

Assessing the Condition of Inaccessible Cables Through Correlation of Capacitance and Insulation Microstructure

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Abstract

For aging nuclear power stations and other facilities, a need exists for monitoring aging degradation effects in electric wire insulation. Our current research efforts are pursuing a non-destructive, *in situ* approach for determining remaining life of wire insulation through detection of real time age-dependent microvoid characteristics and comparison to end of life void parameters. In many cases, a critical cable may be inaccessible because of location within conduits, in concrete, or underground thus making detection of microvoids impractical. We will report on our efforts to use capacitance as a means of determining nominal microvoid content within the structure of the polyolefin based insulation systems. Our work in this area was prompted by Chang-Liao *et al* (2000) who reported on an age dependent relationship for the capacitance of EPR insulated wire.

In this paper, we will summarize three ways in which microvoid content within the insulation separating two conductors can theoretically affect the measured capacitance. The first the potential change in the insulation medium's effective permittivity (or dielectric constant) caused by the additional un-ionized microvoids within the polymer matrix. The second is a virtual decrease in the distance between the conductors caused by any ionization effects. And the third relates to ionization effects within the voids affecting the amount of energy stored in the electric field between the conductors.

Our preliminary results demonstrate that, of the three effects investigated, microvoid growth only significantly affects the energy stored within the electric field between the wires. Thus it is theoretically possible that properly measured capacitance can be correlated to microvoid content and thus to a determination of acceptable or unacceptable remaining life. Although usable for all installed electric cables and wiring, this technique would have greater value in applications involving inaccessible systems.

1. Introduction

For aging nuclear power stations and other facilities, a need exists to be able to accurately assess aging degradation and remaining life of electrical cable insulation. Our current research efforts are pursuing a non-destructive *in situ* approach for determining remaining cable insulation life through the imaging of real time age-dependent void characteristics and comparison to known end of life void parameters [1]. Although imaging techniques work proficiently for readily accessible cable, imaging is not feasible for inaccessible cables such as those found in conduit, in bundles, or running underground. Thus, an alternate void detection scheme or correlation to another measurable parameter is necessary.

In the past, attempts to measure and trend changes in per unit capacitance as a function of aging have not been successful. However, recently, Chang-Liao *et al.* [2] reported differences in cable capacitance values over time that appear to be consistent with the Arrhenius aging

model for thermal exposure [3]. This paper reports on initial efforts to use our age dependent void growth model to theoretically predict the capacitance values measured by Chang-Liao *et al.*

Capacitance is the property of a cable system that permits a conductor to maintain a potential across the insulation. Any two conductors with an applied voltage and separated by an insulation medium experience capacitance effects. Capacitance, C , is generally described as the magnitude of charge, Q , per unit potential difference, V_{ab} , between conductors.

$$C = \frac{Q}{V_{ab}} \quad (1)$$

In general, the electric field developed between conductors is a function of the conductor-insulator geometry. For parallel plate capacitors, the potential difference between the plates is simply a function of the plate area and the distance between the plates. Thus, capacitance for a parallel plate capacitor is given by

$$C = \epsilon \frac{A}{D} \quad (2)$$

where for a wire the "plate" area would equal the product of wire diameter and length.

To properly account for the geometry of a multi-conductor cable, we must derive an appropriate description of the equipotential surfaces created by a cylindrical wire. Using the principle of superposition, the voltage drop from conductor A to conductor B due to the charges on both conductors is simply the sum of the voltage drop caused by each charge alone.

$$V_{AB} = \frac{\lambda_A}{2\pi\epsilon} \ln \frac{D}{r_A} + \frac{\lambda_B}{2\pi\epsilon} \ln \frac{r_B}{D} \quad (3)$$

