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B1 Insulated Cables
P2 - Future Functionalities and Applications

Evaluation of the HVDC VSC cable system behavior in presence of transient voltage phenomena

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SUMMARY

The present research study was carried out to verify the effects of chopped transient over voltages, (chopped TOVs) on HVDC cable systems, for this reason a specific test set-up was implemented on a HVDC laboratory and chopped TOVs were applied on the same samples of two different cable systems rated Uo=320kV that previously meet and exceed respective PQ tests.

The cable systems were set to different temperatures and at each temperature the following sequence was applied:

1. At 70°C, 8 cycles, in each cycle 5 chopped TOVs, corresponding to 80 polarity reversals, this sequence covers all expected polarity reversals that could occur along the entire lifetime of a cable system.
2. At 70°C, 8 additional cycles, in each cycle 5 chopped TOVs, to verify cable system safety margin.
3. At 80°C, 8 additional cycles, in each cycle 5 chopped TOVs, for investigational purpose.
4. At 90°C, 3 additional cycles, in each cycle 5 chopped TOVs, for investigational purpose.

A total of 27 cycles equivalent to 27 faults, with 135 chopped TOVs and 270 polarity reversals were performed.

Before each cycle of 5 TOVs, two diagnostic measurements were performed (tangent delta and leakage current) in order to assess any sign of aging on the insulation of the cable systems.

At the end of the 27 cycles, the insulation of the two cables were laminated in tapes of 150 microns thickness and several breakdown tests were performed. The results were compared with insulation tapes of the same cables before and after PQ test.

This research study shows that both cable systems were able to fulfil severe tests sequence without experiencing any breakdown, furthermore the diagnostic measurements were not showing any sign of aging, which were also confirmed from the Weibull’s breakdown analysis that showed practically no variation on the insulation dielectric strength.

KEYWORDS

HVDC Cable system- Transient overvoltage- Ageing- Leakage current- Tang δ measurements.

1. INTRODUCTION

In the framework of HVDC extruded cable interconnections, the assessment of the effect of transient voltage phenomena on the cable system receives increasing attention from cable manufacturers and TSOs. In fact, the HVDC cable system shall demonstrate high reliability throughout its entire service life.

Various insulation coordination studies executed on HVDC VSC cable links have shown that voltage transitory events can occur in case of cable insulation failures. These constraints are not considered during the qualification tests, even though they could bring to accelerated ageing of the HVDC cable system [1], [2], [3], [4] and [5].

Transient simulations have been conducted for the France-Spain HVDC VSC symmetric monopolar underground cable link (project Baixas-Santa Llogaia, INELFE) [6], in case of pole-to-ground fault on the DC cable. [7]

The pole-to-ground fault on the DC cable can cause an instantaneous voltage increase on the unaffected pole at around 1,8 U0, when the travelling wave reaches the other converter which acts almost as an open end which persist even after the system has been disconnected from the a.c. networks by opening the corresponding circuit breakers. This overvoltage may be reduced by surge arresters and cleared by the circuit breaker after a certain delay. This overvoltage or TOV (very slow front temporary overvoltage) is now considered in the new TB852 (Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV) [8].

The faulty pole will experience transitory voltage oscillations around the zero value at the occurrence of the default and this transient voltage appear at the other side of the link. This type of transients (zero crossing damped temporary overvoltage) are also now considered by TB852 [8] but were not considered in existing TBs dealing with HVDC cable systems at the time of the development of the present research study.

The results of these simulations can be seen in figure 1.

