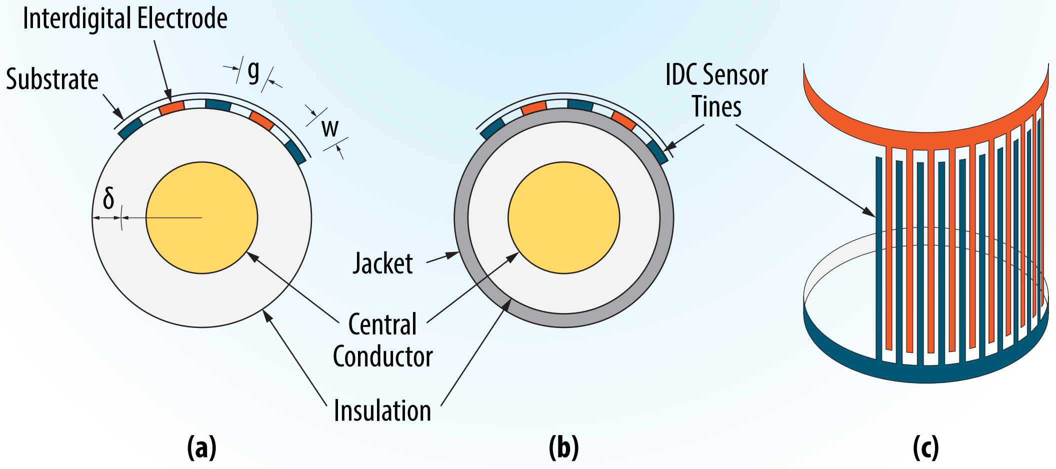
There are a number of nondestructive approaches to assess cable insulation [1]. Bulk and distributed tests, applied from the cable ends, provide an overall cable condition assessment (e.g., withstand resistance, Tan-Delta, dielectric spectroscopy). Distributed tests (e.g., partial discharge, time-domain, frequency-domain, and joint time-frequency domain reflectometry) also identify potential damage location information for follow-up by local tests. Local tests include visual inspection, thermographic infrared inspection, Fourier-transform infrared spectroscopy, near infrared, indenter modulus, and interdigital capacitance (IDC) [2]. IDC is the only local test that directly evaluates electrical characteristics of insulation, arguably the most relevant feature, and is applicable to cables without shield, foil, or semiconductor isolation between the IDC sensor and the insulation to be tested. This constraint still leaves a large population of cables that can be tested.

Frequently, the external jacket of a cable is significantly degraded while the underlying insulation is good. LWRS Program researchers at Pacific Northwest National Laboratory (PNNL) have extended the IDC test to evaluate insulation through an intact jacket, significantly extending the number of cables that can be assessed. By exploiting depths of field of the measurement with wide and narrow sensor tine spacing, insulation condition can be inferred through a jacket. This is the only known test that can assess the insulation condition through a polymer jacket and adds to the appeal of an IDC measurement approach.

Motivated by the need to inspect wire insulation in aircraft, spacecraft, and nuclear power plants, single-sided access capacitive sensors whose two electrodes conform to the cylindrical surface of the insulated wire have been developed [3] to infer permittivity of the wire insulation from measured sensor capacitance. The cable IDC test consists of two electrodes, with fork-like tines interspersed and separated by a small gap, printed on one side of a flexible substrate that can be conformed to the surface of a cylindrical cable, as observed in Figure 5.

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 approximately 37% of its surface value. In a low-loss (dielectric) material like cable insulation, the depth of field

Figure 5. (a) Unjacketed cable cross section with IDC; (b) jacketed cross section, and (c) orthogonal view of IDC.



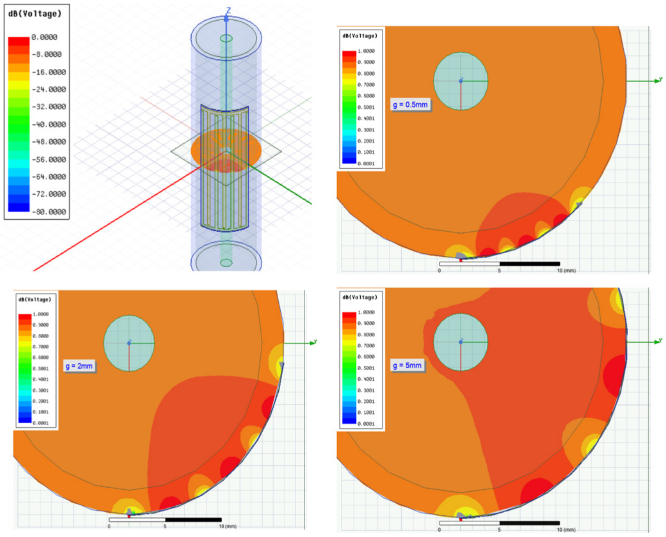


Figure 6. Finite element simulation of field penetration depth (red) as a function of tine (yellow) gap (upper right – tight; lower left-medium, lower right-wide tine gap.

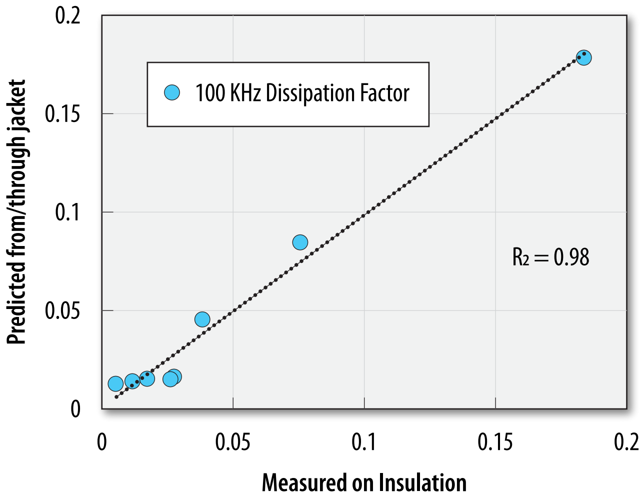


Figure 8. Measured vs. predicted dissipation factor of insulation based on measurements through jacket.

was found to be approximately linearly equal to the tine gap. This is important for the dual tine IDC sensor to assess the insulation condition beneath a polymer jacket, as observed in Figure 6.

A set of ethylene-propylene rubber insulated cables with a chlorinated polyethylene jacket were thermally aged at 140°C to produce a range of age-related permittivity values for IDC capacitance and dissipation factor measurements, as observed in Figure 7. The cables were aged and measured using both a wide and narrow tine IDC used to infer the condition of the insulation through the jacket. Jackets were removed on half of each sample and inferred condition of the insulation verified through direct measurement. Measurement versus prediction is plotted in Figure 8, with an observed correlation R2 value of 0.98 (where a perfect R2 correlation = 1.0).

Figure 7. Pink EPR insulation; chlorinated polyethylene jacket aged samples with jacket removed from half of the sample.

Conclusions

Various forms of IDC sensors can either be used to manually test local cable conditions or as permanently installed sensors to measure cable jacket and insulation conditions. PNNL advancement has expanded applicability of IDC insulation measurement to include unshielded jacketed cables.

Dual gap IDC sensors are confirmed to be able to sense the insulation condition beneath a polymer jacket and, moreover, the IDC is the only known way to assess the insulation condition through the jacket. PNNL has filed a patent for this approach and is exploring commercial partnerships to exploit IDC technology for actionable field measurements.

References

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