Modelling the Effects of Temperature and Moisture Ingress on Capacitance and Dissipation Factor Measurements within Oil Impregnated Paper Transformer Bushings

D. J. Smith[*,1], S. G. McMeekin[1], B. G. Stewart[1] and P. A. Wallace[1]
[1]Glasgow Caledonian University
*Corresponding author: School of Engineering & Computing, Glasgow Caledonian University, Glasgow, G4 0BA, Scotland, UK. Email: david.smith2@gcu.ac.uk

Abstract: The majority of high voltage power transformer bushings today are of the condenser oil impregnated paper (OIP) type. The ingress of moisture, through the deterioration of the bushing over time, can result in a significant reduction in life and is a major failure mode of these bushings. Currently, the measurement of capacitance and dissipation factor is the most common method used to assess the bushing condition in industry. Frequency domain simulations are made using COMSOL Multiphysics software to analyse the dielectric changes and the resultant capacitance and dissipation factor variation from temperature and moisture ingress. The modelled results are compared to those published in the literature, and it is shown that COMSOL can accurately model capacitance and dissipation factor for bushing geometries. It is expected that the results will provide an improved understanding of how to model and analyse faults within OIP bushings.

Keywords: COMSOL Multiphysics, oil impregnated paper, condenser bushings, capacitance, dissipation factor.

1. Introduction

Electrical bushings are a fundamental component of high voltage power transformers; their reliability is crucial for the successful operation of the transformer. A condenser bushing is made up of a condenser core, oil coolant, porcelain or composite body and a central conductor. However, the exact design of a bushing is specific for each application. The literature suggests 25 to 30% of large power transformer failures are due to failure of the bushing [1,2,3]. As transformer bushings have no moving parts, most failures are attributed to insulation deterioration from moisture ingress [4] and discharges.

Variation in moisture for OIP systems directly changes the dielectric properties of the insulation, which in bushings, results in variation in capacitance and resistance, and subsequently variation in dissipation factor. In this paper, a technique to model the effects of temperature and moisture on capacitance and dissipation factor is developed using finite element method software. The changes in capacitance and dissipation factor are modelled and analysed over a temperature range of 0 to 90^{0}C.

2. Governing Equations

Dynamic electric field problems can be described as an expression of the Poisson equation, where ∇ is the gradient operator, σ is the conductivity, ε is the permittivity, and ω is the angular frequency (2πf), as given by:

$$-\nabla.(\sigma + i\omega\varepsilon)\nabla V = 0 \qquad (1)$$

In an electric field, the electric field intensity **E**, where V is the potential, is given by:

$$\vec{E} = -\nabla V \qquad (2)$$

Using a lumped parameter method, COMSOL has an output variable for admittance Y, this can be expressed as a resistance R and a reactance X, where Z is the impedance, as given by:

$$Z = Y^{-1} \qquad (3)$$

$$R = real(Z) \qquad (4)$$

$$X = imag(Z) \qquad (5)$$

The capacitance C and the dissipation factor tanδ, where f is the frequency, can be expressed as:

$$C = \frac{1}{2\pi f X} \quad (6)$$

$$\tan\delta = \frac{1}{2\pi f C R} \quad (7)$$

3. Theory

When an electric field is applied across a dielectric material, the permittivity describes its ability to store electrical energy, and the conductivity describes its ability to conduct electric current.

3.1. Relative Permittivity

In a bushing, changes in relative permittivity result in changes in the insulation capacitance. For this paper, the variation in relative permittivity, based on the values specified in the literature [5,6], is considered to be a linear function of OIP moisture content.

3.2. Conductivity

The literature indicates that AC conductivity is highly dependent on temperature and moisture content [5,6,7,8]. In a bushing, changes in conductivity vary the resistance of the main insulation. The conductivity in the model is considered as a temperature and moisture dependent exponential function.

4. Numerical Model

A two-dimensional axisymetrical model was built in COMSOL Multiphysics 4.0a, using the AC/DC electric currents application mode. A frequency domain study was completed, solving equation (1), at power frequency 50Hz.

4.1. Bushing Condenser Geometry

The condenser core is built from a series of very thin parallel floating foils, commonly aluminium, placed between layers of OIP. One complete layer of the OIP contains multiple paper layers; the thickness of the individual layers is commonly 100 to 120um. The first conductive foil is at high voltage potential and the final foil is earthed. Between the layers, cylindrical capacitance is formed. Layers are in series and the combination of cylindrical capacitance forms a lumped capacitance; this is known as the main insulation capacitance. A bushing condenser was designed for use in the model, which comprises of eight 2.0mm layers. The condenser system was drawn in AutoCAD and then imported into COMSOL. The condenser geometry is modelled within a rectangular geometry; this simulates the oil coolant, as seen in Fig. 1. In this figure, domain 1 is the oil coolant and domain 2 to 9 represents the condenser layers.