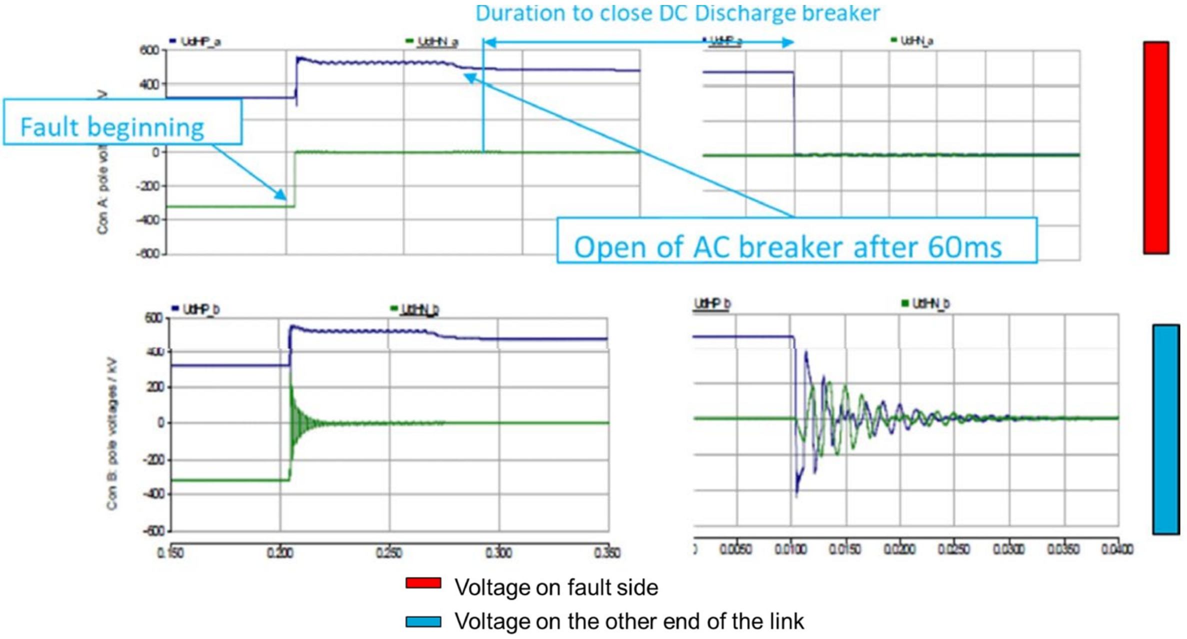


Figure 1. Results of EMTP simulations for a pole-to-ground fault on a HVDC monopolar symmetrical cable system. Voltages on the affected pole and on the unaffected pole [5]

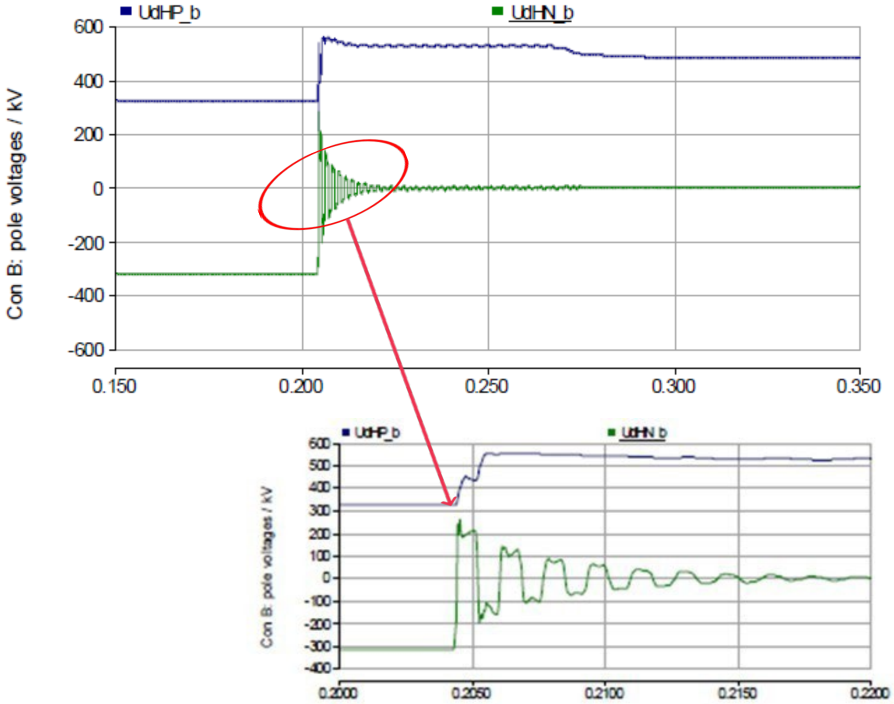


Figure 1. cont'd Results of EMTP simulations for a pole-to-ground fault on a HVDC monopolar symmetrical cable system. Voltages on the affected pole and on the unaffected pole [5]

The purpose of this research study was to reproduce these transient overvoltage phenomena in a high voltage laboratory, in order to study and test the behaviour of the cable and its accessories subjected to such repeated stresses. These tests were intended not only to demonstrate the quality and the robustness of the cable systems but also to monitor eventual ageing during the testing sequence. This has been achieved by performing tangent delta measurements on the different components of the loop, conductivity measurements on the entire loop and dielectric strength to breakdown Weibull analysis.

This paper is structured as follows, first a presentation of the test setup followed by a description of the protocol used for this test and the results obtained. It will end with a short discussion.

2. TEST SETUP

The cable system under test consists of two different HVDC XLPE cables rated for U0 = 320 kV (one with Aluminium and one with Copper conductor), two outdoor terminations and one pre-moulded straight joint that were previously subjected to a PQ test.[4]. The two cables were connected by means of a new pre-moulded joint.

The test equipment consists of an HVDC generator (Umax = 1000 kV and Imax = 20 mA) protected by a blocking resistance, an impulse generator (Umax = 2400 kV and Pmax = 240 kJ) protected by a sphere gap and a chopping device (multiple cut-off spark gap) connected in parallel to the test loop. Two heating transformers were used to heat the test loop and the dummy loop by means of current circulation in the conductor. Heating tapes have been placed above the outer sheath of the cables to minimize the different conductor temperatures due to the different conductor design, and to allow a more reliable temperature drop across the two cable insulations. The mentioned test setup allows to reproduce superimposed chopped impulses on the HVDC loop (figure 2).

