Modelling of Partial Discharges in Polymeric Insulation Exposed to Combined DC and AC Voltage

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Abstract

This paper addresses the influence of an AC voltage superimposed on DC voltage on the partial discharge activity in artificial cylindrical cavities in polymer insulation. The main purpose was to investigate the feasibility of calculating the electric field distribution in such a configuration using a simple lumped parameter model. Two models for calculating the electric field have been compared, the lumped parameter classic ABC-equivalent and the finite element method.

Keywords; AC ripple, HVDC insulation, partial discharge, modeling

1. Introduction

Polymeric insulation systems for HVDC subsea cables have become a feasible alternative to the traditional oil-paper insulation systems. This is due to the lower production costs, smaller size and lower weight of such cables. However, there have been and are still many challenges with polymeric cables, namely: build-up of space charge, presence of impurities and highly temperature dependent resistivity resulting in inhomogeneous electric fields [1]. These challenges are mainly related to the DC electric field in the insulation, but there may also be significant AC electric fields present in the cable insulation. New technology within HVDC transmission systems employs VSC IGBT converters between the AC power grid and the DC power grid. The AC ripple voltage on such cables due to the VSC IGBT converters may be in the range of 1-10% of the nominal DC voltage, depending on the design of the HVDC station filter [2].

The aim of this study is to describe the effects of the AC ripple voltage on the partial discharge activity within unaged cavities in polymeric insulation, using a resistor-capacitor network model and comparing the results with electric field calculations using finite element analysis (FEA).

2. Partial Discharges in dielectric bounded cavites

The development of partial discharges within cavities in insulation materials depends on:

1. the availability of free electrons to start the avalanche
2. critical electrical field value to start an avalanche

The free electrons can come from volume or surface generation of electrons, such as radioactive gas ionization by energetic photons, electron release by ion impact and detrapping of electrons from traps at insulation surface [3]. The critical field value is assumed to follow Paschens law, i.e. it will depend on the type of gas in the cavity, pressure and size of the cavity.

The actual electric field distribution which enables the discharge is governed by the shape and amplitude of the applied voltage, the permittivity and conductivity of the involved materials, and the geometry of the object and the cavity, see Fig.1. The AC field distribution is determined by geometry and permittivity of the involved materials, the DC stationary field distribution is governed by geometry and conductivity of the involved materials. The permittivity will vary with frequency of the field, due to different polarization mechanisms in the dielectric materials. Permittivity will also vary with temperature, but very much less so than conductivity. The conductivity of the materials is significantly influenced by temperature, amplitude of the electric field and the ion species present due to humidity/contaminants.

3. Lumped parameter Model - The ABC circuit representation

Partial discharge (PD) is a very complex phenomenon that often exhibits chaotic, non-stationary, or fractal type behavior with seemingly unpredictable transitions between different modes, the modes exhibit distinctly different time dependent characteristics [4]. The main focus for this investigation is the partial discharge behavior under combined AC and DC field in a cylindrical, polymer bounded cavity, see .

When choosing a model it is important to consider if the model can be related to measurable quantities and thus be

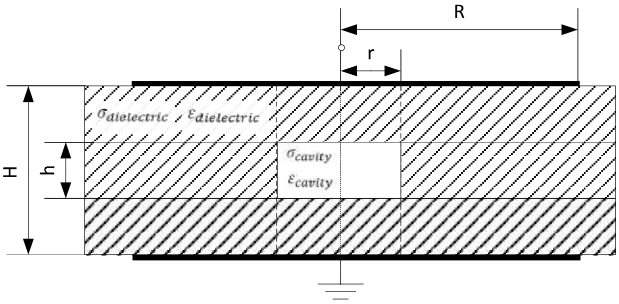

Fig. 1 - Gas filled cylindrical cavity in polymer insulation.

investigated experimentally, the classic ABC-equivalent have merits in this respect [5]. The ABC circuit equivalent is a good starting point for the analysis, further physical effects and higher complexity can be added to the model by interfacing it with a numerical computing environment, like MATLAB. It also provides a more intuitive, less computational intensive and less complex tool than the FEA tools available.