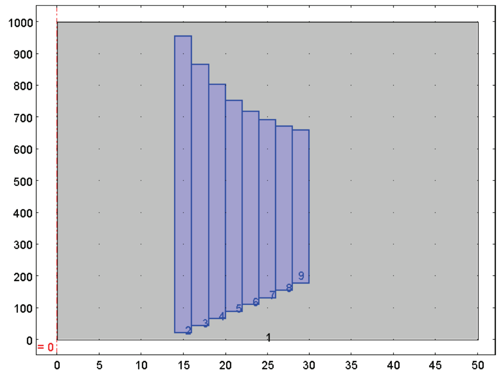

Figure 1. Bushing condenser geometry with an oil boundary.

4.2. Dielectric Properties

The relative permittivity of the eight condenser layers is modelled as a linear function over a range 4.2 to 5. The relative permittivity of the outer oil coolant is considered to be 2.3. The conductivity of the eight condenser layers is modelled as an exponential function. The literature reports [9] that changes in temperature result in changes in conductivity for transformer oils, but it was found that the magnitude of these changes does not have a significant effect on the dissipation factor modelled in the condenser system. Therefore, the conductivity of the oil coolant is considered to be a constant $1*10^{-10}$ S/m throughout the simulations.

4.3. Boundary Conditions

The oil boundary at r=0, is modelled as axial symmetry; this is where the complete geometry is rotated. All other outer oil boundaries are modelled as electrical insulation, where the electric field at these boundaries is zero. The first vertical OIP layer boundary is modelled as a voltage terminal with an input voltage of 52kV, and the last vertical OIP layer boundary is grounded. To model the condenser foils, the electric shield boundary condition is utilised, for a foil thickness of 0.1mm. The conductivity of the foils is modelled using the COMSOL linearised temperature dependent equation, where σ_R is the reference conductivity, α is the temperature coefficient, T_R is the reference temperature, as given by:

$$\sigma_{foil} = \frac{\sigma_R}{1+\alpha(T_{foil} - T_R)} \qquad (8)$$

For aluminium foils, $\sigma_R = 3.77 \times 10^7$ S/m at 20°C and $\alpha = 0.0043$ K^{-1}.

4.4. Meshing

The modelling accuracy of capacitive resistive systems using finite element method is highly dependent on the meshing scheme. To ensure an effective meshing scheme, the dielectric properties were fixed and simulations completed over a varying temperature range; thus the resultant dissipation factor should be steady over the complete temperature range. A fine-mesh and two adaptive meshing refinements were tested. All meshing was completed using free-triangular mesh. Table 1. shows the results, where the processing time (based on 3GHz processor with 3GB RAM) is the time per temperature step, and the variation is the dissipation factor variation maximum from average. As can be seen here, modelling without using adaptive meshing can lead to large inaccuracies in the dissipation factor. It was found that using the adaptive meshing technique for two refinements was the optimum for this geometry, and this was used for all simulations.

Mesh scheme	Fine	Adaptive, 2 refinements	Adaptive, 3 refinements
Elements	11,325	73,536	223,978
Processing time	15s	2mins	6mins
Variation	47%	0.3%	0.3%

Table 1. Comparison of meshing techniques

5. Results and Discussions

5.1. Electric Field Distribution

The potential and electric field distributions were modelled to validate the geometry and boundary conditions. As can be seen in Fig. 2, the electric field stress between layers is similar, this verifying the layered geometry dimensions. The potential distribution field lines are in parallel with the layers and extend to the edges of the foils, as expected for this condenser design. Fig. 3 shows the electric field in the radial direction across the OIP layers. The electric field has a stepped distribution, which is consistent with the literature [10] for a condenser bushing. This validates the use of the electric shield boundary condition for the foils.

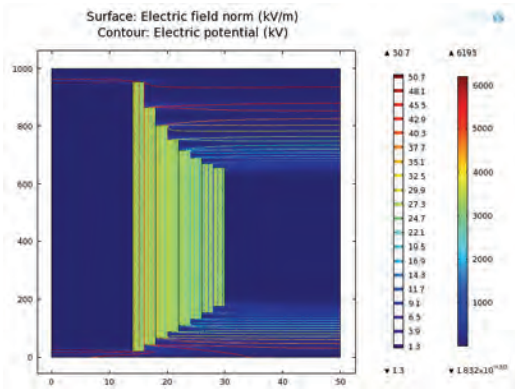

Figure 2. 2D potential and electric field distribution plot.