Assuming that both conductors have an equal charge ($I_A = -I_B = I$) and combining the logarithmic terms, we can write the potential difference between two wires as

$$V_{AB} = \frac{\lambda}{2\pi\epsilon} \ln \frac{D}{r_A r_B} \quad (4)$$

Substituting (3) into (1) the capacitance per unit length between the two conductors is

$$C_{AB} = \frac{2\pi\epsilon}{\ln(D^2 / r_A r_B)} \quad (5)$$

Figure 1 compares equations (2) and (4) for an arbitrary, but equal distance between the wires. As expected, the effect of the wire geometry on the calculated wire capacitance is more pronounced the smaller the wire size. For the purposes of this paper, we only intend to discuss the feasibility of using the microvoid content to explain changes in measured capacitance. Therefore, we will ignore the geometric effects and use the parallel plate assumption throughout the remainder of this paper.

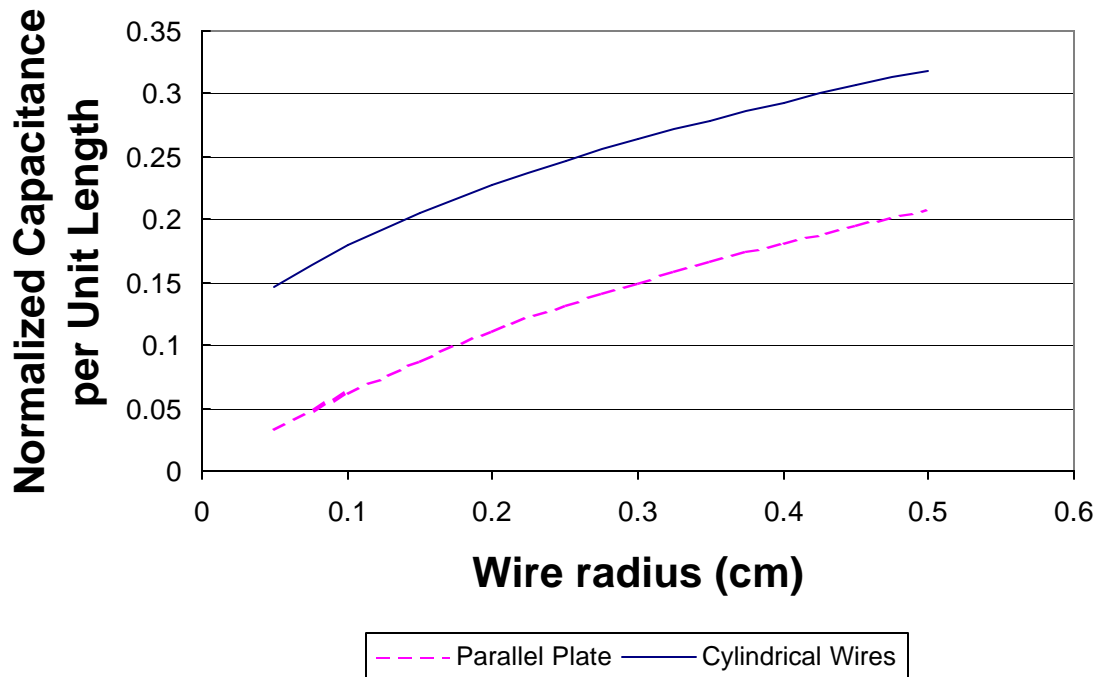


Figure 1 Geometry Effects of the Calculated Capacitance per Unit Length

2. Discussion

Every dielectric material experiences breakdown of its insulating properties when exposed to a sufficiently large electric field. The observed breakdown effect occurs because of partial ionization of the dielectric material, which leads to increased leakage and conduction currents through the insulating material. Electric cable insulation experiences environmental (usage) related breakdown of the dielectric over time. A similar process is believed to occur because of temperature dependent chemical reactions within polymeric insulation materials. These processes are generally referred to as aging.

