Advancing Space Charge Test Techniques: PEA Measurement on 525 kV HVDC Cable

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Abstract

In 2017, the IEEE HVDC Working Group introduced a procedure to assess the impact of space charge accumulation in extruded HVDC cables with rated voltages up to 550 kV, which is known as IEEE std 1732. In this paper, the authors present the results of a Pulsed Electro-Acoustic (PEA) measurement, which has been carried out in compliance with the IEEE guidelines, for the first time on a full-size cable with a rated voltage, U_0, of 525 kV and with more than one hundred metres in length. The aim is to evaluate the maximum absolute percentage variation of the electric field profile, ΔE_{max}, to determine after how long it reaches a stabilization condition (variation less than 10%). Compliance with this condition is checked at three-hour intervals. Results include both positive ($+U_0$) and negative ($-U_0$) volt-on tests, each followed by a volt-off test. The findings reveal a significant reversal of the electric field profile during both the positive and negative volt-on, with electric field stabilisation reached after a total duration of nine hours and six hours respectively. Notably, the reversal of the field is concentrated within the first hour. However, evaluating the ΔE_{max} at three-hour intervals leads to extending the test duration to a minimum of six hours. Furthermore, the evaluation of ΔE_{max} based on profiles acquired at the beginning and end of the interval could make the results overly sensitive to external disturbances. This study demonstrates the reproducibility of the PEA measurement on full-size cables longer than one hundred metres and the applicability of the IEEE Std 1732.

Index Terms

Space Charge, PEA Measurement, HVDC Cable, IEEE Std 1732.

I. INTRODUCTION

In recent years, the growing demand for high-performance High-Voltage-Direct-Current (HVDC) systems has driven significant advancements in cable manufacturing technologies [1], [2]. As the industry continues to evolve, one of the most critical challenges is optimizing the quality and reliability of these cables to meet the operational requirements [3], [4]. Therefore, ensuring the long-term performance and stability of HVDC cables is essential for improving their lifetime and minimizing degradation, which can be influenced by various factors, including the accumulation of space charge [5], [6], [7].

Charge accumulation is a phenomenon that can significantly affect the electric field distribution within HVDC cables, potentially leading to electrical stress, material breakdown, and premature failure. Therefore, accurate measurement and monitoring of space charge behavior are crucial for extending cable lifetime [8], [9].

In response to these challenges, the IEEE HVDC Working Group published in 2017 the 'Recommended Practice for Space Charge Measurements on High-Voltage Direct-Current Extruded Cables for Rated Voltages up to 550 kV', providing a framework for evaluating space charge accumulation and its impact on cable degradation [10], [11]. The guidelines suggest two main methods for measuring space charge: the Pulsed Electro-Acoustic (PEA) method and the Thermal Step Method (TSM) [12], [13], [14], [15]. Both techniques offer valuable insights into the behavior of space charge under high voltage stress, with a clear procedure outlined for conducting measurements. According to the recommendation, space charge measurements should ideally be performed both before and after cable qualification tests to allow for a comparative analysis of the results and assessing the effect of aging [16]. Among the available techniques, the PEA method is widely used due to its ability to provide detailed profiles of space charge distribution along the cable's cross-section.

In this work, the authors employed the PEA method to perform, for the first time, a space charge measurement on a full-size cable, with a rated voltage of 525 kV and with more than one hundred metres in length, following the IEEE 1732's guidelines. The study, carried out in collaboration with a cable manufacturer, helped to understand the feasibility of PEA measurements on cables longer than one hundred metres and the applicability of the measurement protocol in the field of testing for this type of equipment, presenting itself as a witness for possible future updating processes. The following sections of this paper provide a detailed description of the PEA measurement setup, an overview of the protocol established by the IEEE 1732, and a discussion of the experimental results. Finally, the conclusions drawn from this study and their implications for future works conclude the paper.

