Effect of Pre-Qualification Test on Space Charge Accumulation Phenomenon

A. Imburgia[1], P. Romano[1], G. Rizzo[2], A. Di Fatta[1], G. Akbar[1], G. Berardi[2], M. Albertini[2], S. Franchi Bononi[2], G. Ala[1]

[1]L.E.PR.E. HV Laboratory, Department of engineering – University of Palermo, Palermo, Italy
[2]Prysmian Group, Milan, Italy

***Abstract*- This paper is focused on the measurement of space charge in flat specimens deriving from a cable subjected to the Pre-Qualification (PQ) test. In particular, before starting the PQ test and after finishing them, the flat specimens have been taken from the cable. This with the aim to evaluate the effect of PQ test on the space charge accumulation phenomenon. The PEA cell has been used for the space charge detection, while the Standard IEEE 1732-2017 has been followed for the measurement procedure. For both unaged and aged specimens, the space charge and the related electric field distribution have been reported in the paper. Measurement results highlight that the more accentuated electric field distortion has been observed during the test carried out on the aged specimen stressed under positive polarity.**

Keyword: HVDC, Cables, PQ test, PEA, Space charge.

I. Introduction

In the field of High Voltage Direct Voltage (HVDC) systems the main insulation degradation factor is attributed to the space charge accumulation phenomenon [1-2]. The accumulation of charge in dielectric is mainly due to the applied voltage magnitude and thus to the electric field gradient but also to the temperature gradient within the dielectric layer as well as to the dielectric interface conditions [3-8]. Considering the importance attributed to the space charge phenomenon, a Standard IEEE 1732-2017 was issued [9]. The Standard is referred to the cable specimens and introduces the measurement of space charge in the routine test of HVDC extruded cables for rated voltage up to 550 kV. For the space charge test, the Standard proposes a protocol to be followed for two different measurement techniques, such as the Thermal Step Method (TSM) [10] and the Pulsed Electro-Acoustic (PEA) method [11-12]. In addition, the mentioned Standard indicates that the ageing status of a dielectric can be evaluated by means of electric field gradient calculated starting from the accumulated charge.

Based on the above, in the present work the protocol proposed by the Standard IEEE 1732-2017 has been followed in order to evaluate the accumulated charge in flat specimens deriving from an HVDC cable subjected to Pre-Qualification (PQ) test [13-14]. The PQ tests belong to the routine tests carried out on cables before being installed and have the purpose of evaluating the long-term performance of the cables themselves. However, the aim of the present work is to evaluate the effect of PQ test on space charge accumulation phenomenon which, in turns, indicates how much these tests influence the cable lifetime [15]. For this aim two set of specimens have been obtained from longitudinal slicing of a HVDC full-size cable before and after it has been subjected to the PQ test. As indicated in the Std, starting from the detected charges, the electric field gradient is calculated as well as its maximum absolute percentage variation, ΔE. The latter value indicates if the electric field is stable or not and therefore it provides an indication regarding the ageing status of the dielectric under test.

The choice to measure the accumulated charge in flat specimens was mainly due to the fact that several difficulties are still present in the charge measurement on the cable sample [16]. However, by means of the new PEA cell developed by S. Zahra et al. some issues were overcome [17]. Therefore, in future works, by using the proposed new PEA cell the effect of PQ test could be evaluated directly on the cable.

The followed protocol for the measurement of space charge and for the evaluation of ΔE is given in the next Section. In the other Sections, instead, the specimens under test, the measurement procedure and the experimental results are reported.

II. The Standard IEEE 1732-2017 and Measurement Procedure

In 2017, the IEEE Standard 1732-2017 named “Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV” was proposed [9]. The Standard is conceived for cable specimens and suggests the procedure to be followed for the space charge measurements during routine tests. However, for the purpose of this work the guidelines proposed by the above-mentioned Standard have been adapted for flat specimens. The protocol suggested by the Std in its original form for cable specimens has been summarized and reported in a previous work [18]. In the present work, instead, because our PEA cell for flat specimens is not able to carry out measurement under thermal gradient, the test procedure has been slightly modified as below.

A - Sample preparation. The unaged and aged samples have been obtained from a HVDC cable before and after the PQ test, respectively.

B - Positive voltage pooling time. The space charge measurement starts by applying a positive voltage with magnitude 10 kV in order to obtain the rated electric field of 20 kV/mm.