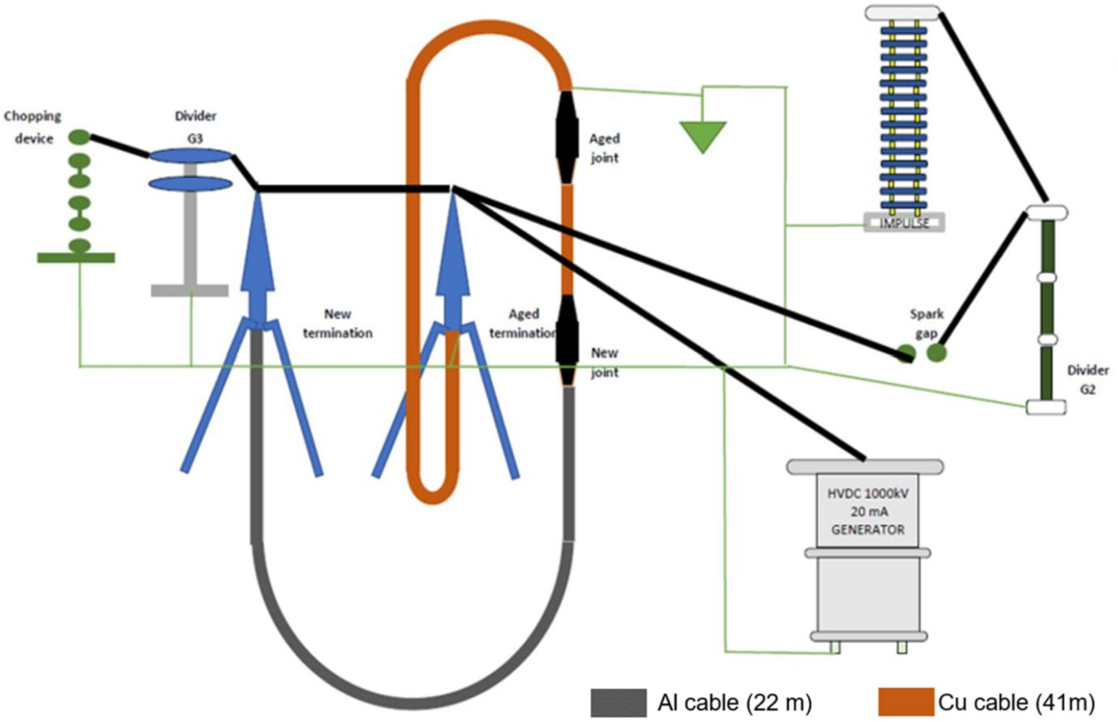


Figure 2. Test setup for the superimposed chopped impulses.

This research study was presenting important challenges. The first was to obtain a good thermal setup for the cables, allowing to heat the different conductors at the same temperature and to have the correct temperature drop across the insulation to reproduce the one existing on the cable at site. It was needed to properly fix the outer heating of the cable and place different heating insulators outside the two cables during the feasibility study. Then, the superimposed chopped impulse waveform was calibrated.

The multiple spark gap is the device that cuts the impulse voltage generated by the lightning impulse generator after 1 ms.

To measure the current flowing through the cable insulation, a micro-ammeter was introduced in series between the metal screen of the cable and the laboratory earth. Since the expected leakage current was very low (approximately a few tens of microamperes), it was very important to properly prepare the connections to avoid stray currents which could lead to incorrect measurements.

To protect the different measuring devices of the laboratory from damage, the measurement chain was using a digital radio link. Conductivity measurements were taken over the entire loop with and without terminations to eliminate the contribution of surface leakage currents that could exist on terminations at different atmospheric conditions.

3. TEST PROTOCOL AND EQUIPMENTS

Along the 40 years of expected lifetime of INELFE interconnection, 8 faults are expected to happen as per following assumptions:

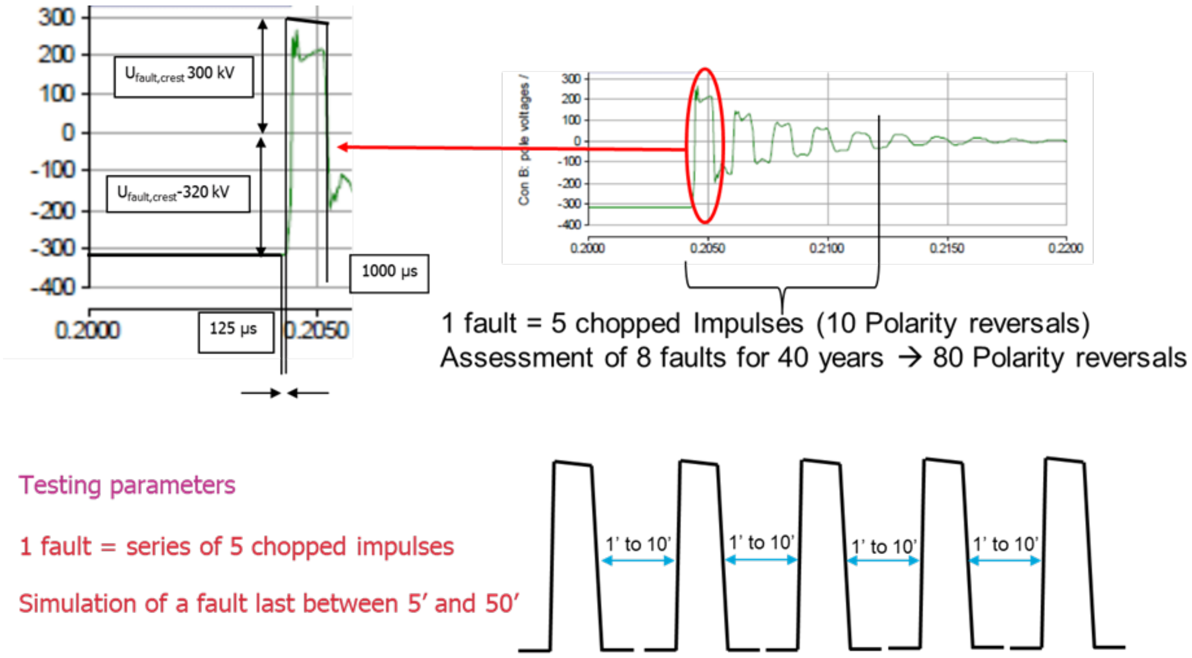
- 4 faults from cable system side on the basis of 0.1 fault/year/320 km of INELFE cable (CIGRE 379 of 2009 cable failure rate + joint + termination AC 220-500 kV [9]) i.e. and 4 faults/40 years/320 km of cable from France to Spain
- 4 faults on the converter station side.

Each fault will generate a transient phenomenon shown on the right part of figure 3, that is characterized by quick time to front and repeated polarity reversals:

1. For the first pulse, the voltage values go from - 320 kV to + 300 kV in a time interval of about 125 µs
2. follows a plateau of 1 ms
3. followed by a polarity inversion ranging from +300 kV to -200 kV. Then, we observe a decrease in the amplitudes of the voltages as a function of time.

These 3 parameters define the first transient overvoltage circled in red in figure 3, which contain 2 polarity reversals.

The authors proposed a conservative approach (not taking into account the damping effect of the following polarity reversals) and considered that the occurrence of a fault leads to the repetition of 5 times this first transient overvoltage, which is equivalent to a series of 5 chopped impulses (10 Polarity Reversals), (see figure 3). The time allowed between each chopped impulse was kept between 1 and 10 minutes.



1 fault = 5 chopped Impulses (10 Polarity reversals)
Assessment of 8 faults for 40 years → 80 Polarity reversals

Testing parameters

1 fault = series of 5 chopped impulses

Simulation of a fault last between 5′ and 50′

Figure 3. Voltage transient with polarity reversal imposed on the test loop which represents 1 fault, i.e. a series of 5 chopped impulses (10 polarity reversals)

One test cycle (equivalent to 1 fault) is defined as follows:

1. Measurement of capacitance and tan delta
2. Polarization of the cable system at -320 kV DC, for at least 10 hours
3. Measurement of the leakage current
4. Execution of 1 fault, it consists of a series of five superimposed chopped impulses with
    - first polarity reversal from U0 = -320 kV and Upeak = +300 kV,
    - plateau time of 1ms and
    - second polarity reversal from +300kV to -200kV.

The cable systems have been set to different temperatures and at each temperature the following sequence has been applied:

1. At 70°C, 8 cycles, in each cycle 5 chopped TOVs, corresponding to 80 polarity reversals, this sequence covers all expected polarity reversals that could occur along the entire life of a cable system.
2. At 70°C, 8 additional cycles, in each cycle 5 chopped TOVs, to verify cable system safety margin.
3. At 80°C, 8 additional cycles, in each cycle 5 chopped TOVs, for investigational purpose.
4. At 90°C, 3 additional cycles, in each cycle 5 chopped TOVs, for investigational purpose.

A total of 27 cycles equivalent to 27 faults, with 135 chopped TOVs and 270 polarity reversals were performed.

The transient voltage curve that has been obtained is shown in figure 4.