The ABC-equivalent of the test object given in Fig. 1, is represented in Fig. 2. C_c and R_c represents the impedance between the top and bottom of the cavity; C_b and R_b represents the series impedance between the cavity and the electrodes; C_a and R_a represents the remaining capacitance of the test object including stray capacitance of leads and any coupling capacitor or resistance that appear in parallel with the test object.

When a PD occurs at a voltage $V_{c,inception}$ across the void, the capacitance C_c is partly or completely discharged through a breakdown path with a small series impedance R, as indicated in Fig. 2. After a few ns the voltage across the void has dropped to a residual voltage v_e and the PD extinguishes. During the PD a certain charge is deposited on the top and bottom surface of the cavity, which then become insulating until the voltage across C_c again builds up to exceed $V_{c,inception}$. Then another PD takes place and the process continues.

The discharge magnitude at the cavity is not directly measurable, only apparent charge can be measured in the external circuit; i.e. the charge supplied to the object to restore voltage after a discharge. The apparent discharge magnitude will depend on the capacitances in the the ABC circuit and is thus influenced by the test setup. The bc-branch will give the voltage over the cavity and thus the resulting average electric field in the cavity,E_{cavity}, and the discharge repetition rate, n.

In the present model the following conditions are assumed:

- Temperature is constant and evenly distributed in the dielectric
- Breakdown voltage of the void follows Paschens law, pressure in cavity is assumed to be 1 atm.
- There is no time lag, i.e. no waiting time for initiation electrons
- Restricted cavity geometry: flat cylindrical cavities,$h \ll r$.

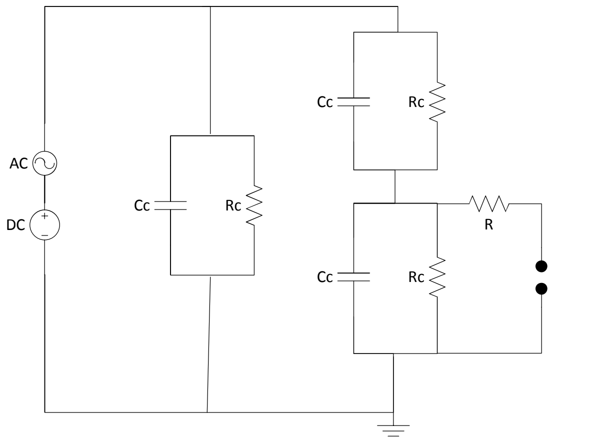

Fig. 2 - ABC-equivalent, lumped parameter model of dielectric

- Virgin cavity conditions apply, no memory or ageing effects causes the material parameters to change during the application of voltage.
- No space charge effects, for polymers this may influence field distribution when local fields exceeds 10-15 kV/mm [6].
- Extinction voltage in cavity, $V_e \approx 0$
- The dielectric object has been exposed to DC voltage for a long time, such that the DC voltage distribution is purely resistive.

A. Voltage and electric stress distribution

A combined DC and AC voltage is applied to the test object:

$$V_{input} = V_{dc} + \hat{V}_{ac} \cdot \sin \omega t \quad (1)$$

where V_{dc} is the DC voltage, $\hat{V}_{ac}$ is the amplitude of the AC voltage with angular frequency $\omega = 2\pi f$. The voltage over the cavity after a discharge has occurred will be given by superposition of the DC and AC voltage over the cavity:

$$V_c = Vc_{dc} + \hat{V}c_{ac} \quad (2)$$

where:

$$Vc_{dc} = \left(1 - e^{(-t/\tau)}\right) \cdot \left(\frac{R_c}{R_b+R_c}\right) \cdot V_{dc} \quad (3)$$

$$\hat{V}c_{ac} = \left(\frac{C_b}{C_b+C_c}\right) \cdot \hat{V}_{ac} \cdot \sin(\omega t) \quad (4)$$