C – Charge detection. After a two minutes of voltage application, the first space charge distribution has been acquired. This profile is used as reference for the signal processing.
D - Subsequent measurements. Every 60 min and until 3 h of applied voltage the space charge distributions are acquired.
E - Electric field evaluation. Starting from the charge acquisitions, the electric field profiles have been carried out. A comparison between the electric field at 0 hours (two minutes) and three hours, has been made. Then, the maximum absolute percentage variation between the two electric field profiles, ΔE, is calculated by a formula reported in the Standard. If ΔE results lower than the 10% the electric field is considered stable and the subsequent point F can be neglected (go directly to point G).
F - If ΔE results greater than the 10% the acquisition of space charge continues for another three hours (from 3 to 6 hours). In this case ΔE is calculated between the electric field acquired at 3 and 6 hours. If $\Delta E < 10\%$ go to point g. On the contrary, the acquisition of space charge continues for another three hours and ΔE is calculated between the electric field at 6 and 9 hours.
G - Voltage removal and Volt-off phase. The high voltage generator is switched off, while the pulse generator is active. During the depolarization time, with duration equal to three hours, the trapped charge is acquired. The charge distributions at 0,1,2 and 3 hours are evaluated as well as the residual electric field.
H – End of the test. The test at positive voltage is concluded. The specimen is short circuited for 24 hours.
I – Negative voltage pooling time. The points from B to H are repeated by applying the high voltage stress in negative polarity.

III. Specimens Under Test and Measurement Procedure

With the aim to evaluate the effect of PQ test on the space charge accumulation phenomenon, the samples have been obtained from longitudinal slicing of a HVDC full-size cable before and after it has been subjected to the PQ test [13]. Therefore, unaged and aged samples have been tested with same measurement conditions previously reported in Section II. The samples, with thickness 0.5 mm, are made of XLPE dielectric material. The applied DC voltage for the tests was ±10kV in order to stress the samples with an electric field gradient of ±20 kV/mm, as in the normal operating condition of the cable itself.

IV. Measurement Results - Unaged Specimen

Concerning the unaged specimen, under the DC stress in positive polarity a no significant accumulation of charge has been detected within three hours of voltage application, as can be seen in figure 1. Therefore, the electric field distribution does not present significant distortion, as shown in figure 2. The value of ΔE calculated between the electric filed at 0 and 3 hours results equal to 3% and thus, as indicated in the Standard, it can be considered stable. The measurement under DC in positive polarity has ended.

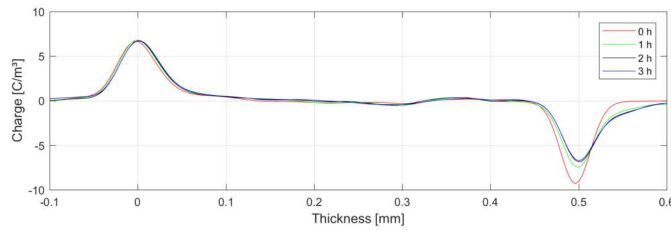

Fig. 1. Space charge distributions in the unaged specimen during positive polarity.

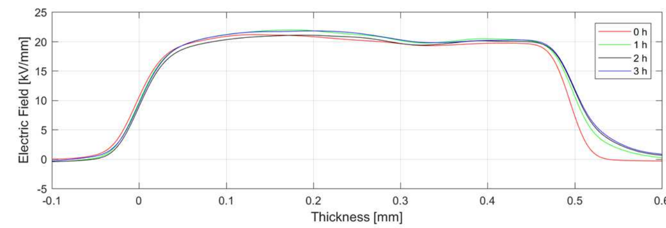

Fig. 2. Electric field distributions in the unaged specimen during positive polarity.

With reference to the acquisitions under negative DC stress, the accumulated charge and the related electric field gradient are depicted in figures 3 and 4, respectively.
As for the previous case, the amount of trapped charge is low and therefore the measured ΔE between the maximum electric field at 0 and 3 hours results 4.9%. This means that the step E is satisfied and therefore it is possible to move directly to step G of the Standard protocol.

In the step G the residual charge and the electric field are evaluated during vol-off phase. Considering that no particular phenomena were detected, the related graphs have not been reported here.

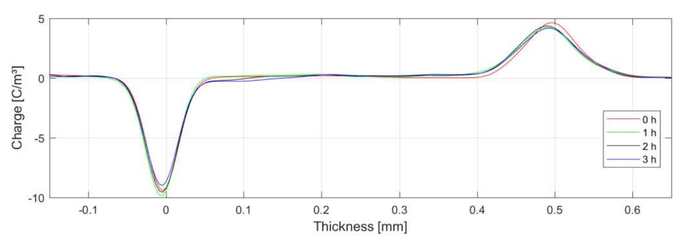

Fig. 3. Space charge distributions in the unaged specimen during negative polarity.

