Breakdown Voltage of Polymeric HVDC Insulation at DC Stress and Superimposed Lightning Impulse Voltages

E. Ildstad, F. Mauseth and E.T. Olsen
NTNU, Department of Electrical Power Engineering, Trondheim, Norway

Abstract

Space charge formation makes it difficult to predict the resulting electric field distribution within HVDC cable insulation.

The main purpose of the work presented here has been to experimentally study how the lightning impulse breakdown strength of thin (0.1 mm thick) insulation foils of polypropylene (PP) and Polyethylene Terephthalate (PET) are affected by DC prestress, polarity of the impulse voltage and the temperature.

Tests were performed using parallel plate electrodes and prior to DC prestressing the lightning impulse breakdown strengths were found to be approximately 17.5 kV for samples of both PP and PET. Prior to superimposing lightning impulse breakdown voltages, a DC voltage of 8 kV was applied for 60 seconds. The effect of DC prestressing was to significantly increase the impulse breakdown strength during aiding and reduce the breakdown strength during opposing impulse polarity. This strongly support the assumption of homo-charge formation close to the metal electrodes during DC stress. The results showed higher and more temperature dependent charge accumulation in samples of PET. It is indicated that at 22 °C the homo-charge formed during DC stressing approximately reduced the electric field at the electrodes from 100 to 48 kV/mm in the PP samples and from 80 to 22 kV/mm in the PET samples, respectively.

1. Introduction

If high voltage DC stress is applied to a polymer, space charges are formed to balance the effects of charge injected at the electrodes and any local differences in electrical conductivity and permittivity. In general, the conduction dominated space charge formation within the insulation is slow compared to the rapid injection processes near the electrodes. In addition, it is a challenging task to distinguish between conduction mechanisms caused by either ions or electrons.

Anyway, such space charge formation alters the electric field distribution within HVDC insulation, causing high local field enhancements and reduced breakdown strength in case of rapid reversal of the voltage polarity.

While XLPE, PE and EPR cable insulation have been thoroughly examined with respect to AC, DC and impulse breakdown strength [1-4], few reports have been published on the electrical performance of alternative insulating materials as Polypropylene (PP) and Polyethylene terephthalate (PET).

The aim of this ongoing investigation is to study how the impulse breakdown strength of thin foils of such polymers are affected by the polarity of the DC prestress voltage. In addition, reference measurements of AC 50 Hz as well as lightning impulse breakdown strength were performed at selected temperatures from 20 to 100 °C.

2. Brief Theoretical background

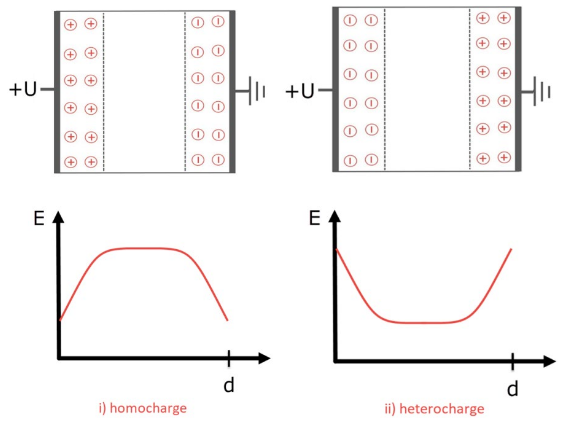


Figure 1 – Illustrations of possible resulting electric field distribution due to the combined effect of an applied voltage and space charge located close to the electrodes. i)In case same polarity of the space charge as the adjacent electrode (homo-charge) and ii) in case of opposite polarity of the charge (hetero-charge).

When considering charges trapped near the electrodes, it is common to distinguish between two types of dominating space charge distributions, either homo-charge or hetero-charge. As shown in Figure 1, the homo-charge has the same polarity as the electrode, while hetero-charge has opposite polarity to the electrode.

