The effect of DC superimposed AC Voltage on Partial Discharges in Dielectric Bounded Cavities

P.K. Olsen, F. Mauseth, E. Ildstad
Department of Electric Power Engineering,
Norwegian University of Science and Technology
O. S. Bragstads plass 2E, Trondheim, Norway
palkeim@ntnu.no

Abstract: **Voltage source converters is used in HVDC stations in offshore HVDC transmission systems, between the AC and DC power grid. The AC ripple voltage on the DC side of the HVDC stations can be in the range of 1-10 % of the nominal DC voltage, depending on the size of the filter employed. For offshore HVDC grids, there is a drive to use polymeric insulated cables on the DC side. This work investigates how an AC voltage at power frequency superimposed on DC voltage influence the partial discharge magnitude and repetition rate in artificial cylindrical cavities in polymeric insulation. The AC voltage is kept below the AC partial discharge extinction voltage, and the DC voltage is kept above the DC partial discharge inception voltage. A resistor-capacitor ABC-circuit model is used for prediction of partial discharge magnitude and repetition rate under combined AC and DC voltage. Measurements has been performed on a test object of 3 layers of PET film with 1 mm radius cylindrical cavity in the middle layer. The results indicate that an AC voltage ripple with an amplitude lower than the AC partial discharge extinction voltage will increase the number of large discharges, compared to a DC voltage without ripple, but the repetition rate will be several orders lower than the AC voltage frequency.**

I. Introduction

Voltage source converters (VSC) are used in modern offshore HVDC transmission systems, between the AC grid and the DC grid. The VSC will produce a high DC voltage with an overlaid AC ripple, and little is known about the influence this kind of voltage distortion has on the insulation found in HVDC systems. It is known that partial discharges (PD) with a repetition rate higher or proportional to the AC power frequency can lead to a significant reduction of life time in polymeric insulation systems [1]. The PD occur in small voids in the insulation, e.g. imperfect production conditions or damage during operation. The aim of the present paper is to shed some light on the effect of an AC voltage ripple on the partial discharge characteristics in a dielectric bounded cavity.

The AC ripple voltage on the DC side due to the VSC can be about 1-10 % of the nominal DC voltage, depending on the size of the filter employed. The harmonic content of the ripple can range up to 30-100 times the switching frequency, with the dominant components close to the switching frequency [2]. The switching frequency is normally around 1 kHz, but can be up to 2 kHz [3].

The measurements of partial discharges under high frequency voltage can represent a challenging measuring problem. The present study will focus on a single 50 Hz sinusoid voltage component superposed the DC voltage, the AC voltage is set below the AC partial discharge inception voltage. This is a first step in understanding the effect of an AC ripple containing several sinusoid components simultaneously, as for the VSC case.

II. Partial discharge under combined AC and DC voltage

Partial discharges is a very complex phenomenon that often exhibits chaotic, or non-stationary type behavior with seemingly unpredictable transitions between different modes, the modes exhibit distinctly different time dependent characteristics [4]. Keeping this in mind, the ABC-circuit used in this paper gives a simplified model for understanding partial discharges, their frequency and magnitude.

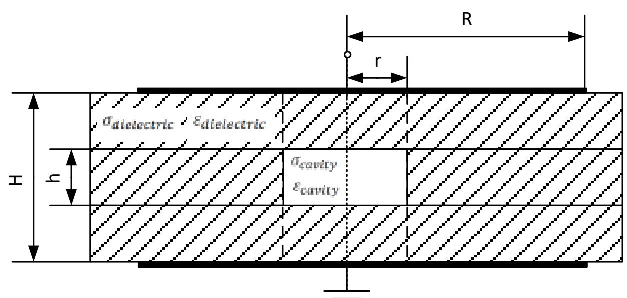

Figure 1. Structure of test object, three layer of films with cylindrical hole in the middle layer

The ABC-circuit of the test object is given in Figure 2. The classic ABC-circuit consist only of capacitances, but it must be expanded with shunt resistors to model the DC phenomena.

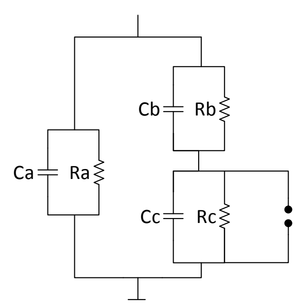

Figure 2. ABC equivalent circuit with RC-elements

When a PD occurs at a voltage $V_{c,inception}$ across the void, the capacitance C_c is partly or wholly discharged through a breakdown path with a small series impedance. 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.