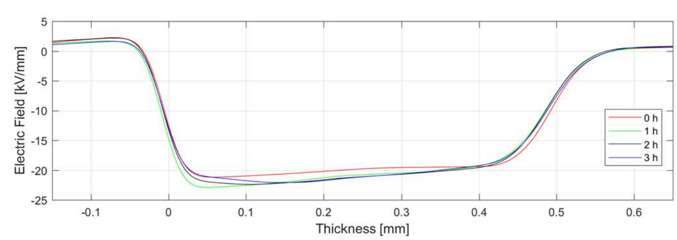

Fig. 4. Electric field distributions in the unaged specimen during negative polarity.

The obtained electric field values at 0 hours (Et_{0h}) and at 3 hours (Et_{3h}), under both positive and negative polarity, as well as the calculated ΔE%, are reported in Table I.

Table I. Measurement results of the unaged specimen

	Positive Polarity	**Negative Polarity**
$E(t_{0h})$ [kV/mm]	21.14	-21.18
$E(t_{3h})$ [kV/mm]	21.77	-22.09
ΔE% (0-3) hours	3	4.9

V. Measurement Results - Aged Specimen

The space charge and the electric field distributions measured in the aged specimen derived from the same cable (after having subjected it to the PQ test) are reported in the follow.

From 0 to 3 hours of positive DC stress the accumulated charge and the related electric field profiles are depicted in figures 5 and 6, respectively.

In this case, the maximum electric field at 0 and 3 hours result 20.72 and 23.47 kV/mm, respectively. The value of ΔE calculated between (Et_{0h}) and (Et_{3h}) results 13.28%, therefore a significant electric field distortion occurs. Considering that this value is greater than the 10%, the detection of the accumulated charge continues for another 3 hours, as suggested by the Standard.

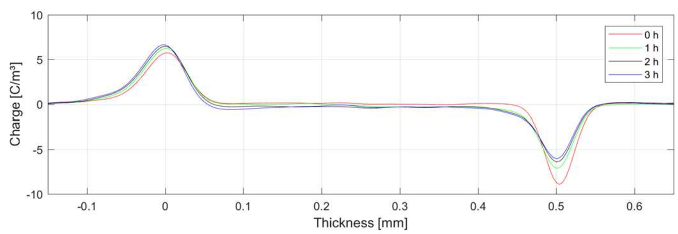

Fig. 5. Space charge distributions in the aged specimen during the first three hours of positive polarity.

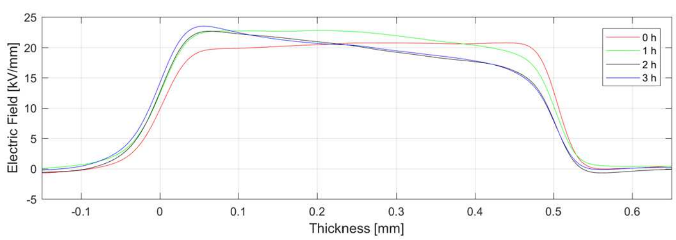

Fig. 6. Electric field distributions in the aged specimen during the first three hours of positive polarity.

From 3 to 6 hours the measured space charge and the related electric field distributions are show in figures 7 and 8, respectively. At 6 hours the maximum electric field value is Et_{6h} = 24.47 kV/mm and the value of ΔE calculated between Et_{3h} and Et_{6h} results 3.4%. This last value is lower than 10% and thus the measure under positive polarity can be concluded.

In the next step the HV generator is switched off and the trapped space charge during volt-off phase has been detected for 3 hours. After that, the specimen has been grounded for 24 hours to clear the specimen from the residual charge. Then the measure under negative polarity (-10kV) has been carried out. The charge and the electric field profiles from 0 to 3 hours are illustrated in figures 9 and 10, respectively. Under negative DC stress the maximum measured electric field is -20.59 kV/mm at 0 hours, and -21.63 kV/mm after 3 hours. Therefore, the calculated ΔE results lower than 10% and equal to 5.02%. On the basis of this last value, the acquisitions at -10kV can end.

After detecting the residual charge for the three hours following the shutdown of the DC generator, the measurement is completed.

All the obtained results for the aged specimen are summarized in Table II.

