A Power Cable Thermal Aging Insulation Resistance Degradation Model

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***Abstract*- An Insulation Resistance (IR) degradation model for a power cable under thermal aging conditions is developed. The power cable insulation is constructed from the combination of a number of small segments. Segment types are classified into two types - degraded and non-degraded according to a previously published Dichotomy model. The ratio (V_d) of the volume of degraded segments to the total cable insulation volume is evaluated as a function of aging time and aging temperature where V_d degradation is determined using the cumulative distribution function (CDF) of an exponential distribution and the Arrhenius Model. The total resistances of the power cable insulation is evaluated by summing the resistances of all segments. The relationship between the size of segments and the calculated volume IR as a function of time is investigated to establish the sensitivity of the model as a function of segment size.**

I. INTRODUCTION

Extruded high-voltage and medium-voltage power cable is widely used in electric power transmission-distribution networks. The most common materials for power cable insulation are polymers like the cross-linked polyethylene (XLPE), because of its excellent electrical dielectric properties and reliable thermomechanical performance [1, 2].

However, cable insulation ages under thermal stress during operation, where the thermal stress is mainly generated by the resistive heating of the cable core which disseminates through the insulation. It is well known that the performance of power cable insulation deteriorates with aging process [3] with potential safety issues for power system operators, as well as cable maintenance and replacement costs. To assist in preventative maintenance, cable lifetime estimation is helpful to quantify or understand the degradation nature of cable insulation and to provide some determination of remaining cable lifetime.

Insulation Resistance (IR) testing is a well-known condition monitoring technique commonly performed to indicate the electrical condition of power cable insulation. In some studies of power cable aging, attention has focused on IR degradation during cable aging processes. As an example, in [3], it was found that the resistivity of power cable insulation reduces by a factor of several hundred from its original IR value over a period of 5000 hours under different temperature profiles.

One of the challenges in understanding dielectric insulation condition is to establish a quantitative method for evaluating insulation degradation over time. In this paper a quantitative degradation model of IR for power cable aging is constructed based on the Dichotomy model originally proposed by Chang and Mosely [4].

In the Dichotomy model, a bulk of insulation material is regarded as combination of degraded and non-degraded elements, where the resistivity of the two element types are different. The total electrical resistance of a bulk insulation is determined by V_d, which is defined as the ratio of the degraded volume elements to the entire volume. The value of V_d depends on aging time and aging temperature and is represented by a cumulative distribution function (CDF) of exponential form and evaluated according to an Arrhenius Model.

IR degradation trend under thermal aging is divided into three time processes: Phase 1: the degraded elements are randomly distributed in the cable insulation as the degradation is assumed to be homogeneous [4], after which the IR can be determined according to material aging condition and aging time. Transition phase: the degraded parts form percolation (easier current flow path), starting from a time t_s and ending at a time t_f - there is a sudden drop of IR value during this phase. Phase 2: the degradation of the insulation resistance approaches saturation towards a fixed value. In this paper, the IR degradation model of cable under thermal aging as a function of aging time in phase 1 is developed.

The original Dichotomy model was developed for rectangular/unit cube insulation blocks to permit ease of calculations and validate experimental resistivity data. In this paper the Dichotomy model is now transitioned into a cylindrical geometry to enable application to cylindrical cable structures and to evaluate IR across a cable insulation length.

In this paper Section II formulates the modelling geometry and summarizes the Dichotomy degradation model. Section III provides the methodology and initial results of model implementation to determine IR as a function time. Section IV investigates the IR sensitivity as a function of element size. Section V is a conclusions section.

II. MODELLING METHOD

A. *Segments*

A sample of extruded power cable insulation can be regarded as a cylindrical volume comprising a large number of small volume segments in radius, angle and length as shown in Fig. 1. The cable insulation inner radius is represented by x, the outer radius by X and the length by L.