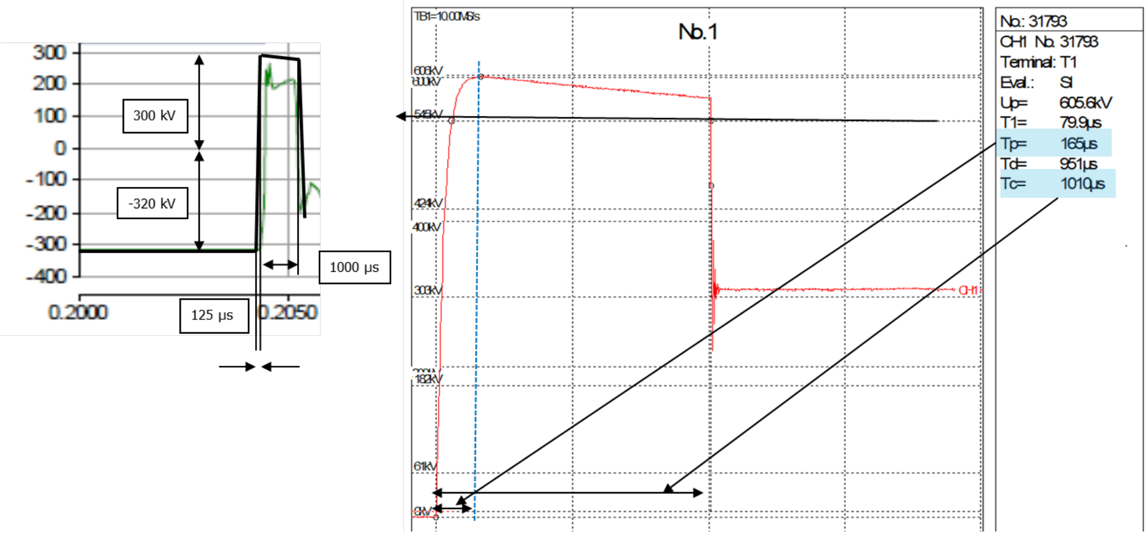


Figure 4. Example of chopped superimposed impulse waveshape with zoom on the high-frequency polarity reversals of the curve. On the left: example of voltage applied on the test loop.

The preparation of specific guard rings in the test loop was giving the possibility to execute the tangent delta measurement on the different parts of the system under test separately, and the tangent delta measurement was executed.

The measure of the leakage current was performed with a micro-ammeter in series between the cable screen and the laboratory earth, thus being able to measure a current in the range of some tens of micro Amps. The leakage current has been measured with steps of 50 kV on the applied voltage, up to 320 kV.

After all tests sequences and in order to perform a condition assessment of the cable insulations, insulation tapes between 145 and 155 microns thickness were prepared from the insulations of:

- Both reference cables before any test,
- Both cables having passed the PQ test
- Both cables having passed the PQ test and all 135 TOVs applied in this study.

Tapes were 35 mm wide and from 8 to 12 m long.

The tests were performed according to methods based on those described in the standards EN 60243-1 [10] and EN 60156 [11]. An automatic high accuracy Weibull test bench conceived according to IEC 60243 was used to perform the test.

The insulation tape to be tested was then inserted between the 30mm electrodes in silicon oil bath.AC Voltage was increased from zero Volts until breakdown occurs. The voltage increase was 500V/s in accordance with § 9-1-2 of the EN 60243-1 standard [10] (breakdown time of the sample between 10 and 20s).

In figure 5 it is possible to visualize the test bench.

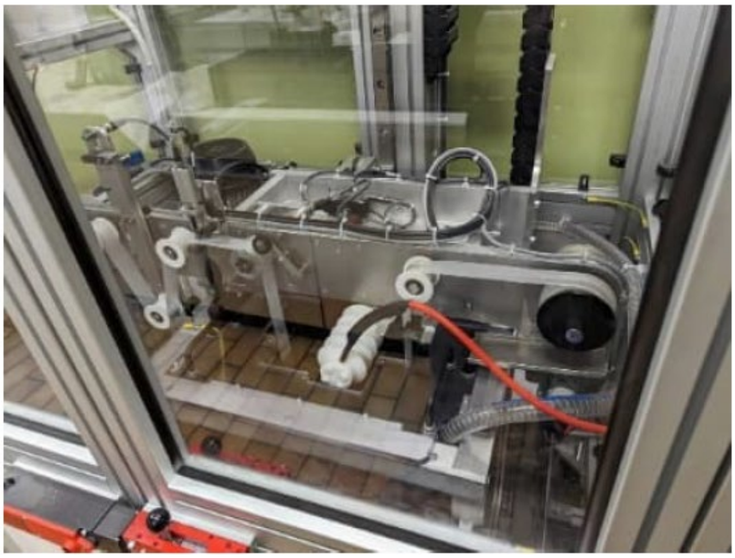


Figure 5. Test bench used to perform the Weibull's breakdown on insulation tapes samples.

4. RESULTS

The tangent delta measurement was performed on four different cable positions of the loop. Figure 6 shows the evolution of the tangent delta measurements along the three sequences of the test.

