Relationship of electric insulation void content with electric cable normalized capacitance

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Abstract: For aging nuclear power stations and other facilities, a need exists for monitoring aging degradation effects in electric cable insulation. Our current research efforts are pursuing a non-destructive *in situ* approach for determining remaining life of cable insulation through detection of real time age-dependent void characteristics and comparison to known end of life void parameters. In many cases, a critical cable may be inaccessible because of location within conduits, in concrete, or underground making void detection impractical. This paper reports on initial efforts to correlate our void detection approach to a technique proposed by Chang-Liao *et al.*, which appears to be promising for inaccessible cable. This paper postulates that the detected change in capacitance reported by Chang-Liao *et al.* is related to the void growth that occurs with aging and discusses a possible correlation between ionized void content (caused by the applied dc potential) and the value of capacitance.

1. Introduction

A need exists to be able to accurately assess aging degradation and remaining life of electric cable insulation in order to be able to improve operability and reliability of industrial facilities (including nuclear and fossil fired power plants) and various forms of transportation (including commercial and military aircraft).

Previous research has shown that microvoid content in electric insulation may grow in a way that can be correlated to the degree of aging. Literature reviews and preliminary experimental results [1] lead us to believe that a promising technique for predicting remaining life in electric cable insulation based on microvoid content and proximity to void limiting parameters can be developed [2]. A conceptual outline of the technique is briefly described below.

First limiting values for volumetric void content (based on preventing partial discharge in high and medium voltage cable and preventing excessive embrittlement in low voltage cable) are determined. Next, void content growth rates as a function of environmental (e.g., temperature, radiation) and operational stressors (voltage and mechanical stresses) are established for commonly used insulation materials (e.g., CLPE, EPR, Polyimide, etc.). These two pieces of data are incorporated into a relational database. Several methods of three-dimensionally imaging void content are being considered for both laboratory analysis and in situ portable detection. These in-situ images then provide current cable void content parameters that can be compared to the relational database allowing estimation of the margin to end of life. Such imaging is expected to work proficiently for readily accessible cable; however, imaging is not feasible for inaccessible cables such as those found in conduit, in bundles, or running underground. Thus, an alternative to the actual imaging of voids is sought.

This paper reports on initial efforts to correlate our age dependent void growth model to a technique proposed by Chang-Liao, Chung, and Chou [3] that appears to be promising for inaccessible cable. They have shown an age dependent relationship for capacitance when detected through the use of a low frequency signal imposed on a much larger amplitude dc potential.

2. Age-dependent per unit capacitance changes

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.* reported differences in cable capacitance values over time that appear to be consistent with the Arrhenius aging model for thermal exposure [3]. Separate from the paper, we determined that the authors measured the capacitance values by applying a low frequency ac signal on top of a 1000 vdc potential. We speculate that any gaseous cavities within the insulation matrix would be ionized under exposure to the electric field produced by this dc potential. Such ionization would have a direct effect on the measured capacitance values.

The work by Chang-Liao *et al.* has a potential, two-fold value to our proposed void detection methodology. First, the age dependent capacitance approach complements our void detection by allowing a workable technique for both accessible and inaccessible cable to be developed. Secondly, use of our void technique on accessible cable allows an independent calibration option for identical or similar nearby material assessed using the capacitance approach or vice versa. These potentially valuable contributions to our research prompted us to investigate a capacitance relationship that is a function of void content.

3. Analyses of relationship between capacitance and void content for a single conductor cable

Capacitance is the property of a cable system that permits a conductor to maintain a potential across the insulation. Any two conductors separated by an insulator form a capacitor. Capacitance, C, is generally described as the ratio of the magnitude of the charge, Q, on either conductor to the magnitude of the potential difference, V_{ab}, between the conductors.

$$C = \frac{Q}{V_{ab}} \tag{1}$$

In general, the actual value of capacitance for a specific capacitor is a function of the conductor-insulator geometry. To properly account for the geometry of our cylindrical cable capacitor, we must derive the appropriate capacitance relationship. First, the equation for the potential difference across the insulation is written as

$$V_{ab} = \frac{\lambda}{2\pi\varepsilon} \ln\left(\frac{r_i}{r_c}\right) \tag{2}$$

where:

λ = Linear charge density of the cable.

ε = Dielectric constant for the medium between the conductors.

r_i = Radius of the cable insulation (from the center of the wire to below the jacket)

r_c = Radius of the conductor.

Substituting (2) into (1) and rearranging, we arrive at the capacitance for a single conductor cable.

$$\frac{C}{L} = \frac{2\pi\varepsilon}{\ln\left(r_i/r_c\right)} \tag{3}$$

Similar equations for single conductor cables were found in recently published electrical power cable books by Thue and Gilbertson [4, 5].

Example of per unit Capacitance Change with Void Content: We can calculate theoretical capacitance ratios for cable samples by assuming failure at a void content equivalent to a percentage of the initial thickness, r_{1i}. Then this assumed failure capacitance ratio can be compared to the data in [3]. The expression for the ratio of initial to final capacitance is given as

$$\frac{C_1}{C_2} = \frac{\ln r_{2i}/r_c}{\ln r_{1i}/r_c}. \tag{4}$$

Using the typical data for electric cable insulation provided below, we calculated the capacitance ratio values shown in Table 1.