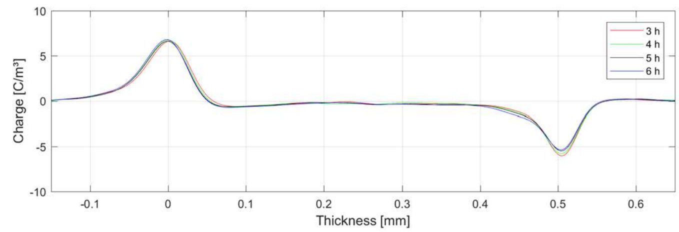

Fig. 7. Space charge distributions in the aged specimen from three to six hours of positive polarity.

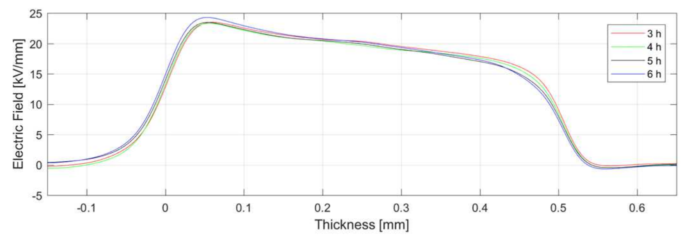

Fig. 8. Electric field distributions in the aged specimen from three to six hours of positive polarity.

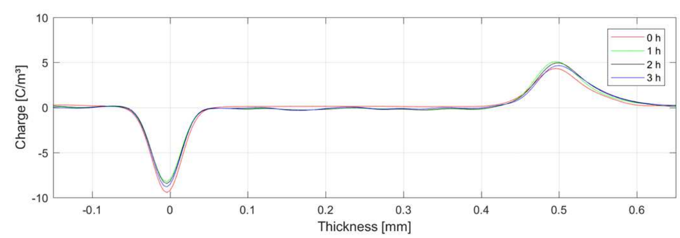

Fig. 9. Space charge distributions in the aged specimen during the first three hours of negative polarity.

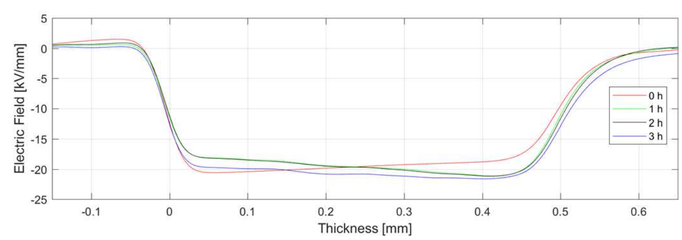

Fig. 10. Electric field distributions in the aged specimen during the first three hours of negative polarity

Table II. Measurement results of the aged specimen

	Positive Polarity	**Negative Polarity**
$E(t_{0h})$ [kV/mm]	20.72	-20.59
$E(t_{3h})$ [kV/mm]	23.47	-21.63
$E(t_{6h})$ [kV/mm]	24.47	-
ΔE% (0-3) hours	13.28	5.02
ΔE% (3-6) hours	3.4	-

V. Conclusions

In the present work the effect of the PQ test on the ageing phenomenon in HVDC cables is investigated. For this aim the accumulation of space charge has been measured in flat specimens derived from a cable before and after it has been subjected to the PQ test. To detect the space charges the protocol proposed by the Standard 1732-2017 has been applied. Measurement results show a no significant accumulation of charge in the unaged specimen. In fact, for both polarities the maximum absolute percentage variation ΔE resulted lower that 5%. For the aged specimen, instead, some differences in the space charge accumulation behavior have been observed. In particular, during the test under positive polarity the maximum electric field value changes from 20.72 kV/mm to 23.47 kV/mm in the first three hours of voltage application. This, in turn, has generated a value of ΔE equal to 13.28% and therefore an unstable electric field. For this reason, as suggested by the adopted Standard, the charge acquisition has been carried out for another three hours. However, the maximum electric field value after six hours, compared to that previously obtained at the end of three hours, provides a ΔE equal to 3.4%. Therefore, no further acquisitions have been made. Under negative polarity, instead, the space charge test was completed within the first three hours because the value of ΔE resulted lower than the 10%.

Small differences in the aged specimens, not compromising the insulation quality, were expected since PQ test has the aim to simulate 40 years of life. The ageing effect in term of lifetime reduction, due to the electrical stresses applied by the PQ test, could be evaluated by means of the Inverse Power Law. For a better and more accurate analysis, additional space charge measurements are ongoing on further specimens deriving from other HVDC cables, results will be shown in future works.

Acknowledgment

This work was realized with the co-financing from: European Union – FSE, PON Research and Innovation 2014-2020 – DM 1062/2021;

References

[1] G. Mazzanti, M. Marzinotto, “Space Charge in HVDC extruded insulation: storage, effect, and measurement methods”, in *Extruded Cables for High Voltage Direct Current Transmission: Advances in Research and Development*, Power Engineering Series, Wiley-IEEE Press, New York, USA, 2013, pp. 99-207.