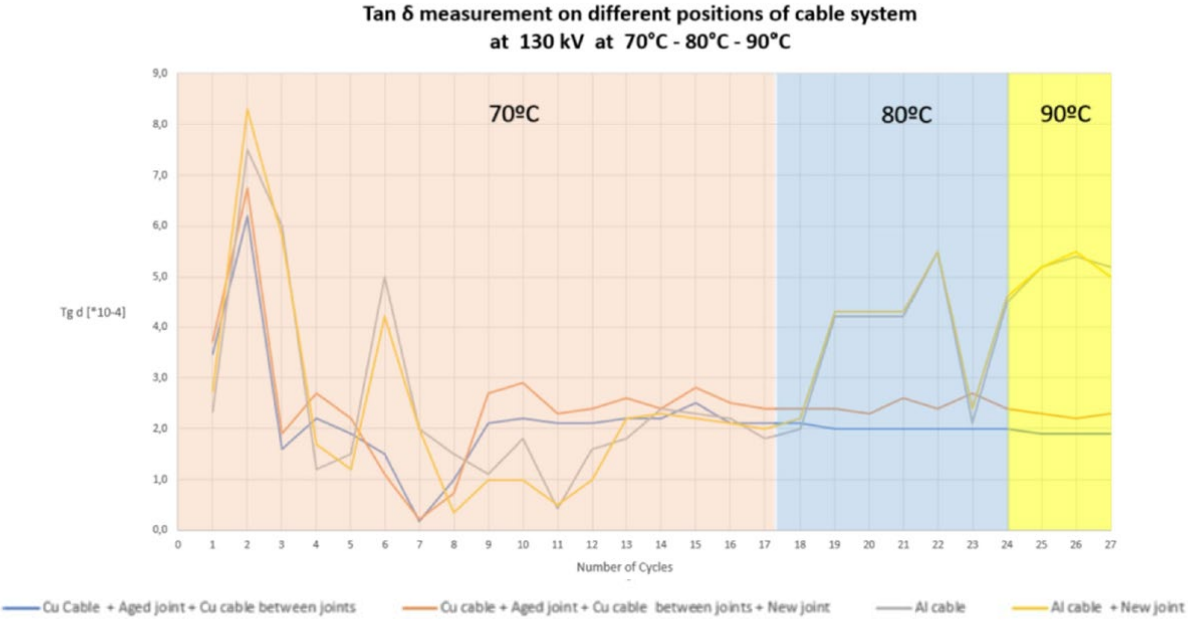


Figure 6. Evolution of the tangent delta measurement along the three-test sequences.

The measurements of the leakage currents have shown good stability along the cycles at different temperatures. The expected exponential behaviour of the leakage current as function of the applied voltage is noted starting from 150 kV and above. Below this voltage level the measured current is approximately a few micro amps and, as a hypothesis, the measuring device uncertainty strongly affects the result when the applied voltage is below 150 kV. In figure 7 it is possible to see the results of the leakage current measurements (one measurement at each temperature step), and in figure 8 its evolution along the test sequence at 70°C, 80°C and 90°C.

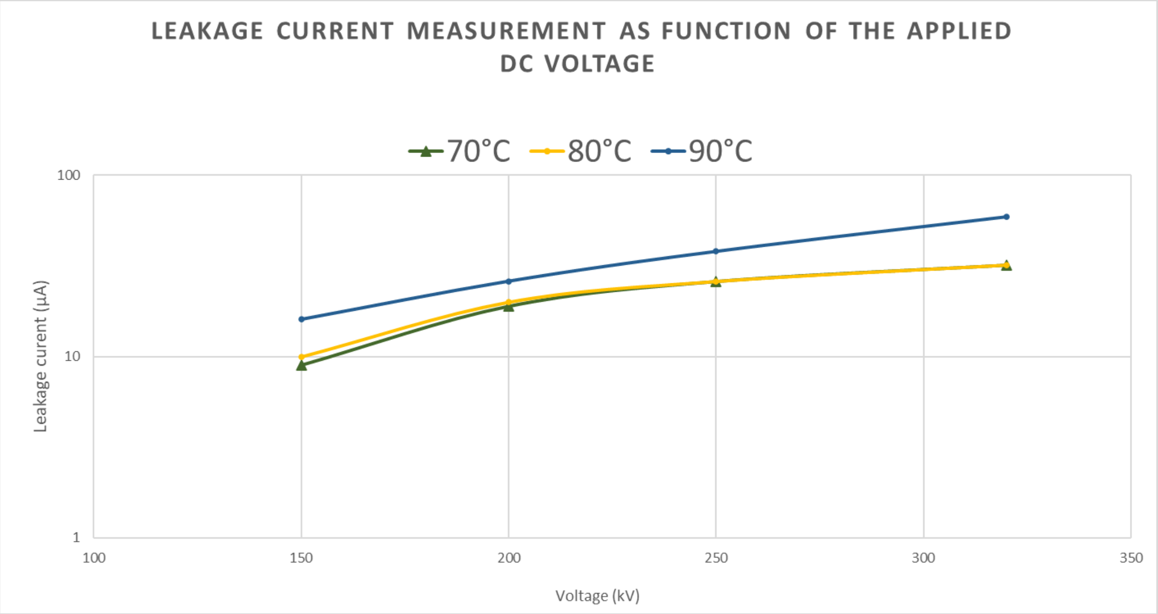


Figure 7. Measurement of the leakage current at the three temperature conductor values (logarithmic scale).