The frequency of the AC cavity voltage is $\omega = 2\pi f$ and the time constant of the DC cavity voltage given by:

$$\tau = \left(\frac{R_b R_c}{R_b+R_c}\right)(C_b + C_c) \quad (5)$$

As long as $h \ll r$, the amplitude of the electric field in the cavity will be:

$$E_c = \frac{V_c}{h} \quad (6)$$

4. Distributed model - the finite element method

The governing equations for the finite element method (FEM) are (7) and (8). $\boldsymbol{D}$ is the electric displacement field, ρ_f is the free charge density and $\boldsymbol{J_f}$ is the free current density. For linear isotropic non-dispersive dielectrics exposed to slowly varying fields, i.e. kHz range, (7) and (8) combine to (9). Here V is the electric potential, σ is the electric conductivity and ε is the permittivity.

$$\nabla \boldsymbol{D} = \rho_f \quad (7)$$

$$\nabla \boldsymbol{J} + \frac{\partial \rho_f}{\partial t} = 0 \quad (8)$$

$$\nabla \left(-\sigma \nabla V - \varepsilon \nabla \frac{\partial V}{\partial t}\right) = 0 \quad (9)$$

The FEM analysis was executed with Comsol 4.2.a, for the DC field the time-dependent electric currents module was used and for the AC field the stationary electrostatic module was used. The combined AC and DC field solution was obtained by super positioning the AC and DC field solutions. The voltage over the cavity, V_c, is found by integration of the electric field along the center line of the cavity:

$$V_c = \oint E dl \quad (10)$$

The time constant, τ, is found by measuring the time to 63.2% of the final value of V_c.

5. Results

In the simulations $V_{DC} = 100\,V$ and $\hat{V}_{AC} = 100\,V$ was used. This gives a voltage distribution in percentage of the applied voltage. The dimensions of the test object is constant, radius R = 22 mm, H = 0.75 mm. The radius of the cavity has a constant radius r = 2 mm and height h between 0.02 – 0.25 mm. Material parameters are chosen to match the values for a PET film. The permittivity of the dielectric is ε_b= 3.3 and the conductivity σ_b = 1e-15 S/m. The cavity is filled with air at 1 atm pressure, with a permittivity of $\varepsilon_c = 1$. The conductivity of air is between 3 – 8e-15 S/m [7]. However, the conductivity in a small cavity exposed to discharges is difficult to predicate, the conductivity is therefore set to be between 1 - 100e-15 S/m which corresponds to $\sigma_c =< 1{,}100 >\cdot \sigma_b$.

The calculated voltage distribution for different cavity heights for σ_c =1e-15 S/m and σ_c =1e-13 S/m is given in Table 1 and Table 2.

The voltage over the cavity as a function of time is shown in Fig. 3.

A plot of the total electric field distribution from FEM calculations are shown in Fig. 4.

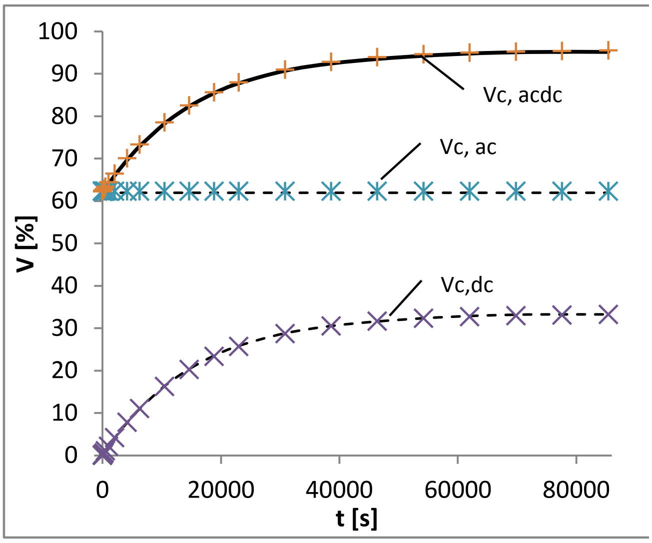

Fig. 3 - Plot of voltage over cavity, just after a discharge, for ABC and FEM values. h=0.25 mm, $\sigma_c = 1 * \sigma_b$. Data from ABC model represented by markers, data from FEM model represented by lines.