A. *Voltage distribution within the dielectric*

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 peak voltage over the cavity, V_c, 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

$$Vc_{dc} = \left(1 - e^{(-t/\tau)}\right) \cdot K_{DC} \cdot V_{dc} \quad (3)$$
$$\hat{V}c_{ac} = K_{AC} \cdot \hat{V}_{ac} \cdot \sin(\omega t) \quad (4)$$

K_{AC} and K_{DC} is given by

$$K_{DC} = \frac{R_c}{R_c + R_b} \quad (5)$$

$$K_{AC} = \frac{C_b}{C_b + C_c} \quad (6)$$

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

$$\tau = \left(\frac{R_b R_c}{R_b + R_c}\right)(C_b + C_c) = R_b C_b \frac{K_{DC}}{K_{AC}} = \frac{\varepsilon_b}{\sigma_b} \frac{K_{DC}}{K_{AC}} = (7)$$

The discharges will start at some critical field, $E_{paschen}$ given by Panchen's law [5]. The partial discharge inception voltages measured over the terminals of the test object are defined as:

$$V_{PDIV,DC} = \left(\frac{1}{K_{DC}}\right) V_{c,inception} \quad (8)$$

$$V_{PDIV,AC} = \left(\frac{1}{K_{AC}}\right) V_{c,inception} \quad (9)$$

For AC voltage, the inception voltage give meaning as the voltage that will give at least 4 discharges per period, according to (15). The inception voltage for DC is not well defined, operationally, because there will be no discharges at the inception voltage at $V = V_{PDIV,DC}$. In practice, the inception voltage for DC is better defined as the voltage that will give a certain number of discharges per time. Nevertheless, for the sake of evaluation of the equations we use the mathematical definition in (8), and accept that V_{DC} must be well above $V_{PDIV,DC}$ before it is possible to measure any occurrence of PD.

B. *Discharge repetition rate*

The time between discharges, t_r', when only DC voltage is applied is given by [6]:

$$t_r' = -\tau \cdot \ln\left[1 - \frac{V_{PDIV,DC}}{V_{DC}}\right] \quad (10)$$

For $V_{dc} > V_{PDIV,DC}$. Equation (10) can be modified to take into account the AC voltage. Since the frequency of the AC voltage is much higher than the time constant (7), it will appear as the DC voltage is offset by the peak value of (4), see Figure 3. The new time between discharges can written as:

$$t_r = -\tau \cdot \ln\left[1 - \left(\frac{V_{PDIV,DC}}{V_{DC}} - \frac{\hat{V}c_{ac}}{Vc_{dc}}\right)\right], \quad (11)$$

which can be rewritten

$$t_r = -\tau \cdot \ln\left[1 - \frac{V_{PDIV,DC}}{V_{DC}}\left(1 - \frac{\hat{V}_{AC}}{V_{PDIV,AC}}\right)\right]. \quad (12)$$

The repetition rate *n* is the inverse of t_r and can be approximated by ignoring all after the first of term in the Taylor series of *n*:

$$n = \frac{1}{t_r} \quad (13)$$

$$n \approx \frac{1}{\tau} \cdot \frac{V_{dc}}{V_{PDIV,DC}} \cdot \left(\frac{1}{1 - \frac{\hat{V}_{ac}}{V_{PDIV,AC}}}\right) \quad (14)$$

It can be observed that *n* goes to infinity when $\hat{V}_{ac}$ approaches $V_{PDIV,AC}$, see Figure 4. This is clearly not the case, for $\hat{V}_{ac} \geq V_{PDIV,AC}$ the discharge frequency should be proportional to:

$$f_{pd,ac} = \frac{4 f K_{AC} \hat{V}_{ac}}{V_{c,inception}} \quad . (15)$$

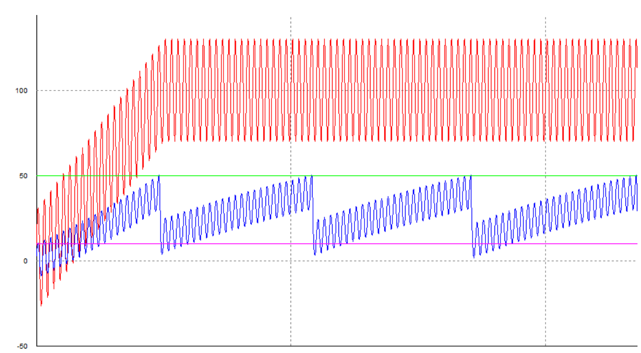

Figure 3. Breakdown of cavity voltage under combined AC and DC voltage, generalized plot. AC frequency lowered to better show the waveform. Red line: voltage over the test

object. blue line: voltage over the cavity. Green line is PD inception level, pink line is PD extinction level.

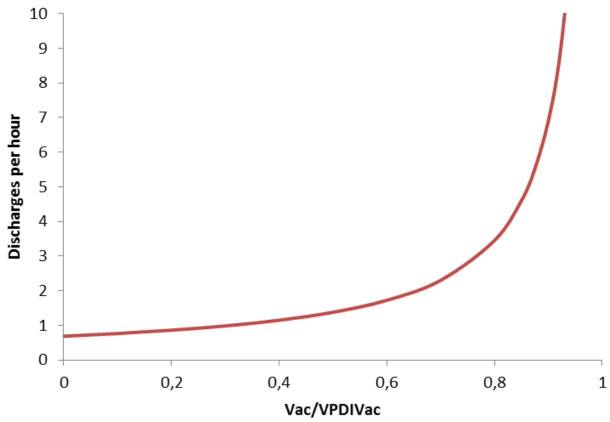

Figure 4. Discharge repetition rate as a function of ratio of AC voltage to AC partial discharge inception voltage, according to (13). The DC voltage is constant and above the DC partial discharge inception voltage.

III. Experimental Setup

The setup consisted of a test cell with parallel plane Rogowski shaped electrodes; the test cell was filled with degassed mineral oil to avoid discharges at the edges. The pressure on the test object was controlled by weights, and set to 50 $^{kN}/_{m^2}$. The oil temperature could be controlled within ± 0.1°C and was set to 80 °C. The test material used was PET-film. All parameters are given in Table I.

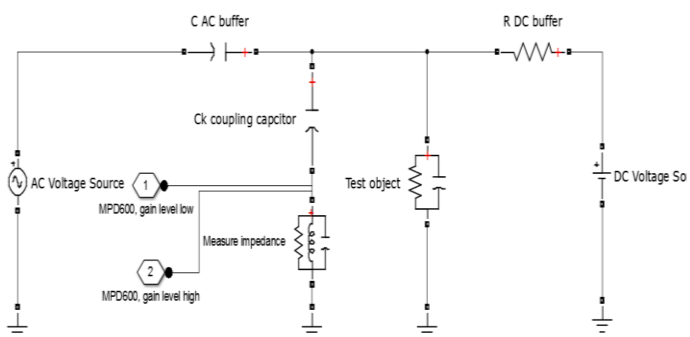

Figure 5. The test circuit – straight circuit with coupling capacitor.

The DC voltage was held constant at 10 kV, after 1 hour the AC voltage was increased from zero to 300 V_{rms}, and then stepped up to 500 and 700 V_{rms}, resting 30 minutes at each voltage step, and then decreased again in the same manner, as indicated with a dashed line in Figure 7.

The detection circuit is a straight circuit for PD measurements, with measuring impedance in series with the coupling capacitor. The voltage and PD magnitude were recorded with two MPD600's from Omicron. Two MPD's was needed to be able to record large and small discharges simultaneously, using a high gain level to record small discharges and a low gain to record large discharges. The total measuring range was between 2 pC to 1700 pC. Calibration levels was set to 5 pC and 50 pC respectively.