[2] G. C. Montanari, "Bringing an insulation to failure: the role of space charge," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 2, pp. 339-364, April 2011.

[3] A. Imburgia, P. Romano, E. R. Sanseverino, F. Viola, N. Hozumi and S. Morita, "Space charge behavior of different insulating materials employed in AC and DC cable systems," 2017 International Symposium on Electrical Insulating Materials (ISEIM), Toyohashi, Japan, 2017, pp. 629-632, doi: 10.23919/ISEIM.2017.8166568.

[4] M. De Araujo Andrade et al., "Different Space Charge Behavior of Materials Used in AC and DC Systems," 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP), Fort Worth, TX, USA, 2017, pp. 114-117, doi: 10.1109/CEIDP.2017.8257619.

[5] Rizzo, G.; Romano, P.; Imburgia, A.; Viola, F.; Ala, G. The Effect of the Axial Heat Transfer on Space Charge Accumulation Phenomena in HVDC Cables. Energies 2020, 13, 4827.

[6] A. Imburgia *et al.*, "Effect of Space charge accumulation inside the thermoplastic insulation of a loaded HVDC model cable," *2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Vancouver, BC, Canada, 2021, pp. 221-224, doi: 10.1109/CEIDP50766.2021.9705359.

[7] G. Rizzo et al., "Space charge accumulation in undersea HVDC cables as function of heat exchange conditions at the boundaries – water-air interface," 2020 IEEE 20th Mediterranean Electrotechnical Conference (MELECON), Palermo, Italy, 2020, pp. 447-452.

[8] G. Rizzo, P. Romano, A. Imburgia and G. Ala, "Partial Discharges in HVDC Cables - The Effect of the Temperature Gradient During Load Transients," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 5, pp. 1767-1774, October 2021.

[9] "IEEE Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV," in *IEEE Std 1732-2017*, vol., no., pp.1-36, 26 June 2017.

[10] Notingher, P.; Toureille, A.; Agnel, S.; Castellon, J. Determination of Electric Field and Space Charge in the Insulation of Power Cables with the Thermal Step Method and a New Mathematical Processing. IEEE Trans. Ind. Appl. 2009, 45, 67–74.

[11] Rizzo, G.; Romano, P.; Imburgia, A.; Ala, G. Review of the PEA Method for Space Charge Measurements on HVDC Cables and Mini-Cables. *Energies* 2019, *12*, 3512.

[12] Mazzanti *et al.*, "A protocol for space charge measurements in full-size HVDC extruded cables," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 1, pp. 21-34, Feb. 2015.

[13] S. Hou *et al.*, "Experimental practice implemented to improve meaningfulness of prequalification tests for extruded HVDC 525kV land and submarine cables," *22nd International Symposium on High Voltage Engineering (ISH 2021)*, Hybrid Conference, Xi'an, China, 2021, pp. 691-696, doi: 10.1049/icp.2022.0244.

[14] M. Marzinotto and G. Mazzanti, "Some hints at the combined effects of load cycles and electrothermal stress on HVDC extruded cable reliability in the long-term prequalification test," *2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, Montreal, QC, Canada, 2012, pp. 391-394.

[15] G. Mazzanti, "Life Estimation of HVDC Cables Under the Time-Varying Electrothermal Stress Associated With Load Cycles," in IEEE Transactions on Power Delivery, vol. 30, no. 2, pp. 931-939, April 2015.

[16] A. Imburgia, P. Romano, E. R. Sanseverino, L. D. Rai, S. F. Bononi and I. troia, "Pulsed Electro-Acoustic Method for specimens and cables employed in HVDC systems: some feasibility considerations," *2018 AEIT International Annual Conference*, Bari, Italy, 2018, pp. 1-6, doi: 10.23919/AEIT.2018.8577421.

[17] S. Zahra *et al.*, "Space Charge Measurement Equipment for Full-Scale HVDC Cables Using Electrically Insulating Polymeric Acoustic Coupler," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 29, no. 3, pp. 1053-1061, June 2022, doi: 10.1109/TDEI.2022.3169106.

[18] Imburgia, A.; Romano, P.; Chen, G.; Rizzo, G.; Riva Sanseverino, E.; Viola, F.; Ala, G. The Industrial Applicability of PEA Space Charge Measurements, for Performance Optimization of HVDC Power Cables. *Energies* 2019, *12*, 4186. doi:10.3390/en12214186.