$\Delta t_{insulation}$ = 280 mils = 0.7112 cm = 7.112 mm
wire diameter, d = 3 mm
initial insulation thickness, r_1 = 8.612 mm

Table 1: Failure capacitance as a function of assumed void content

Void Content	1%	5%	10%	20%
C_1/C_2	0.994	0.971	0.940	0.872

The capacitance ratio for 20% void content (i.e., 3.44 mm of the initial insulation thickness becomes voids) correlates with the capacitance ratios reported in Figure 2 and Table 1 of Chang-Lao *et al.* for EPR and XPLE cable [2].

4. Analyses of relationship between capacitance and void content for a multi-conductor cable

To analyze the relationship between capacitance and void content, two adjacent insulated conductors are considered. For simplicity, the insulation of the two conductors is assumed to be of the same polyolefin material and to be of similar age.

The insulation of adjacent conductors is assumed to be flattened at their area of contact because of the 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.

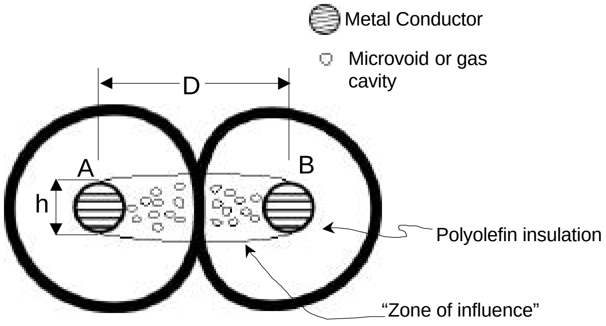

Figure 1: Cross section of adjacent insulated conductors A and B sharing "zone of influence" for capacitive induced leakage current. The dimensions are exaggerated to illustrate the effect.

Since capacitance is a function of the insulation thickness between conductors A and B, we combine the voids at one end of the "zone of influence", as shown in Figure 2. The effective insulation thickness is now given by the expression D-x, where x is the effective void thickness.

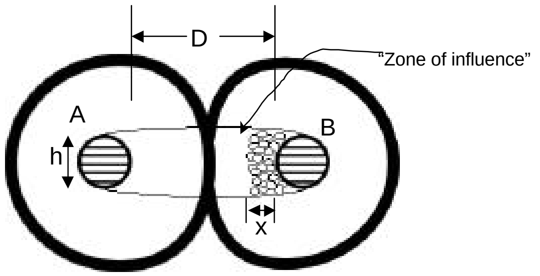

Figure 2: Configuration electrically equivalent to Figure 1 with all microvoids gathered at one end of the "zone of influence"

The conceptual situation depicted in Figure 2 can now be arranged to form the equivalent circuit provided in Figure 3.

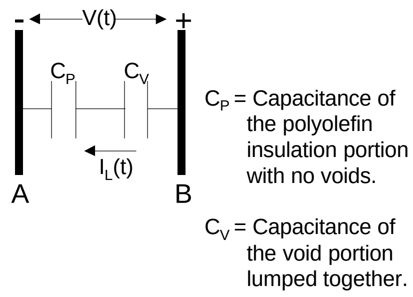

Figure 3: Equivalent circuit for Figure 2 showing leakage current I_L as a function of time for voltage V applied between conductors A and B.

As a first approximation, treat the equivalent circuit as a parallel plate capacitor. Then we can write the general relationship for capacitance as

$$C = \frac{\varepsilon A}{D} \qquad (5)$$

where:

ε = Dielectric constant for the medium between the conductors.
A = The cross-sectional area of the "zone of influence." This area is equal to the height (h) of the zone times the length (L) of the cable.
D = The distance between the conductors, which is approximately equal to the insulation diameter.

Thus, the polyolefin capacitance per unit length is simply given by

$$\frac{C_p}{L} = \frac{\varepsilon h}{D - x} \qquad (6)$$

and the void capacitance per unit length is given by

$$\frac{C_v}{L} = \frac{\varepsilon h}{x}. \qquad (7)$$

Unfortunately, this approximation does a poor job of accounting for the geometry of the electric field, and thus the potential, between the wires. Therefore, a better approximation should be developed in the future.

5. Discussion and Conclusions

With increased age, void content is expected to increase in the form of larger void sizes and increased void density. Under exposure to a sufficiently high electric field, the gaseous content within the voids is assumed to ionize. A primary effect on capacitance is that the ionized gas volume behaves like a near-perfect conductor and the net result is that the conductive portion of the metallic conductors extends outward. Thus, the equivalent distance between the wire conductors decreases and capacitance, which is inversely proportional to this distance, is directly affected.

A secondary effect is that the non-ideal conductive state of the gaseous voids is more effective in storing electric field energy than the surrounding insulation matrix. Capacitance is a measure of this storage ability. Thus, the increased energy storage capability represented by the increased void content from aging will further increase the equivalent capacitance between the conductors.

6. References

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