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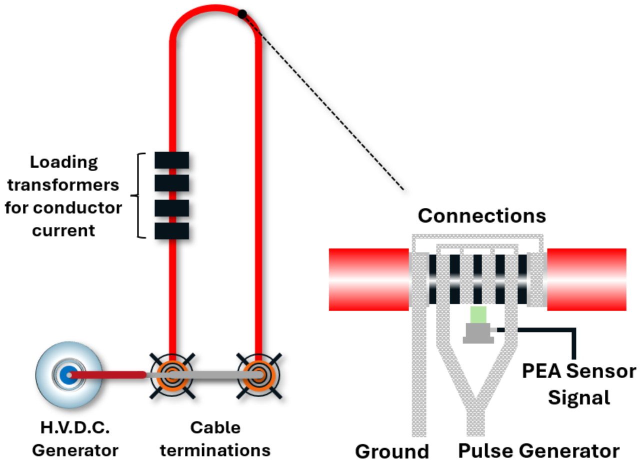

Fig. 1. Schematic picture of PEA setup connections.

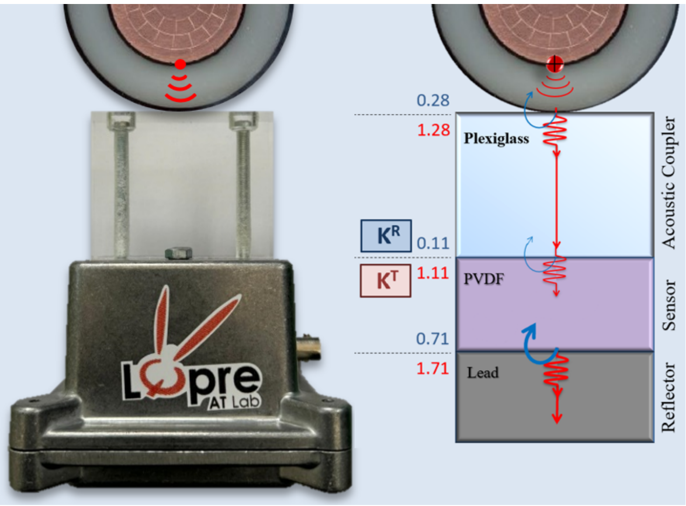

Fig. 2. Schematic picture of PEA sensor.

II. PEA MEASUREMENT

The PEA method is a widely adopted technique for investigating space charge behavior in HVDC cables. The measurement procedure is based on the generation, propagation, and subsequent detection of acoustic waves, which are directly proportional to the charge distribution. When a high voltage is applied to the cable through an HVDC generator, a distribution of charge forms at the interfaces between the semiconductive layers and the dielectric insulation. The accumulation of space charge is closely linked to two primary mechanisms: charge injection at the semicon-dielectric interfaces and physical-chemical processes occurring within the insulating layer itself. These processes can lead to significant alterations in the cable's electric field, potentially resulting in electrical stress concentrations that accelerate aging or even cause failure. By accurately measuring the space charge distribution, it can better understand the impact of these phenomena on cable performance and durability. In the context of HVDC systems, space charge measurement is crucial for optimizing insulation design, improving reliability and predicting the long-term behavior of cables under operating conditions. For these reasons the PEA method is particularly effective because it allows for the real-time profiling of this charge along the cable's cross-section, providing valuable insights into the electric field distribution. The setup shown in Fig. 1 was designed to allow for precise measurements using the PEA method, ensuring that the results reflect the actual charge distribution. Using a voltage pulse generator, accumulated charges within the cable can be induced to vibrate, resulting in the generation of acoustic waves. The detection of these acoustic waves is carried out by a cell containing a piezoelectric sensor, made with PolyVinyliDene Fluoride (PVDF), which converts the pressure variations into an electrical voltage signal [17], [18]. This signal is then amplified and recorded using an oscilloscope. Fig. 2 shows a diagram of the sensor used for this measurement [19]. The latter has been made according to technology optimised by S. Zahra et al. in [18] and, compared to a traditional cell, features a plexiglass acoustic coupler. It can be seen that when an acoustic wave originates from the inner semiconductor/dielectric interface, or from a charge located within the dielectric

Fig. 3. Photos of the measurement setup.