TABLE I
LIST OF PARAMETERS

Parameter	Definition	Value
ε_b	Relative permittivity in dielectric	3.5 []
ε_c	Relative permittivity in cavity	1[]
σ_b	Conductivity in dielectric	1.65e-15 [S/m] (@80 °C)
σ_c	Conductivity in the cavity	1e-15 [S/m]
h	Height of cavity	0.1 [mm]
H	Height of test object	0.3 [mm]
r	Radius cavity	1 [mm]
R	Effective radius electrodes	25 [mm]
T	Temperature in test object	80 [°C]
C ac buffer	Buffer capacitance	10 [nF]
R dc buffer	Buffer resistance	100 [MΩ]
Ck	Coupling capacitance	800 [pF]
Vdc	Applied DC voltage	10 [kV]
Vac	Applied AC voltage	300,500,700 [V_{rms}]

IV. Results

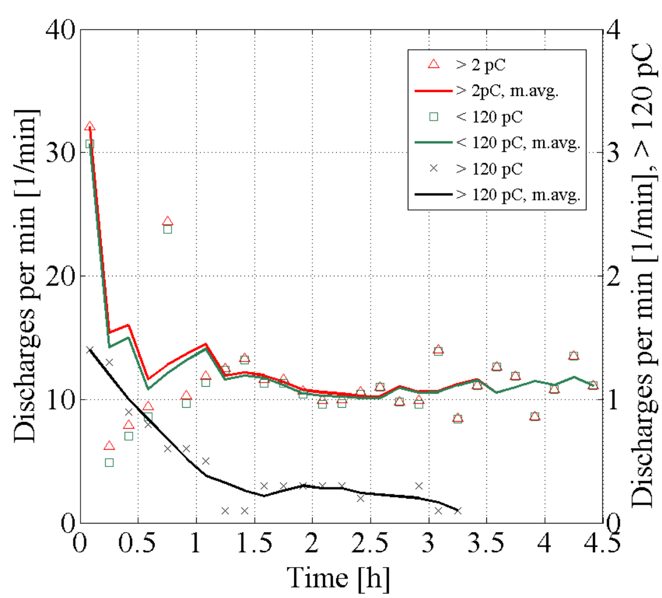

Figure 6. Discharge repetition rate for discharges for all, above and below 120 pC in test object at 10 kV DC, 80 °C. Sampling interval is 10 min. The y-axis on the left give the repetition rate for discharges above 120 pC.

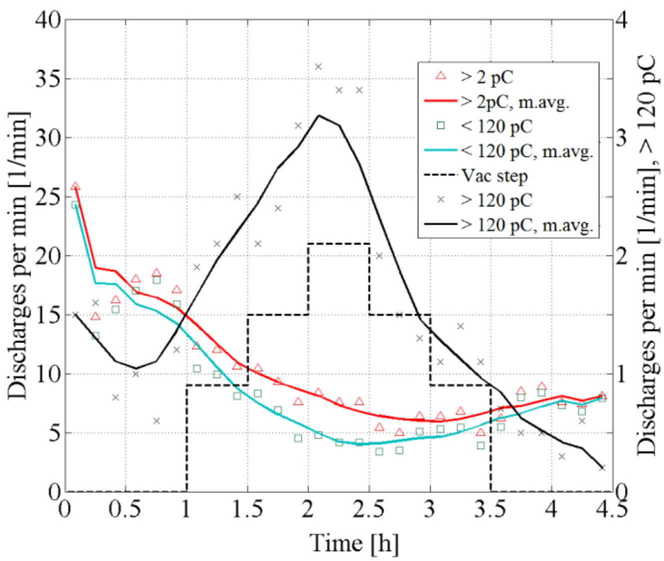

Figure 7. Discharge repetition rate for discharges for all, above and below 120 pC. 10 kV DC and 300, 500 and 700 V_{rms}, at 80 °C. Sampling interval is 10 min. The y-axis on the left give the repetition rate for discharges above 120 pC.

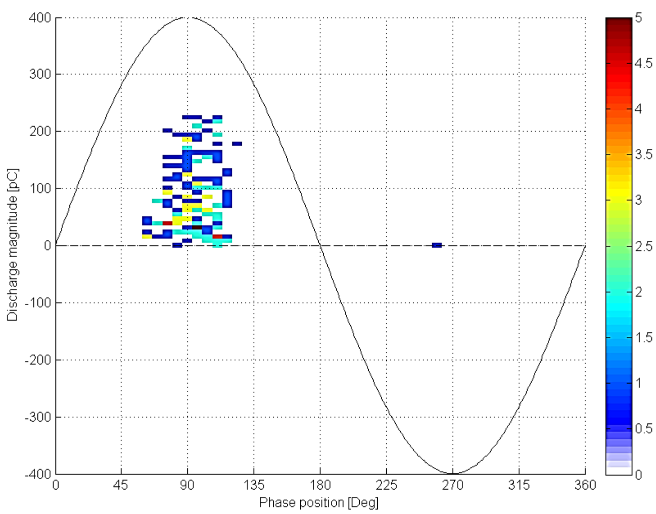

Figure 8. Discharge density plot versus phase angle of the AC voltage. Measured at 10 kV DC + 500 V_{rms} AC, color bar shows number of discharges occurring during 20 minutes of applied voltage.