During DC voltage application, homo-charge can be considered created by injection of electrons or holes (lack of electrons) at the cathode and anode, respectively. While hetero charge can be created by accumulation of chemical ionized species in the polymer.

The effect of injected homo-charge is to reduce the electric field close to the electrodes and increase the stress in the bulk of the insulation. Hetero charge has an opposite effect.

In the following, it is assumed that electric breakdown by impulse occur when the local maximum field reaches the critical impulse breakdown field $E_{breakdown.}$ and that such breakdown is caused by electronic avalanche processes associated with statistical and formative time lag.

It is previously documented that if the applied superimposed impulse voltage is of the same polarity as the DC stress, the breakdown strength will be increased. A phenomenon explained by formation of a thin layers of

homopolar space charges near the electrodes during DC prestressing. This space charge can be considered a new "virtual electrode" that will smooth out microscopic inhomogeneities at the interfaces. The result of such decreased stress is to increase the breakdown strength of the insulation [1]. This is valid if the expansion of the space charge regions is small compared to the insulation thickness.
If the buildup or removal of homo space charge need longer time than that of the short (1.2/50 µs) impulse, it is very likely that such homo-charge has a detrimental effect of opposite polarity impulse breakdown strength.
In case of EPR cable insulation, different levels of DC prestress cause a considerable influence of the impulse breakdown strength, whereas longer periods of DC prestress did not alter the effect of space charge, varied from 15 min – 100 hours [1].
Such relative rapid charging and slow decay mechanism was also found when examining DC prestress effects on impulse breakdown strength of Poly-p-xylene (PPX) films.
The space charge in the PPX film was formed in less than 1 second but remained for more than 500 s after short circuit [5].
In the literature, the impulse breakdown strength for the same polarity as the DC prestress is denoted field aiding E_{b+}, and for the opposite impulse polarity, field opposing E_{b-} . The impulse breakdown strength, without DC pre-charge is denoted E_{b0} and is the average electric stress, i.e., the applied voltage divided by the thickness of each sample.
In ref. [6] an attempt was made to estimate the amount of homo space charge accumulated in the specimens during the DC prestress. In these thin films, space charge limited current (SCLC) was considered, which is based upon free injection of electrons at the cathode, reducing the cathode stress to $E = 0$.
This means that the difference in impulse breakdown voltage between the field aiding U_{b+} and the strength in case of no DC prestress U_{b0}, yields the total amount of injected accumulated space charge:

$$\Delta Q_+ = C\cdot \Delta U_{b+} = C\cdot (U_{b+} - U_{b0}) \qquad (1)$$

where C is the capacitance of the examined test object.

In case of geometric symmetry, the amount of total injected or accumulated space charge can in a similar manner be determined by the observed difference between the opposing impulse breakdown strength U_{b-} and the strength prior to DC stressing, U_{b0}:

$$\Delta Q_- = C\cdot \Delta U_{b-} = C\cdot (U_{b0} - U_{b-}) \qquad (2)$$

3. Experimental Methods

Experiments were performed using 60 x 60 mm squared samples cut from foils of both Polypropylene (PP), with a thickness of 0.08 mm, and Polyethylene 0.1 mm thick films of terephthalate (PET).
During testing the sample was placed between two Rogowski-shaped brass-electrodes with a diameter of 50 mm. The edge curvature of the electrodes is 4 mm. A weight of 5 kg was put on top of the test cell as shown in Fig. 2. To prevent external flashover, the electrode system was submerged in insulating oil at selected temperatures
The DC prestress voltage level was set to +8 kV for both PET 0.10 mm and PP 0.08 mm. A voltage level selected to be close to the effective AC (50 Hz) breakdown voltage, which was found to be slightly higher than 8 kV for both materials. Combined DC and impulse voltage were applied using a lightning impulse generator, connected to the sample and the DC source via a 10 nF blocking capacitor, as shown in Figure 3. During impulse breakdown testing the breakdown value was measured using a high voltage measuring probe, resulting in typical graphs as shown in Figure 4. The surge impulse generator was charged such that breakdown always occurred within the raising front of the voltage with a raise time of 40 kV/µs. The duration of the DC-prestressing was in all cases set to 60 seconds and the temperature was varied from 20 to maximum 100 °C.