bulk, and reaches the dielectric/outer semiconductor interface, it splits: part of the wave (in red) continues toward the sensor, while the other part (in blue) reflects back in the opposite direction. The transmission and reflection coefficients (K^T and K^R respectively) depend on the properties of the two materials forming the interface, specifically on their acoustic impedances. In this configuration the K^T coefficients in the dielectric/acoustic-coupler interface and in the acoustic coupler/sensor interface are equal to 1.28 and 1.11, respectively. Therefore, the direct acoustic wave sensed by the sensor is equal to the 142.22% of the generated wave. Thanks to the lead used as “Reflector”, the acoustic wave passing through the sensor is not fully absorbed, but it is partially reflected, with $K^R = 0.71$, in the sensor/reflector interface. This means that, the 142.22% of the direct detected wave that passed though the sensor, is reflected, for the 71.61%, in the sensor direction. The 71.61% of the 142.22% results 101.84%. This reflected wave is added to the direct wave and thus the total acoustic wave sensed by the sensor is given by the 244% of the generated wave. The structure of this cell guarantees the acquisition of a better quality signal than a traditional cell, making PEA measurements on full-size cables possible [17]. The cell with piezoelectric sensor is positioned at a location on the cable where the semiconductive layer has been exposed by removing the sheath and metal screen. The application of voltage pulses is accomplished through metal electrodes that are wrapped around the cable at the designated measurement point. To investigate the behavior of accumulated charges under varying thermal gradient conditions, the cable is heated using a current induced with transformers. This technique allows for the simulation of thermal operating conditions that the cable may experience in real-world applications. In Fig. 3 some photos of the experimental setup employed to perform the space charge measurements discussed in this paper are reported. The voltage signal captured by the oscilloscope represents a voltage profile as a function of time, which must subsequently be converted into a charge profile in relation to the dielectric thickness. This conversion is crucial for understanding the charge distribution within the cable. The measurement phase is therefore followed by a detailed signal processing phase, which is generally divided into five steps. A preconditioning step guarantees that the acquired signal is optimized to remove any noise or artifacts that could distort the results. This step stabilizes the analysis and ensures that the measurements are representative of the actual behavior of the space charges in the cable. Proper preconditioning helps to improve accuracy in the subsequent analysis of the charge profile [20]. The subsequent deconvolution step allows the recovery of the cell’s input signal, which is modified by convolution with the cell’s transfer function [21], [22]. The deconvolved signal must be corrected from distortions suffered due to the geometry of the system. Another correction concerns the attenuation and scattering that the signal undergoes due to the behavior of the dielectric as a dissipative acoustic transmission medium [23], [24]. The last step is signal calibration, in which the voltage signal is converted to charge density. It is important to note that this process is done by comparison between the acquired profile and the expected surface charge density based on the applied supply voltage. For this reason, the calibration process can be performed only on a profile acquired in the absence of accumulated space charge. Each of these steps plays an essential role in ensuring the accuracy and reliability of the final charge distribution profile. Once the charge profile across the dielectric thickness has been established, the next step is to derive the electric field distribution by applying the differential form of Gauss’s law. This law allows to relate the charge density to the electric field. Following the determination of the electric field profile, the voltage profile can then be obtained by integrating the electric field. This integration ensures that the resulting voltage profile overlaps the voltage applied by the HVDC generator. By comparing the calculated voltage profile with the applied voltage, the accuracy of the processing procedure can be assessed.

III. IEEE 1732-2017 RECOMMENDATION

The IEEE 1732-2017 Recommendation outlines the procedure for measuring space charge in extruded cables for HVDC applications with rated voltages up to 550 kV. It is a document written with the vision of increasing the quality and reliability of a cable through the analysis of one of its main degradation phenomena. Another objective of this recommendation is to evaluate the impact of the aging process on the electric field behavior. Accordingly, it is suggested that space charge measurements must be made both before and after qualification tests by which the aging of the cable can be accelerated. Measurements can be made either on a single sample loop or on two separate loops but belonging to the same product. In the first case, after the first space charge measurement (unaged sample test), the measurement section is cut off and replaced with a joint. Then qualification tests are performed and finally the second space charge measurement (aged sample test) can be carried out. In the second case, the two loops are used for two separate measurements, one of which follows the qualification tests. Furthermore, in order to obtain cable behaviour similar to real operating conditions, measurements must be made with a heated sample. It is important to note that these tests are not designed to evaluate compliance with specific maximum limits for electric field or accumulated charge, but rather to observe their variations over time. A single PEA measurement performed on an unaged sample according to the procedure suggested by the recommendation is reported in this paper. Regarding the procedure, the authors of the recommendation suggest to proceed with the following steps:

1. *Cable heating:* by the circulation of a current (AC or DC) the conductor is brought to operating temperature. This phase continues until the cable has been subjected to a constant thermal gradient, equal to the designed value, for at least 24 hours.