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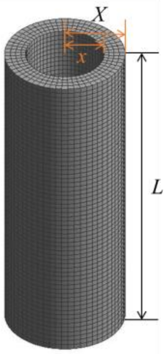

Fig. 1 Model of cable insulation divided into segments

The position of each segment is represented by the segment center point location in a cylindrical coordinate system in the form as (x_i, φ_j, l_k) shown in Fig. 2. In Fig. 2, x_i represents the radial position (m) of a segment center point, φ_j represents the segment angle position (arc degree) and l_k the position (m) of the segment along the cable length.

For each segment let the radial size be represented by Δx, the angle size by $\Delta\varphi$ and the length size by Δl. Let M = number of radial elements, N = number of angular segments and P = number of length segments. The total number of elements in the model is then equal to $N_t = M\times N\times P$. For given values of M, N and P then

$$\Delta x = (X-x)/M \tag{1}$$

$$\Delta\varphi = 360^{\circ}/N \tag{2}$$

$$\Delta l = L/P \tag{3}$$

The electrical resistance of any insulation material not only depends on its material resistivity, but also on its shape and volume [5]. It is presumed, as a first approximation, that the current flow direction is parallel with the radial axis (i.e. radially from center to any surrounding outer ground sheath) shown as the red arrow in the Fig. 2. For each segment, the current flows through two parallel curved surfaces that have unequal cross-section areas. The volume of any element is dependent on its location on the radial axis; the segments located at the outer parts of the cable insulation have a larger volume than those nearer the inner radial positions.

The evaluation of the resistance of a given geometry can be determined using the general formulations described in [5]. The electrical resistance (R) of a homogeneous material with parallel curved ends of cylindrical curvature, for which the electrical terminals are placed at radii x_1 and x_2 ($x_2 > x_1$), respectively is given by equation (4):

$$R = [\rho/k_0\times A(x_1)]\times \ln(1+k_0\times(x_2-x_1)) \tag{4}$$

where k_0 is the signed principal curvature of the surface located at x_1 with area $A(x_1)$. ρ is the resistivity of the material. The values of k_0 and $A(x_1)$ are represented by (5) and (6) respectively when the geometry of the conductive path terminals are cylindrical surfaces.

$$k_0 = 1/x_1 \tag{5}$$

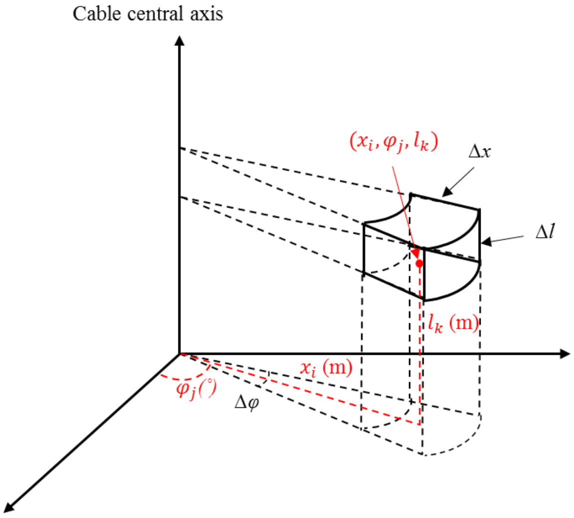

Fig. 2 Shape and location of segment in the cable insulation model

$$A(x_1) = \Delta\varphi\times\Delta l\times x_1 \tag{6}$$

The resistivity is assumed to be the same within any individual insulation segment. For any element (x_i, φ_j, l_k) $(i = 1,2 .. M;\ j = 1,2 \ldots N;\ k = 1,2 \ldots P)$, based on (4), the element resistance $R_e(x_i, \varphi_j, l_k)$ can be formulated as in (7)

$$R_e(x_i, \varphi_j, l_k) = \frac{\rho(x_i,\varphi_j,l_k)}{\Delta\varphi\Delta l} log_e\left(\frac{x_i+\frac{\Delta x}{2}}{x_i-\frac{\Delta x}{2}}\right) \tag{7}$$

B. Dichotomy model

For the Dichotomy model the segments in the cable insulation are classified into two types: virtually degraded segments and virtually non-degraded segments. The resistivity of virtually non-degraded type elements is represented by ρ_0 (Ω-m), while the resistivity of virtually degraded type elements is represented by ρ_d (Ω-m). The value of ρ_0 is considered to be much greater than the value of ρ_d.