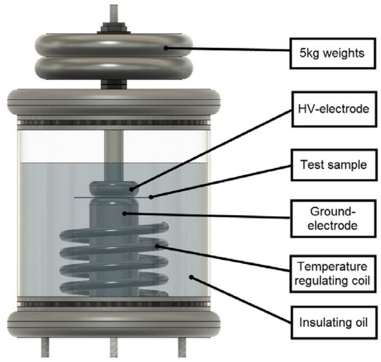


Figure 2 - Test cell with electrodes and heating elements.

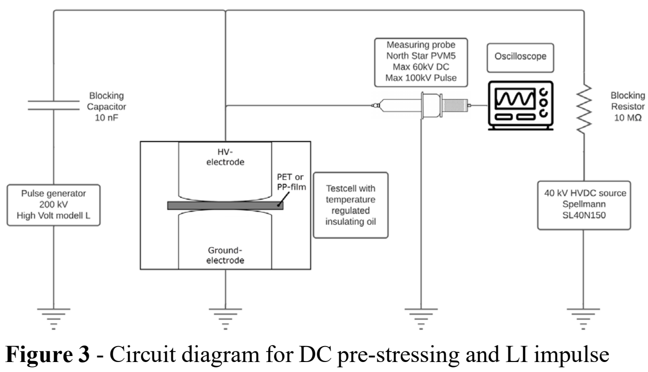


Figure 3 - Circuit diagram for DC pre-stressing and LI impulse testing. The test cell is described in Fig. 2.

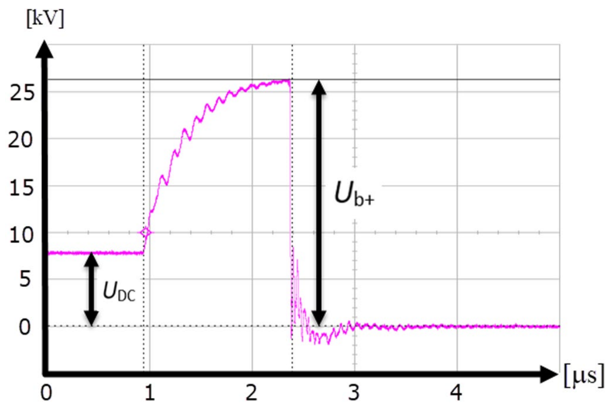


Figure 4 – Breakdown at DC-prestress and superimposed lightning impulse at positive polarity. $U_{DC} = 8$ kV, $U_{LI} = 20$ kV and $U_{b+} = 26.3$ kV.

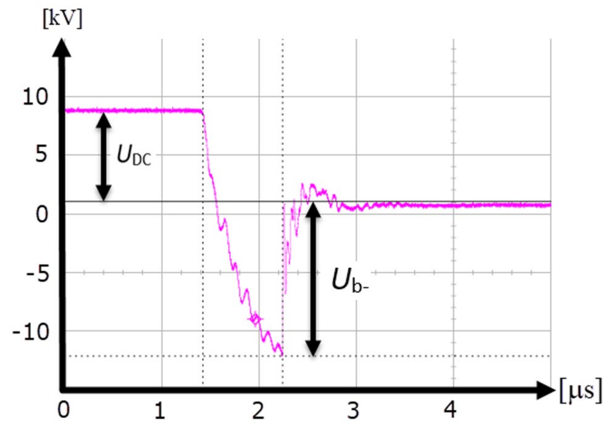


Figure 5 – Breakdown at DC-prestress and superimposed lightning impulse at negative polarity. $U_{DC} = 8$ kV, $U_{LI} = -25$ kV and $U_{b-} = -13.1$ kV.