All manufactured cable insulation materials contain some microvoids, although, the size and number of these voids (for newly produced insulation) have decreased significantly with improvements in the manufacturing process. With increased age, this void content is expected to increase in the form of larger microvoid sizes and increased microvoid density [1]. One effect of this increased content is the altered effective permittivity of the polymer matrix. Second, under exposure to a sufficiently high electric field, some of the gaseous content within the voids will ionize. One result of this ionization would be that the ionized volume would behave more like a mini-conductor dispersed within the insulation matrix. The net result is that the void ionization would extend the effective conductive portion of the conductor resulting in a reduced effective insulation thickness. A third effect of this ionization would be a change in the amount of potential energy stored in the electric field between the conductors.

The remainder of this paper focuses on a theoretical discussion of the three ways in which increased ionized void content can affect cable capacitance or effective capacitance. For this discussion, refer to the wire configuration graphically depicted in Figure 2 with the following

additional stipulations and assumptions:

- Both conductors are identical 10 awg
- Each conductor has an insulation thickness of 280 mils (0.7 cm)
- An applied voltage of 1000vdc is sufficient to cause ionization of the void volume
- The void volume is modeled as nitrogen gas (N₂) where one of the nitrogen atoms is ionized with a first ionization energy of 14.5 eV
- The “end of life” condition is 1% void volume throughout the insulation (corresponds to voids of 5 micron diameter at a density of approximately 500,000 per cubic millimeter).

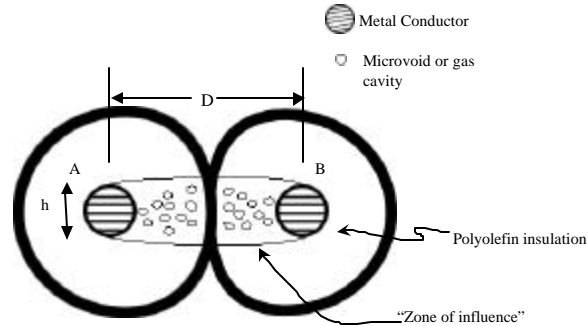


Figure 2 Cross section of two adjacent conductors.

3. Effect of Microvoids on Permittivity

Since the capacitance is always greater when a dielectric material is present between the conductors, the dielectric (or permittivity) constant, K, is always greater than unity. Since the dielectric constant of a vacuum is 1, we would expect that as voids are created or grow in size that the effective dielectric constant of the cable insulation material would decrease until it approached the limit of all of the dielectric material being converted to void. However, since “end of life” void contents are assumed to be 1% or less, the effective permittivity would be highly dominated by the dielectric material.

As a simplified illustration of the magnitude of this effect of microvoid growth with aging, consider the wire configuration depicted in Figure 2. If we assume we can treat the two long wires as a parallel plate capacitor, the capacitance per unit length is given by

$$\frac{C}{L} = \frac{\epsilon h}{D} \quad (6)$$

where ϵ is the effective permittivity, h is the wire diameter, and D is the distance between the wire centers. Assuming 1% voids (6) can be rewritten as

$$\frac{C}{L} = \frac{(0.01 + 0.99k)\epsilon_0 h}{D} \quad (7)$$

Plugging in the appropriate values we find that the contribution to capacitance per unit length due to microvoid content is ~0.02 pF/m. The corresponding contribution associated with the remainder of the dielectric material is ~ 4 pF/m. Thus, for the above stipulated parameters, the contribution of microvoids to a corresponding decrease in capacitance is small and may not be practical for trending or correlation purposes.

4. Effect of Ionized Microvoids on the Effective Insulation Thickness

To analyze the relationship between capacitance and microvoid content, two adjacent insulated conductors are considered as previously shown in Figure 2. The insulation of the two conductors is assumed to be of the same polymer material and to be of similar age. The insulation of adjacent conductors is slightly flattened at their area of contact because of cable jacketing or bundling. The flattening, as depicted in Figure 1, allows the creation of a "zone of influence" for capacitive leakage current between adjacent conductors A and B.