2. *Positive volt-on test:* application of the rated voltage U_0, with positive polarity, by means of an HVDC generator. From the moment the applied voltage reaches the value U_0 the PEA measurement can be started ($t = 0h$).

3. *PEA Reference acquisition:* once the PEA measurement has been started, the reference signal is acquired. Through it the parameters of the processing phase will be calibrated.

4. *Acquisition phase:* a PEA profile is acquired every hour up to a total time of three hours. At the end of the third hour, the charge profiles are processed, and the electric field profiles are evaluated.

5. *Condition check:* once the field profiles have been obtained, the maximum absolute percentage variation between the field profile at $t = 0h$ and the field profile at $t = 3h$ is evaluated using the following relationship:

   $$\Delta E_{max}(0h, 3h) = max\left\{100 \cdot \left|\frac{E_{0h} - E_{3h}}{E_{0h}}\right|\right\} \tag{1}$$

   The electric field is considered stabilized if the following condition is satisfied:

   $$\Delta E_{max}(0h, 3h) \leq 10\% \tag{2}$$

   In this case, it is recommended to go directly to step 10. If the condition is not met, proceed to the next step.

6. *Acquisition phase:* proceed with a second series of PEA profile acquisitions every hour until a total time of six hours. At the end of the sixth hour, the charge profiles are processed, and the electric field profiles are evaluated.

7. *Condition check:* at the end of this second measurement interval, the maximum electric field variation between the field profile at $t = 3h$ and the field profile at $t = 6h$ is obtained again with the following relation:

   $$\Delta E_{max}(3h, 6h) = max\left\{100 \cdot \left|\frac{E_{3h} - E_{6h}}{E_{3h}}\right|\right\} \tag{3}$$

   The electric field is considered stabilized if the following condition is satisfied:

   $$\Delta E_{max}(3h, 6h) \leq 10\% \tag{4}$$

   In this case, it is recommended to go directly to step 10. If the condition is not met, proceed to the next step.

8. *Acquisition phase:* proceed with a third series of PEA profile acquisitions every hour until a total time of nine hours. At the end of the ninth hour, the charge profiles are processed, and the electric field profiles are evaluated.

9. *Condition check:* at the end of this third measurement interval, the maximum electric field variation between the field profile at $t = 6h$ and the field profile at $t = 9h$ is evaluated with the following relation:

   $$\Delta E_{max}(6h, 9h) = max\left\{100 \cdot \left|\frac{E_{6h} - E_{9h}}{E_{6h}}\right|\right\} \tag{5}$$

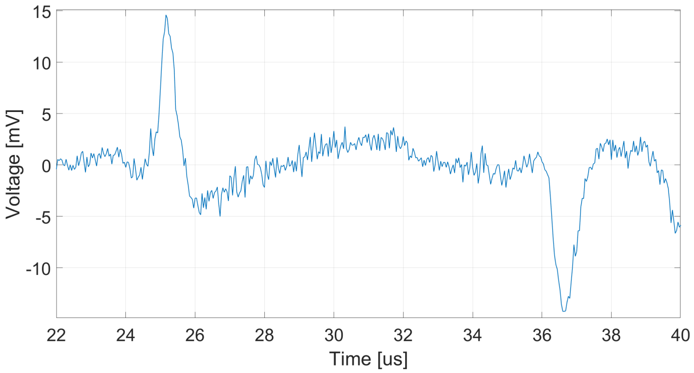

Fig. 4. Acquired reference signal for positive volt-on test.

The electric field is considered stabilized if the following condition is satisfied:

$$\Delta E_{max}(6h, 9h) \leq 10\% \tag{6}$$

Even if the condition is not met, proceed with step 10.

10. *Volt-off test:* after the volt-on test the applied voltage must be removed. The conductor and the metal screen of the cable must be short-circuited. From this moment the volt-off test starts in which a PEA profile is acquired every hour for the following three hours. In this phase no evaluation of percentage variation of the field must be carried out. The recommendation only requires acquiring and report the charge and field profiles over the three hours of volt-off.