According to (7), the resistances of virtually non-degraded and degraded elements types can be denoted respectively by R_0 and R_d expressed through (8) and (9):

$$R_0(x_i, \varphi_j, l_k) = \frac{\rho_0}{\Delta\varphi\Delta l} log_e\left(\frac{x_i+\frac{\Delta x}{2}}{x_i-\frac{\Delta x}{2}}\right) \tag{8}$$

$$R_d(x_l, \varphi_m, l_n) = \frac{\rho_d}{\Delta\varphi\Delta l} log_e\left(\frac{x_l+\frac{\Delta x}{2}}{x_l-\frac{\Delta x}{2}}\right) \tag{9}$$

noting that for subscript segments, $(x_i, \varphi_j, l_k) \neq (x_l, \varphi_m, l_n)$.

C. Degradation

For thermal degradation, the aging temperature is considered as uniformly distributed throughout the cable insulation and also within each segment. The number of degraded segments, N_d, randomly distributed in the model depends on the total number of segments N_t and the degradation volume ratio V_d. The CDF utilized to estimate V_d changing with aging time t is represented by (10) [4]:

$$V_d(t) = 1-e^{-\lambda t} \tag{10}$$

where $\lambda(T)$ is the degradation rate of the material which is a function of the aging temperature T and insulation material properties. λ may be estimated based on the Arrhenius model in equation (11) [4]:

$$\lambda(T)=\lambda_0 \exp(-E_a/k_B T) \tag{11}$$

where λ_0 is a constant obtained from experimental data, E_a is material activation energy (J), k_B is the Boltzmann constant (1.38×10^{-23} J/K) and T is absolute temperature (K).

D. Determining Bulk Resistance

There are three steps to calculate the total resistance of all segments. Firstly, determining the series resistance of all segments within an individual fixed radial column where the angle location and length location are fixed i.e. $R_c(\varphi j,\ l_k)$, as shown as Fig. 3, resulting in

$$R_c(\varphi_j, l_k) = \sum_{i=1}^{i=M} R_e(x_i, \varphi_j, l_k) \tag{12}$$

The second step is calculating the total resistance of segments in one plane $R_p(l_k)$ at every length. For simplicity, it can be calculated by the parallel connection of all $R_c(\varphi_j,\ l_k)$ on the same length axis as represented in (13).

$$R_p(l_k) = \frac{1}{\sum_{j=1}^{j=N}\left[\frac{1}{\sum_{i=1}^{i=M} R_e(x_i,\varphi_j,l_k)}\right]} \tag{13}$$

Finally, the total resistance R_t of the cable insulation model is calculated by the parallel connection of all $R_p(l_k)$ as represented in (14).

$$R_t = \frac{1}{\sum_{k=1}^{k=P}\left\{\sum_{j=1}^{j=N}\left[\frac{1}{\sum_{i=1}^{i=M} R_e(x_i,\varphi_j,l_k)}\right]\right\}} \tag{14}$$

III. APPLICATION

A. Methodology flow chart

A flow chart of the method for determining the power cable IR using the Dichotomy model is shown in Fig.4. Material properties and values are selected including λ_0, E_a, ρ_0, ρ_d. Geometrical and segment size parameters are selected and the degradation ratio and the number of degraded elements are evaluated over a suitable time period. The degraded elements are randomly placed within the structure, and the resistance of each individual element and total resistance of the cable insulation geometry are calculated.