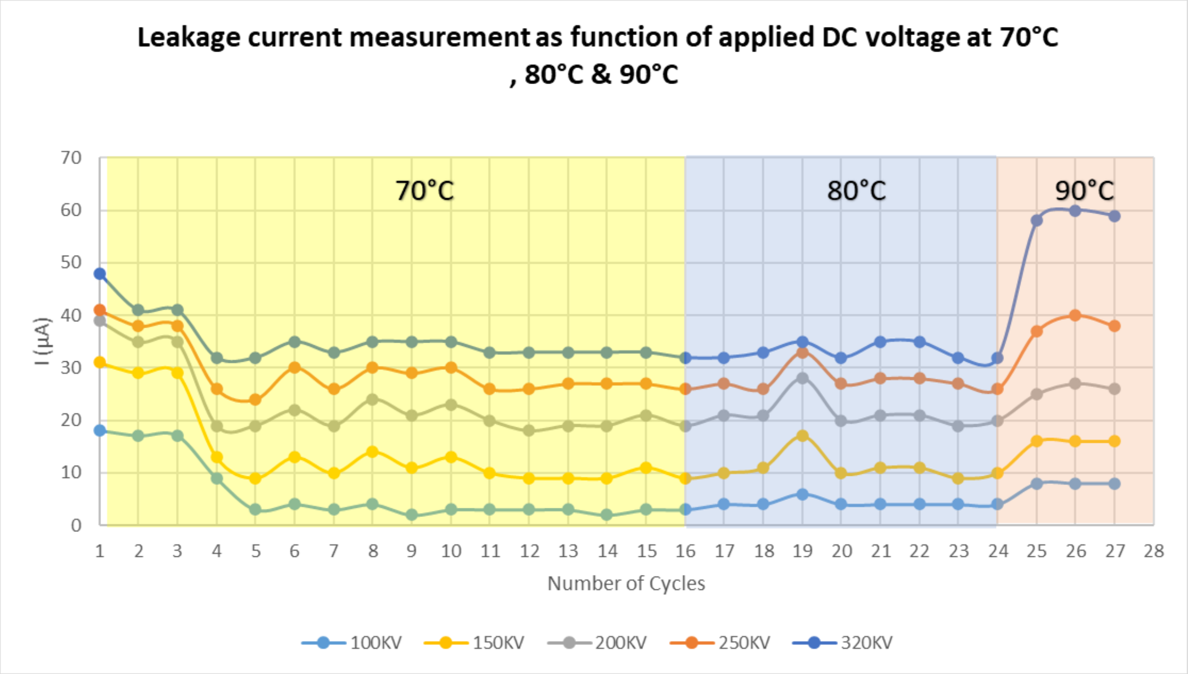


Figure 8. Evolution of the leakage current measurement along test sequence at 70 °C, 80°C and 90°C.

Table 1 summarizes the number of breakdowns obtained on Weibull's dielectric strength from the different tapes analyzed. IEC 60243 in section "Test methods for the determination of electric strength of solid insulating materials at power frequencies" [10] highlights the need to accumulate a minimum of 15 or above breakdowns for a type test. Thus, the sampling is proven to be high enough to provide accurate results as per the standard.

Table 1. Number of breakdowns performed on each insulation tape

Cable designation	New Cable	Cable after PQT	Cable after PQ and 135 TOVs
XLPE 2500 Cu	613	458	222
XLPE 2500 Al	458	111	24

For both types of cables, the Breakdown Strength of all samples were compiled in Figure 9 and Figure 10.

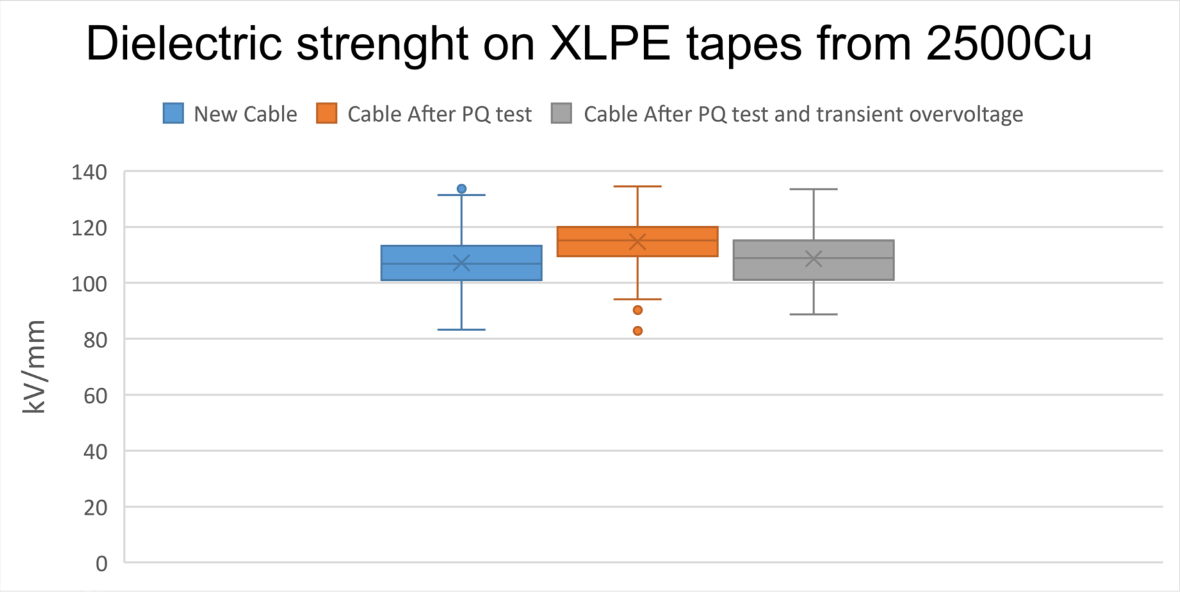


Figure 9. Breakdown strength in the copper cable insulation.