11. *Rest period:* from the moment the positive volt-off test begins, a 24-hour phase is considered in which the conductor and the metal screen remain short-circuited.

12. *Negative volt-on test:* a voltage equal to the rated value but with negative polarity $(-U_0)$ is applied. For the subsequent steps, repeat what was done from step 3 to step 10.

The recommendation also requires considering the dielectric layer of the cable divided into three sectors of identical thickness (inner, central and outer). For engineering purposes, it is recommended to also report the maximum absolute percentage variations of the electric field in correspondence with the inner and outer sectors. These data allow for further evaluation after tests since the same ΔE_{max} has a different weight if it occurs on the inner part rather than the outer part. As stated above, the whole procedure must be applied in two different PEA measurements, before and after the qualification tests.

IV. RESULTS

This section reports the results of a PEA measurement carried out according to the procedure described in the IEEE std 1732. The sample under test is a full-size HVDC unaged cable with a rated voltage, U_0, of 525kV. The PEA setup has been assembled in the middle point of the cable, with a symmetrical position with respect to the cable terminations. The PEA cell used for signal detection has been made with a new plexiglass acoustic coupler. The software used for profile acquisition and processing have been developed independently within the research team. However, the profile processing phase is based on techniques found in the literature. For confidentiality reasons, the electric field profiles shown are expressed in per unit, using U_0 and the dielectric thickness as base quantities.

Fig. 4 shows the profile acquired by the oscilloscope and used as a reference during the positive volt-on test. Fig. 5 shows the result of the reference profile processing. The calibrated charge profile and the associated electric field and voltage distributions are shown. From the comparison, it can be seen how both profiles are superimposed on the expected theoretical trends, highlighted with dashed lines, confirming the processing's efficiency.

Fig. 6 shows the measured and processed charge density profiles for the time intervals over which the stability condition has been evaluated. Regarding the positive volt-on test, stabilisation of the electric field has been reached at the end of the ninth hour, with a ΔE_{max} value of 7.5%. Table I summarises the results obtained. A considerable variation in the electric field has been observed during the first three hours, in which a ΔE_{max} of 60.7% has been reached. This change occurred in the outer thickness of the dielectric. Field variations were smaller during the second three-hours interval, but not to the point of satisfying the stabilised field condition ($\Delta E_{max} = 12\%$). Fig. 7 shows the electric field profiles acquired at the end of the three measurement intervals with positive polarity voltage. In this case, an increase in the field has been observed in the dielectric outer region and a reduction in the dielectric inner region. In general, during the first measurement interval, the inversion of the field profile have been occurred. Having acquired a charge profile every hour, it was possible to observe

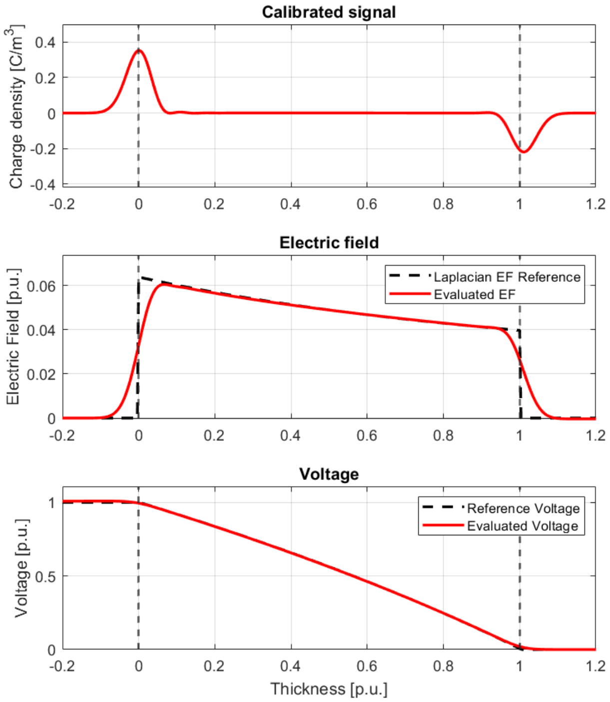

Fig. 5. Results of the processing of the reference acquired during the positive volt-on test.