Since capacitance is a function of the insulation thickness between conductors A and B, we can theoretically combine the "conductive" voids at one end of the "zone of influence", as shown in Figure 3. The effective insulation thickness is now given by the expression $D-x$, where x represents the effective conductance of the ionized voids.

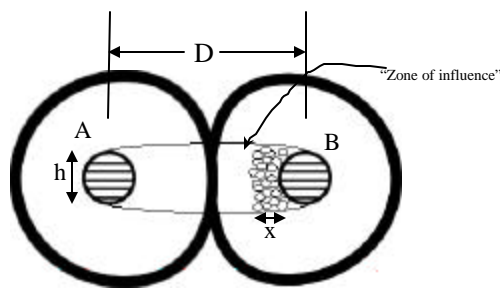


Figure 3 Electrically equivalent configuration with microvoids gathered at one end of the "zone of influence"

As previously discussed, the void approach to estimating remaining insulation life [2] says that thermal aging causes voids to grow in size and density. The primary effect of voids on capacitance is that the ionized gas volume behaves like a conductor. The net result is that the effective conductive portion of the conductor extends outward and the equivalent distance, D , between conductors decreases. (See Figure 3) Thus, the ratio for the change in capacitance due to the change in the effective distance between conductors can be written as

$$\Delta \frac{C}{L} = \frac{\epsilon h}{D} \left(\frac{x}{D-x} \right). \quad (8)$$

Inserting the appropriate values into (8) we find that the change in capacitance per unit length due to microvoids is ~ 0.08 pF/m. Although higher in magnitude than the first effect considered above, this increase in capacitance is also small compared to the normally measured value (~ 4 pF/m), and may also be too small for trending or correlation purposes.

5. Effect of Ionized Voids on Stored Potential Energy

In this example, we attempt to describe the expected increase in energy stored in the electric field and corresponding increases in quasi-capacitance per unit length based on a theoretical discussion of the effect of gaseous ionization within the voids. We call this effect a change in quasi-capacitance because although it represents a change in stored electric field energy, the current producing this effect may not be truly leading the voltage as required by the conventionally manifested capacitance property.

We begin with the energy density equation for a charged capacitor.

$$u = \frac{\frac{1}{2}CV^2}{\text{Volume}} \quad (9)$$

Assuming an applied voltage of 1000vdc is sufficient to cause a first level ionization of 1% of the void gas and for simplicity that the voids are filled with nitrogen rather than air or polymer oxidation products allows us to estimate the quasi-capacitance effect. By equating the energy density above to the energy required for ionization allows us to estimate a quasi capacitance of 600,000 pF/m. Thus, we have shown that the effect of microvoids on the electric field energy storage leads to a significant change in (quasi) capacitance per unit length – almost 4 orders of magnitude larger than normal cable capacitance. Therefore, it is theoretically possible to use the change in electric field energy storage as a correlation to microvoid content in an inaccessible cable. Various capacitance measurement devices exist. One that relies on calculating the lead angle between current and voltage will not be valid but one that relies on electric field energy storage or an RC time constant related charging rate could be applied.

6. Conclusions

Of the three potential effects of microvoids on cable capacitance, the effect of stored electric field energy appears most suitable for detecting a measurable change in capacitance per unit length. However, more work is needed to correlate applied voltages to degree of ionization within microvoids for various expected gas concentrations, as well as, to assess the optimum measurement method for detecting and measuring the stored electric field energy changes representative of a capacitance property. This monitoring technique would theoretically allow correlation to degree of aging and remaining life using the micro-void concept outlined in [2].

7. References

- [1] Horvath, David A., Douglas C. Wood, and Michael J. Wylie, Microscopic void Characterization for Assessing Aging of Electric Cable Insulation Used in Nuclear Power Stations, CEIDP, October 2000.
- [2] Chang-Liao, K.S., T.K. Chung, and H.P. Chou (2000) Cable Aging Assessment by Electrical Capacitance Measuring Technique, American Nuclear Society NPIC & HMIT Proceedings.