V. Discussion

The DC benchmark measurements in Figure 6 show a high repetition rate just after the DC voltage is turned on, and a rapid decrease before a stable plateau is reached. The discharges below 120 pC stabilize faster and occur about 10 times more often than the discharges above 120 pC. At combined voltage, shown in Figure 7, the discharges under 120 pC have a slightly lower repetition rate than under pure DC, but the discharges over 120 pC increase linearly with the applied AC voltage. The AC partial discharge inception voltage was measured to about 1 kV_{rms}, thus the applied voltage is 30 % to 70 % of this voltage. According to (14), the increase in repetition rate should be linear in this area (see Figure 4). The measurements also show that the discharge are positive and occur at the positive peak of the AC voltage, within ±2 ms, Figure 8, but with a much lower repetition rate than the frequency of the AC voltage.

The cavity may only be partly discharged [7]. The predicted maximum discharge magnitude is 445 pC, but the most frequent discharges are well below this limit. This might be explained by small discharges occurring around the edges of the cavity or partial discharge of the cavity surface area. It may also be that charges is deposited at the opposite cavity surface, significantly increasing the residual voltage, which again will decrease the magnitude of the subsequent discharges. The waiting time for available electrons, however, should not have any effect on frequency and magnitude of the PDs for $\hat{V}_{ac} < V_{PDIV,AC}$, the change in voltage is much slower than the statistical time lag: the time lag is in the order of milliseconds [8] while the time constant of the cavity voltage DC offset is in the order of seconds.

VI. Conclusion

The measurements indicate that introducing an AC voltage ripple on the DC voltage will increase the partial discharge repetition rate, but only for the larger discharge magnitudes. The repetition rate measured is significantly lower than the frequency of the AC voltage. This is as predicted with the simple ABC-circuit model. Preliminary results show that for a constant DC voltage, and a varying AC ripple voltage below 70% of the AC partial discharge inception value, the repetition rate will be inversely proportional to the time constant of the material and the cavity, τ, and proportional to the AC peak voltage.

References

[1] D. Fabiani and G. C. Montanari, "The effect of voltage distortion on ageing acceleration of insulation systems under partial discharge activity," *Electrical Insulation Magazine, IEEE,* vol. 17, pp. 24-33, 2001.

[2] C. H. Chien and R. W. G. Bucknall, "Analysis of harmonics in subsea power transmission cables used in VSC-HVDC transmission systems operating under steady-state conditions," *IEEE Transactions on Power Delivery,* vol. 22, pp. 2489-2497, 2007.

[3] M. Barnes and A. Beddard, "Voltage Source Converter HVDC Links – The State of the Art and Issues Going Forward," *Energy Procedia,* vol. 24, pp. 108-122, // 2012.

[4] R. J. Van Brunt, "Physics and chemistry of partial discharge and corona. Recent advances and future challenges," *Dielectrics and Electrical Insulation, IEEE Transactions on,* vol. 1, pp. 761-784, 1994.

[5] D. Adhikari, D. M. Hepburn, and B. G. Stewart, "Comparison of PD characteristics and degradation in PET insulation with vented and unvented voids," in *Electrical Insulation and Dielectric Phenomena (CEIDP), 2011 Annual Report Conference on*, 2011, pp. 444-447.

[6] E. J. M. R. Bartnikas, Ed., *Corona measurement and interpretation* (Engineering Dielectrics. American society for testing and materials, 1979, p.^pp. Pages.

[7] L. Niemeyer, "A generalized approach to partial discharge modeling," *Dielectrics and Electrical Insulation, IEEE Transactions on,* vol. 2, pp. 510-528, 1995.

[8] C. Forssen and H. Edin, "Partial discharges in a cavity at variable applied frequency part 2: measurements and modeling," *Dielectrics and Electrical Insulation, IEEE Transactions on,* vol. 15, pp. 1610-1616, 2008.