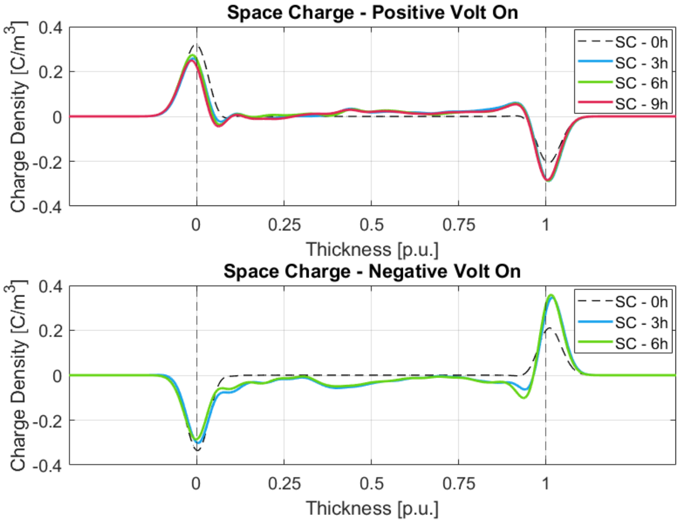

Fig. 6. Charge density profiles for positive and negative volt on test.

TABLE I
POSITIVE VOLT-ON RESULTS

Time Interval	Inner ΔE_{Max}	Outer ΔE_{Max}	ΔE_{Max}
0h - 3h	**30 %**	**60.7 %**	**60.7 %**
3h - 6h	**12 %**	**11.5 %**	**12 %**
6h - 9h	**7.5 %**	**7.4 %**	**7.5 %**

TABLE II
NEGATIVE VOLT-ON RESULTS

Time Interval	Inner ΔE_{Max}	Outer ΔE_{Max}	ΔE_{Max}
0h - 3h	**34.3 %**	**67.4 %**	**67.4 %**
3h - 6h	**7.4 %**	**7.8 %**	**7.8 %**
6h - 9h	**-**	**-**	**-**

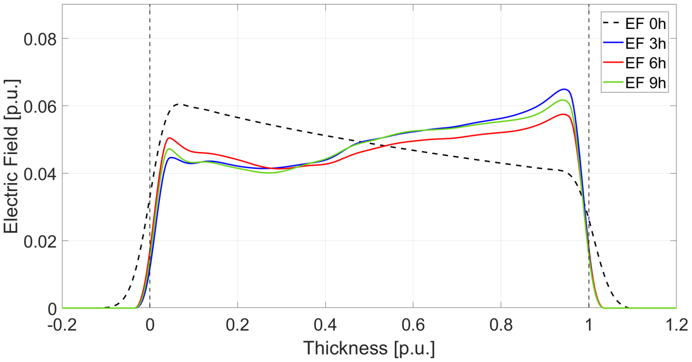

Fig. 7. Electric field profiles for positive volt-on test.

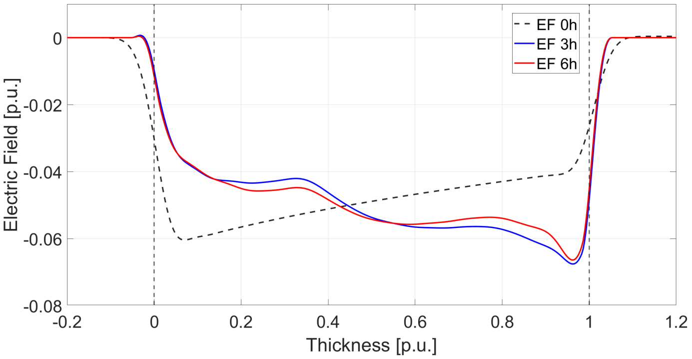

Fig. 8. Electric field profiles for negative volt-on test.

that the complete reversal of the electric field has been concentrated in the first hour and that in the following time the field undergoes continuous oscillations. In the negative volt-on test, the stabilisation of the electric field has been reached at the end of the sixth hour, with a ΔE_{max} value of 7.8%. Again, a considerable variation was observed in the dielectric outer region during the first three-hours interval ($\Delta E_{max} = 67.4\%$). The obtained results are shown in Table II.