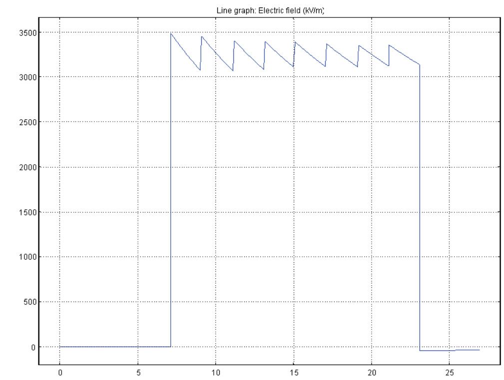

Figure 3. 1D potential and electric field distribution plot.

5.2. Capacitance

High voltage power transformer bushings are designed to have a constant capacitance throughout their life; therefore variation can be an indication of deterioration and a potential fault. The nameplate capacitance for a bushing of similar geometry to that modelled is 205pF. It is assumed that a new bushing will have a moisture content of approximately 0.2%. It was found that an increase in moisture content within the OIP insulation results in an increase in capacitance due to increased permittivity, as given by Table 2.

Different manufacturers have different recommendations of what they consider to be a notable change in capacitance. This typically ranges between 3 to 5% from the nameplate value. Based on the modelled results and the manufactures data, a questionable capacitance increase would be equivalent to an OIP insulation moisture content of approximately greater than 1%. Higher values of increased capacitance can indicate a higher moisture content, but may also indicate a short-circuit between layers.

OIP moisture content	Capacitance (pF)	Nameplate increase
0.2%	205.78	-
1%	212.27	3.2%
4%	236.62	15%

Table 2. Modelled capacitance variation.

5.3. Dissipation Factor

Similar to the insulation capacitance, the bushing dissipation factor is designed to be constant over the bushing life. The dissipation factor is highly dependent on the test temperature and moisture content. The modelled dissipation factor results were compared to published results [11], as given in Fig. 4. As can be seen, the modelling technique adopted is an effective approach to simulate the dissipation factor at varying moisture contents over the temperature range evaluated.

The COMSOL model can be used to evaluate the moisture content at any temperature and easily referenced to the recommendations by the manufacturers at 20°C. For example, if the dissipation factor of a bushing with a nameplate rating of 0.35% was measured at 70°C at 1.4%, the model indicates that this has a moisture content of approximately 1%. Using the chart, this can be corrected to 20°C to 0.51%, which is a 70% increase in dissipation factor.

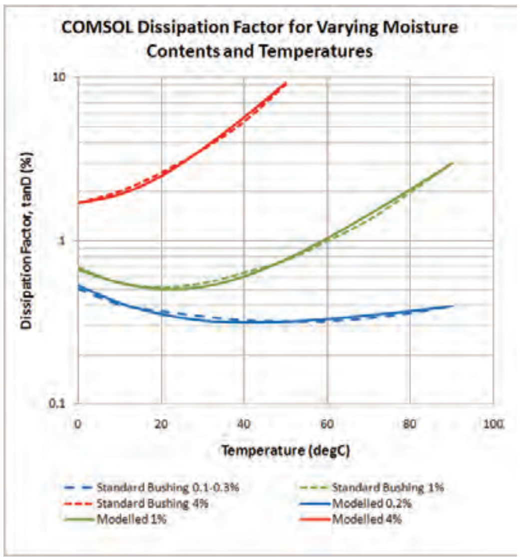

Figure 4. Dissipation factor for varying moisture contents.

6. Conclusions

Using COMSOL Multiphysics, a numerical model has been developed to model the changes in capacitance and dissipation factor for OIP power transformer bushings for varying temperatures and moisture contents. It was found that an accurate solution can be achieved when using an adaptive meshing scheme. The electric field distributions were modelled and used to validate the use of the electric shield boundary condition.

For the geometry modelled, it was found that the capacitance increased for an increase in moisture content from 205.78pF to 236.62pF over the range of 0.2% to 4% moisture ingress. The dissipation factor also increased with increased moisture content. Using an exponential function for AC conductivity, the changes in dissipation factor can be modelled over a temperature range of 0 to 90°C. The modelled results are in agreement with a standard bushing as presented in the literature.

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