4. Results and discussion

The AC breakdown strength of the PP and PET-samples are presented in Fig. 6. It shows that at temperatures below 60 °C, the average AC breakdown field strength of PP is approximately 25% higher than that of PET. The AC breakdown strength of PET is, however, less temperature dependent than the PP samples. A reasonable difference considering the typical melting point of 160 and 260 °C for PP and PET, respectively.

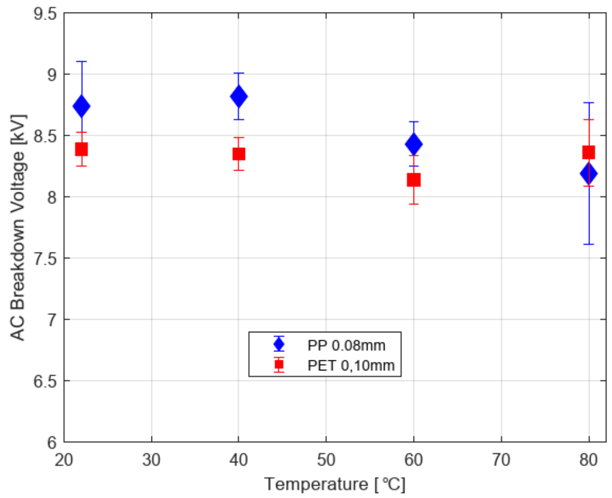
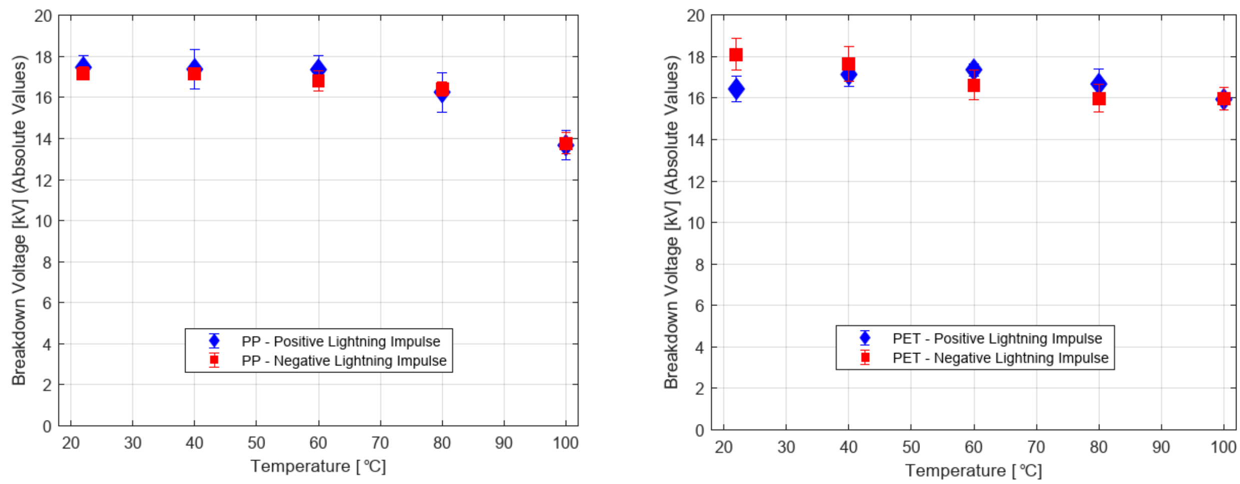


Figure 4 - AC Breakdown Voltage of PP- and PET-film at temperatures from 22 to 80 °C. All measurements are RMS-values.

The measured impulse breakdown values of the reference sample, i.e., prior to applying DC stress, are presented in Fig. 7. The somewhat unexpected polarity effect could be caused by initial space charge formation during storage of the samples. An additional test was therefore performed on PET-samples, which were kept grounded for 7 days before impulse breakdown testing. This resulted in coherent breakdown values of 17.7 kV for both negative and positive lightning impulse.