Fig. 8 reports the profiles acquired at the end of the measurement with negative polarity voltage. Again, a process of reversal of the electric field from the initial trend has been observed. Finally, Fig. 9 shows the results obtained during the positive and negative volt-off test. These latter make it possible to assess how long these charges persist and whether they dissipate over time, providing insight into the conduction and trapping properties of the dielectric. In this case, at the end of three hours of both volt-off, residual charge has been observed.

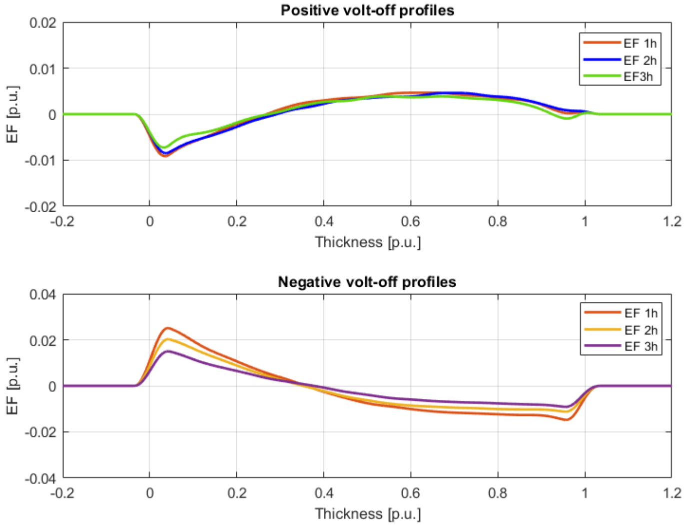

Fig. 9. Electric field profiles for positive and negative volt-off test.

V. DISCUSSION

The results, reported in the previous section, show that the reversal process of the electric field is concentrated in the first hour of the volt-on test. This results in a ΔE_{Max} value significantly higher than 10% both at the end of the first hour (0h-1h) and at the end of the three hours interval (0h-3h) as the inverted profile is always compared with a non-inverted profile. Therefore, it is reasonable to assume that the minimum duration of the volt-on test is six hours for both polarities. Considering also the three hours of volt-off, the duration of the test can be considered between a minimum of nine and a maximum of twelve hours. Taking into account the 24 hours of cable heating and 24 hours of rest period plus half a day to assemble the setup, the total measurement duration is approximately one week. This information is very important for a test laboratory because it is necessary to find the suitable time slot to schedule the measurement. Another aspect to consider is thermal condition. In field applications, there are no cases in which a current is present on the cable without there being an applied voltage. The application of considerable electrical stress under conditions of increased charge carrier mobility due to the presence of a thermal gradient could be the cause of this fast reversal of the electric field. In addition, the presence of background noise from electromagnetic or mechanical sources (vibrations), as well as possible fluctuations in the applied voltage, can influence the measurement results if the ΔE_{Max} calculation is based only on the profiles at the beginning and end of the three intervals. In future work, the results obtained will be compared with the average electric field variations calculated over the entire test interval, in order to assess their stability.

VI. CONCLUSIONS

This paper shows the results of a space charge measurement, performed with the PEA method, according to the guidelines provided by the IEEE 1732 recommendation. The test sample is a full-size HVDC unaged cable with a rated voltage of 525 kV. Based on the recommendation, two tests must be performed with positive and negative polarity. The aim is to evaluate the maximum absolute percentage variation of the electric field profile to establish after how long it reaches a stabilization condition (variation of less than 10%). Compliance with this requirement is checked at three-hour intervals. The results show that following the application of the voltage, the electric field undergoes an inversion process that, with both polarities, is completed within the first test hour. This allows to conclude that, due to the inversion, it is very unlikely to reach a maximum percentage variation of less than 10% in the first three hours of measurement. Therefore, it is believed that applying the IEEE 1732 recommendation necessitates performing at least six-hour volt-on test. Furthermore, the evaluation of ΔE_{max} based on profiles acquired at the beginning and end of the interval could make the results overly sensitive to external disturbances. These conclusions provide a basis for future work on the analysis of the robustness of the results obtained.

ACKNOWLEDGMENTS

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

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