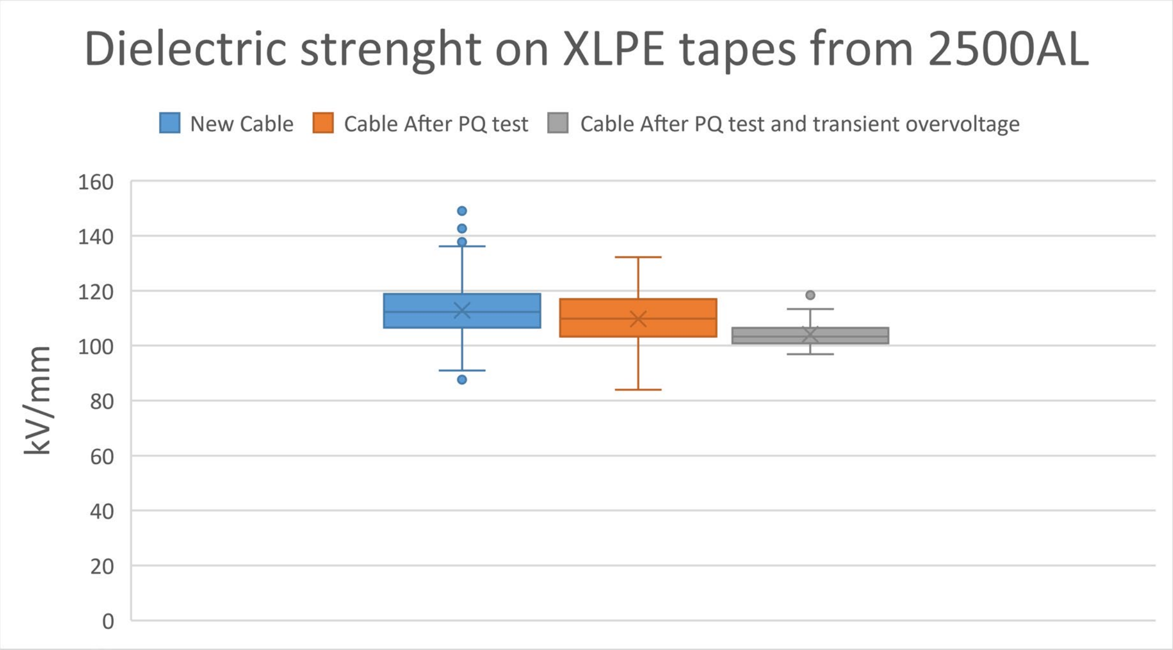


Figure 10. Breakdown strength in the aluminum cable insulation.

In the figures 9 and 10, first, second and third lines of rectangle represent first quartile (25% of the distribution), 50% of the distribution and 75% respectively, and dots represent outliers.

5. DISCUSSION

The transient overvoltage tests were successfully completed on the HVDC cable system, without having any breakdown along all test activity, showing capability of the two cable systems under test to withstand severe overvoltages and polarity reversal activity after its previous pre-qualification tests.
Comparing the Tan δ measurement for the 3 sequences we may conclude:

- The Cu cable system shows no variation on its Tan δ value after the different TOVs cycles at different conductor temperatures up to 90°C.
- Evolution of Tan δ in the Al Cable cannot be explained at this stage. More studies may be required for a complete understanding and to assess the influence of TOVs in the results obtained.

The evolution of the leakage current along the cycles does not show any sign of deterioration. The measurements stabilize at the three different conductor temperature steps.

The dielectric strength to breakdown performed on the insulations of reference cables, cables having passed PQ test and cables having passed PQ test and 135 TOVs with 270 polarity reversals, show slight decrease on the dielectric strength of aluminum cable, while no difference is detected on the Cu cable, but in any case the final dielectric strength value remains at a very high level, therefore the team believes it is proof that the cable systems under this test have been able to support all applied transient overvoltages without breaking down, and at the same time the remaining dielectric breakdown level of the insulation still shows and outstanding level that provides the system with a big safety operative margin.

6. CONCLUSION

Two HVDC cable systems were tested in the same loop, 135 chopped TOVs with 270 polarity reversals were applied at different conductor temperatures on the same cable system samples after successful completion of the respective PQ tests.

Superimposed chopped impulses on HVDC were applied aiming at verifying the system capability to withstand this particular waveform that also induces voltage polarity reversals. At the beginning of each testing cycle, tangent delta measurements and leakage current measurements were performed on the systems under test, in order to assess any possible ageing after the application of the superimposed chopped impulses.

A further verification of the insulation properties was performed assessing the dielectric strength with the Weibull's dielectric test bench.

Both cable system showed an overall positive response to the applied thermo mechanical and electrical stresses and no evident signs of ageing were detected.

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