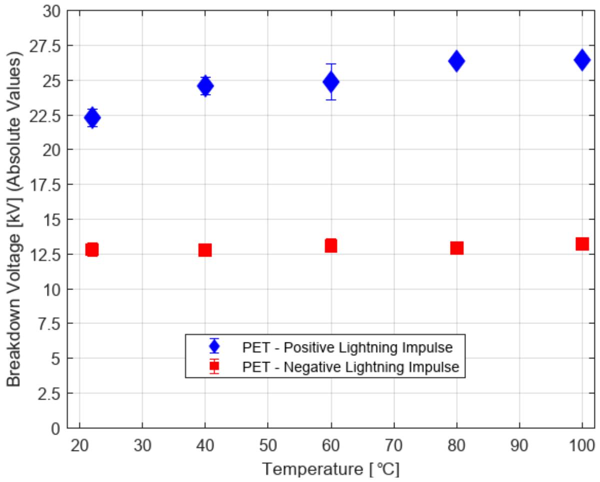
The measured effects of DC prestressing on the impulse breakdown strengths are summarized in Figure 8. The results clearly demonstrate that the impulse strength is increased by aiding and reduced by opposite polarity of



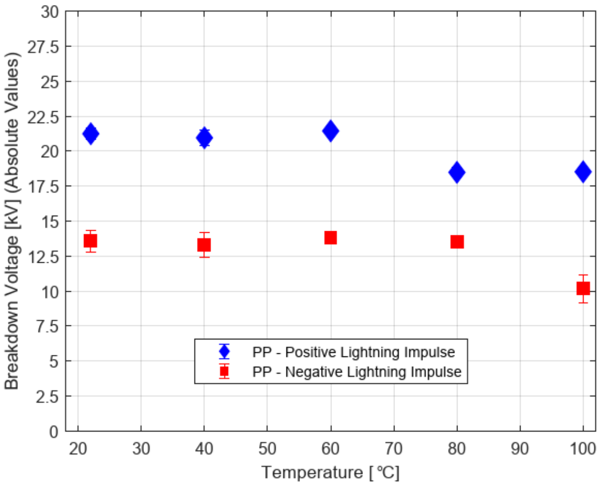
a) Reference 0.10 mm PET-film (DC = 0 kV)   b) Reference sample 0.08 mm PP-film (DC = 0 kV)

Figure 7 - Initial measured impulse breakdown strength versus temperature, prior to DC prestressing. Comparison of applied lightning impulses of both positive and negative polarity.

the superimposed voltage impulse. An observation valid for samples of both PP and PET and at all examined temperatures up to 100°C. It strongly indicates that the impulse breakdown strength is affected by homocharge formation during the DC prestress period. Acting as heterocharge causing field enhancement during application of opposing polarity impulse voltages.



a) 0.10 mm PET-sample (U=8 kV DC)



a) 0.08 mm PP -sample

Figure 8 – Results from measurements of impulse breakdown voltage superimposed 8 kV DC-voltage, versus test temperature

The changes in breakdown voltage compared to that of the non-DC stressed reference objects are given in table 1. The total amounts of apparent injected space charge associated with these values are also presented, using eq. 1 and 2 with measured sample capacitances. In case of the PP samples, it is shown that the amount of injected space charge was nearly temperature independent and also independent of the method of estimation, as equal charge magnitudes were estimated from impulse breakdown values obtained during aiding or opposing breakdown impulses. This indicates that in samples of PP the homo-space charge formed during DC prestressing does not easily decay during the short (1 µs) duration of the applied lightning impulse voltage.

Table 1. Observed increase and reduction of superimposed lightning impulse breakdown strength after 60 s DC stressing at 8 kV at aiding and opposing voltage polarity, respectively. The indicated values of accumulated homo-charge at the electrodes are calculated according to Eq. (1) and (2), based upon measured values of capacitance.