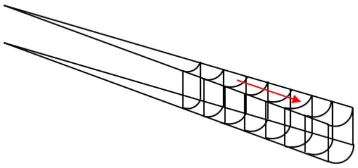

Fig. 3 Segments in one column

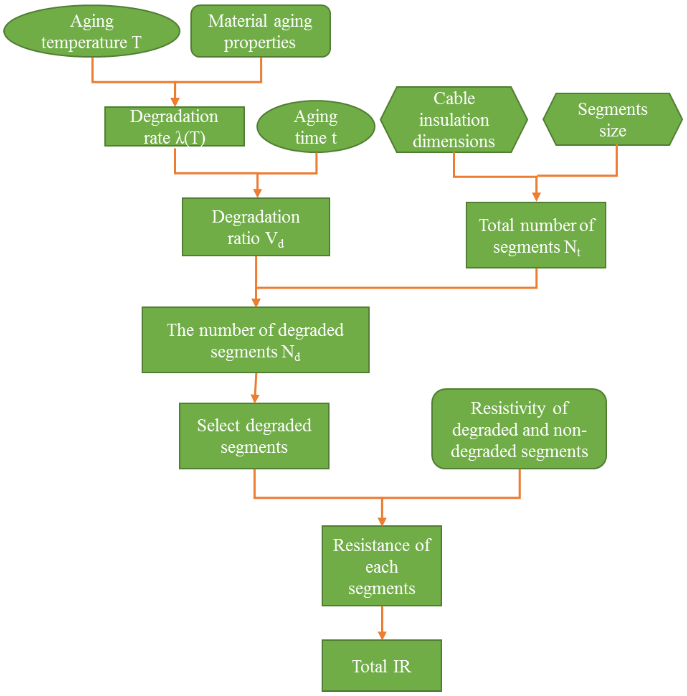

Fig. 4 The flow chart of predicting power cable IR by Dichotomy model

B. Dichotomy model

The experimental data for XLPE subject to thermal degradation is extracted from reference [6]. The parameters for an aging temperature of 100 ˚C are selected, namely $\lambda = 1 \times 10^{-3}$ (h^{-1}), non-degraded XLPE resistivity $\rho_0 = 1 \times 10^{12}$ (Ω-m) and XLPE degraded resistivity $\rho_d = 1 \times 10^{10}$ (Ω-m). In this example, the cable length L = 1m, the insulation inner radius x = 0.0075m, the insulation outer radius X = 0.0115m (equivalent to a 0.004m insulation thickness). The total number of segments $N_t = M \times N \times P = 10 \times 180 \times 50 = 90000$, resulting in segment dimensions: $\Delta x = 0.0004$m, $\Delta\varphi = 2^\circ$ and $\Delta l = 0.02$m.

Pictorial representation examples of the resistance distributions for the cable insulation sample are shown on Fig. 5. The resistance distribution of a presumed perfect (t = 0 hours) insulation model is shown in Fig.5 (a), where the color bar represents the resistance value in Ω. For the presumed perfect power cable, $V_d = 0$. The resistivity of all segments in is equal to ρ_0, and the resistance of each segment relates only to its location (and volume) according to (8). The total resistance of the cable insulation is calculated to be 68 GΩ.

After thermal aging at 100˚C for 2000 hours, the segment resistance distribution within the cable insulation is shown in Fig. 5(b). For this situation, V_d is calculated according to (10), and is equal to 39.35%. The number of degraded segments is 35419. As can be seen, the degraded segments with ρ_d are randomly distributed within the bulk cable insulation model. The total resistance of the cable insulation determined by the Dichotomy model is 38.2 GΩ.

In terms of degradation, the bulk IR has reduced by around 56% from its initial value. The impact on the IR determined by the Dichotomy model above is dependent on the choice of segment size this is investigated in next section.

IV. DISSCUSSION

In order to investigate the influence of segment size on the estimated IR value as a function of aging time, four different segments sizes shown in Table I are compared.

The comparison of Case 1 model and the Case 2 model is aimed at understanding the impact on IR of segment size in the radial axis. Comparison of Cases 2 and Case 3 investigates the influence on IR of segment size in the length axis, while comparison of Case 2 and Case 4 assesses variations in IR of segments size on the angle axis.