Table 1 - Stationary values of relative voltage cavity, $\sigma_c = 1 * \sigma_b$, applied voltage: $V_{DC} = 100\,V$ and $\hat{V}_{AC} = 100\,V$

h [mm]	ABC	FEM	ABC	FEM	ABC	FEM
	Vc_{dc} [%]	Vc_{dc} [%]	$\hat{V}c_{ac}$ [%]	$\hat{V}c_{ac}$ [%]	τ [s]	τ [s]
0.02	2.66	2.65	8.29	8.28	9397	9226
0.1	13.33	13.26	33.67	33.46	1156 9	1136 3
0.25	33.33	33.26	62.26	61.91	1564 2	1550 4

Table 2 - Stationary values of voltage over cavity, $\sigma_c = 100 * \sigma_b$, applied voltage: $V_{DC} = 100\,V$ and $\hat{V}_{AC} = 100\,V$

h [mm]	ABC	FEM	ABC	FEM	ABC	FEM
	Vc_{dc} [%]	Vc_{dc} [%]	$\hat{V}c_{ac}$ [%]	$\hat{V}c_{ac}$ [%]	τ [s]	τ [s]
0.02	0.027	0.027	8.29	8.28	97	96
0.1	0.1536	0.152 7	33.67	33.46	133	132
0.25	0.4975	0.495	62.26	61.92	233	232

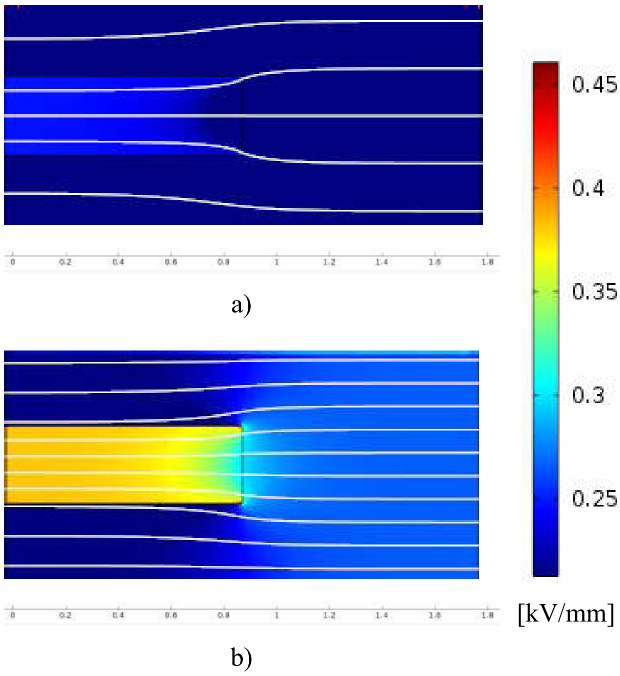

Fig. 4 Total electric field distribution from FEM calculations, same parameters as for Fig. 3 . Radius of cavity set to 0.75 mm to avoid computation of unnecessary elements. a) t = 0 s; b) t = 80 000 s

6. Discussion

The electric field distribution predicted by the ABC model is verified by the FEM calculations, under the given assumptions. The development of the amplitude of the electric field in the dielectric is within 1% of the values obtained in the FEM model. Given that the electric field distribution calculated by the ABC model is correct, the partial discharge inception voltage for AC and DC will then be predictable, given that Paschen's law is applicable to dielectric bounded cavities with height below 0.25 mm.

The fringe effect can be seen in Fig. 4. A quantitative measure of the transition between a homogeneous field to an inhomogeneous field, is given by a 5% change in average field, compared to the average field in the center of the cavity. The transition occurs 0.2 mm from the outer radius of the cavity for the worst case of h = 0.25 mm. In the case of r = 2 mm this means that 81% of the cavity will have a homogeneous field distribution. The fringe effect will decrease with cavity height.

7. Conclusion

A lumped parameter model for calculation of partial discharges characteristics under a combined AC and DC voltage has been presented. The ABC model gives the electric field distribution within 1% accuracy for minimum 81 % of the cavity volume when compared to FEM calculations.

8. Aknowledgement

Part of the work has been sponsored by National Research Council of Norway and the industrial partners: Nexans Norway AS, EDF R&D (France), Statoil ASA, Statnett SF, Statkraft SF and Borealis.

9. References

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