PP+ (aiding)				
Temp [°C]	22	60	80	100
ΔU_+ [kV]	3.8	3.7	2.3	4.8
$\Delta Q = C_{PP} \cdot \Delta U$ [C]	$0.61 \cdot 10^{-6}$	$0.59 \cdot 10^{-6}$	$0.37 \cdot 10^{-6}$	$0.77 \cdot 10^{-6}$
PP- (opposing)				
ΔU_- [kV]	3.6	3	2.9	3.6
$\Delta Q = C_{PP} \cdot \Delta U$ [C]	$0.76 \cdot 10^{-6}$	$0.48 \cdot 10^{-6}$	$0.46 \cdot 10^{-6}$	$0.58 \cdot 10^{-6}$
PET + (aiding)				
ΔU_+ [kV]	5.8	7.5	9.7	10.5
$\Delta Q = C_{PET}\, \Delta U$ [C]	$0.99 \cdot 10^{-6}$	$1.28 \cdot 10^{-6}$	$1.65 \cdot 10^{-6}$	$1.79 \cdot 10^{-6}$
PET- (opposing)				
ΔU_- [kV]	5.3	3.5	3.1	2.8
$\Delta Q = C\Delta U$ [C]	$0.9 \cdot 10^{-6}$	$0.59 \cdot 10^{-6}$	$0.53 \cdot 10^{-6}$	$0.48 \cdot 10^{-6}$
C_{PP} [nF]		C_{PET} [nF]		
0.16		0.17		

In case of PET samples higher total average accumulated charge was observed, particularly so at temperatures above 60°C. In addition, the amount of injected charge in the PET samples was found to increase with increasing temperature while decreasing at opposing impulse voltages.

This asymmetry, either indicate a more non-symmetric distribution of injected space charge prior to the impulse breakdown testing or more rapid and increased charging/discharging during the period of superimposed aiding/opposing impulse voltage. The latter mechanism is supported by the observed increasing asymmetry with increasing temperature.

The overall effect of the homo-charge accumulated during the period of DC stressing is to significantly reduce the electric stress at the electrodes. If at room temperature (22 °C), the space charge is considered located in a thin region close to the metallic electrodes, the resulting electric field at the electrode is approximately reduced from 100 to 48 kV/mm in the PP samples and from 80 to 22 kV/mm in the PET samples.

4. Conclusion

The impulse breakdown strength of both PP and PET films are strongly affected by homocharge injected during a short period of DC prestressing.

Such space charge effects must be taken into account when discussing impulse breakdown strength of HVDC insulation.

5. References

[1] F. Selle, D. Schulte, ”Electric Breakdown of EPR-insulated Cables at DC and Impulse Voltages”, IEEE Trans. on El. Insl. Vol EI-22, April 1987

[2] A. Bradwell, R. Cooper and B. Varlow, “Conductivity in Polyethene with strong electric fields and the effect of prestressing on the electric strength”, Proceedings of IEE, Vol 118, No.1, pp 247-254, 1971.

[3] G. Mazzanti and M. Marzinotto, “Extruded cables for high-voltage direct-current transmission: Advances in research and development”, Book, pp 104, 2003, doi 10.1002/9781118590423.

[4] T.L. Hanley, R.P. Burford, R.J. Fleming, and K.W. Barber. “A General Review of Polymeric Insulation for Use in HVDC Cables.” IEEE Electr. Insul. Mag.,Vol. 19, No.1, pp. 14-24, Feb 2003.

[5] Tatso Mori,et. al. “The breakdown mechanism of Poly-p-xylyene Film, Prestress Effects on Breakdown strength”, IEEE Trans. on El. Insl. Vol 1, No.1 February 1994

[6] K. Kaneko et al.. “Consideration of space charge effects on electrical breakdown of Poly-p-Phenylene sulfide films” Proceedings of 3rd Int. Conf. on Properties and Application of Dielectric Materials”, July 8-12, 1991, Tokyo, Japan