The material properties and parameters are the same as Section III, and the aging temperature is also maintained at 100˚C. To explore IR degradation over a longer period, the aging time t is set from 0h to 2000 hours with the IR determined every 50 hours. The value of IR as a function of aging time for each Case is shown as Fig. 6. It can be seen that the plots of IR for Case 2, Case 3 and Case 4 are very similar, indicating that the effect of segment sizes on IR evaluations in angle and length dimensions is minimal.

However, the change in IR with aging time for Case 1 is larger than the other Cases, and indicates that the segment size selection in the radial dimension has more of an influence on calculated IR values. This is perhaps to be expected, as the radial direction is the direction where surface areas, and thus the resistivity and current flow are determined within the model.

V. CONCLUSION

A physical-based Dichotomy model is constructed in this paper for estimating anticipated degradation of power cable IR under thermal aging conditions.

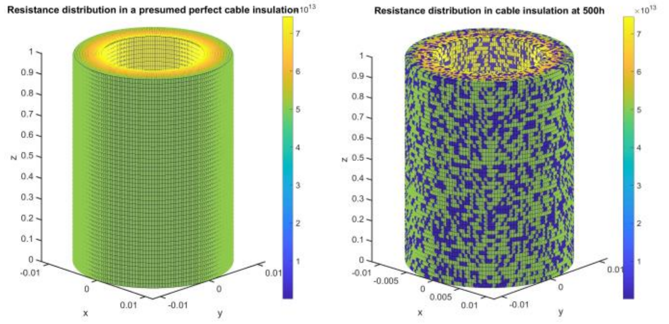

Fig. 5 The resistance distribution of (a) presumed perfect cable insulation model; (b) cable aged 500h under 100^0C

TABLE I

SEGMENTS SIZES AND SEGMENT NUMBERS OF EACH CASE MODEL

Case	Δx (m)	$\Delta\varphi$ (˚)	Δl (m)	M	N	P	Total Number
1	0.0002	2	0.02	20	180	50	180000
2	0.0001	2	0.02	40	180	50	360000
3	0.0001	2	0.01	40	180	100	720000
4	0.0001	1	0.02	40	360	50	720000

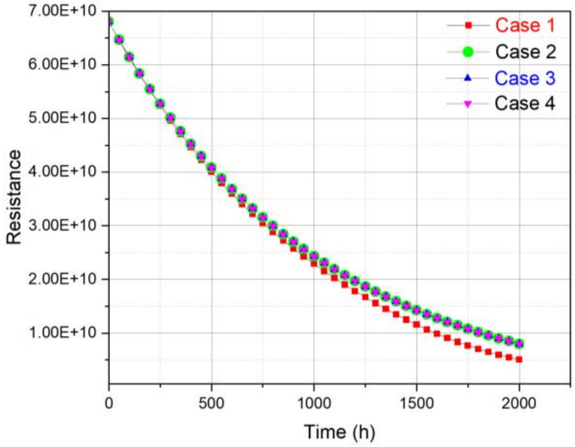

Fig. 6 Comparison of predicted cable IR of models with different segment sizes as a function of aging time

In the Dichotomy Model, virtually degraded segments are considered randomly distributed within the insulation volume. A volume ratio of degraded parts to total insulation, V_d is then assigned based on physical properties of the insulation. The resistance of each segment in a length of cable insulation is modelled as a function of its resistivity, size and location. The total IR of the power cable is then calculated by an equivalence resistance model performed sequentially in three dimensions. In the application of Dichotomy model example, the cable insulation model after thermal aging at 100˚C for 500 hours, the degradation rate increased from 0 to 39.35%. The total resistance determined by the Dichotomy model is reduced from 68 GΩ to 38.2 GΩ.

The influence of segment geometry size on the calculation of segment resistance is also considered in this study. It is shown that segment radial dimension has a greater impact on the predicted cable insulation resistance since this component is essential for determining segment surface current flow area and segment resistivity.

Future work will involve quantifying IR measurements on bulk cable insulation in order to compare model and practical measurements.

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