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B1 INSULATED CABLE SYSTEMS
Future functionalities and applications

Performance and characterization tests on HPTE insulation material

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SUMMARY

High Performance Thermoplastic Elastomer (HPTE) is a cable insulating material suitable for both AC and DC applications. It provides HVDC systems with higher power transmission capability and reliability while decreasing the environmental impact. Thanks to its intrinsic characteristics, mainly linked to the thermoplastic nature of this polypropylene based insulation, in recent years HPTE cable systems were successfully type tested and pre-qualified at 90°C up to 600 kVdc and 525 kVdc, respectively. Three major HVDC projects have been awarded using this insulating technology, which is a perfect candidate to become the HVDC cable insulating material of the future.
In this paper a new set of tests is described to further characterize HPTE and its performances, including Temporary Overvoltage (TOV) tests and materials tests. The novelty of the tests requires specifically developed test loop assemblies, which are described.

KEYWORDS

HVDC, VSC, TOV, transient, overvoltage, extruded cables, HPTE, insulation, tests

INTRODUCTION

HVDC cable systems are used worldwide to transmit high power over long distances in situations where HVAC connections are not feasible or not economically convenient.
High Performance Thermoplastic Elastomer (HPTE) is a cable insulating material suitable for both AC and DC applications. It provides HVDC systems with higher power transmission capability and reliability while decreasing the environmental impact. Thanks to its intrinsic characteristics, mainly linked to the thermoplastic nature of this polypropylene based insulation, in recent years HPTE cable systems were successfully type tested and pre-qualified at 90°C up to 600 kVdc and 525 kVdc, respectively.
The two main types of HVDC converters are the Line Commutated Converter (LCC) and the Voltage Source Converter (VSC).
During the past decade, VSC gained a significant share of the HVDC market due to many technical and economic advantages such as smaller required footprint of converter stations, operational flexibility and independent control of active and reactive power [1][2]. The introduction of VSC boosted the installation of HVDC cables with extruded insulation, since VSC technology enables reversal of power flow direction without voltage polarity reversal.
VSC systems mainly comes into two different types of configurations: symmetrical monopolar (which is the more used scheme) and rigid bipolar. Both configurations yield Temporary Over Voltages (TOVs) typically occurring as a consequence of faults and can be mainly of two types: one, with same polarity, occurs on the healthy pole and the other, with oscillating polarity reversals, occurs on the faulty cable. Same polarity overvoltages are significantly reduced in rigid bipolar configuration while discharge voltage transients with polarity reversals are almost independent of the selected scheme [4].
The voltage shapes of the two TOVs differ considerably if compared to standard lightning and switching impulses and therefore require dedicated test setups.
In 2021 standardized voltage shapes and test methods were proposed in CIGRE Technical Brochure 852 [5] to assess the TOV impact on extruded cable systems, based on the work done by CIGRE B4/B1/C4.73.
Works have been recently published providing test evidence of outstanding HPTE performances under voltage polarity reversals [6]. This is well known to be one of the most severe insulation stresses, as the electrical field polarity is reversed while the cable is still polarised. Even if the use of polarity reversals is limited to Line Commutated Converters (LCCs), which are being less used in favour of Voltage Source Converters (VSCs), it shows HPTE robustness towards overvoltages which have always been deemed critical for extruded cable systems, which are more prone to space charge accumulation than traditional mass impregnated cables. This can be a key advantage for system operations, especially when dealing with new types of temporary overvoltages (TOVs) which are frequently related to VSC applications.
An extruded insulation system capable to withstand polarity reversals is clearly also well suited to withstand such TOVs. HPTE – a polypropylene-based High-Performance Thermoplastic Elastomer – is a technology platform developed with the aim to combine the best dielectric characteristics of materials with thermomechanical performances, production needs and environmental care.
The next paragraph will so provide an overview of HPTE characteristics and an update about on-going experience with its applications.
The third paragraph describes TOV tests methods to be applied to HVDC cables.
In the fourth chapter new material tests are proposed to properly assess the characteristics and quality of HPTE material and of new extruded materials for HVDC in general; part of these tests is already included in CIGRE Technical Brochure 852 [5].

HPTE TECHNOLOGY AND PROJECT EXPERIENCES

The opportunity to develop an insulation technology for MV and HV cables alternative to the well-known and experienced materials like XLPE and HEPR has driven cable manufacturers to investigate in the early 2000s the use of Polypropylene, a polyolephin formerly considered not adequate to provide the requested properties of a high performance electrical insulation for cables. Through the selection of a special polymer blend and the application of an advanced production process, it was possible to overcome the challenges and to finalize the development of the new insulation type, called HPTE (High Performance Thermolastic Elastomer). The selected formulations turned polypropylene into a versatile and high-performance insulating material for power cables [7][8][9][10], both in terms of physic-chemical properties and electrical characteristics.

One important characteristic of HPTE technology is that it doesn't require cross-linking or other chemical reactions to achieve the properties needed for long term electrical integrity of HVDC insulation systems. The lack of cross-linking and consequent absence of scorch phenomena make it also suitable to very fine filtration during the insulation phase, just upstream the extrusion crosshead. Absence of cross-linking gives also the not negligible benefit to avoid by-products, making this the most simple and effective solution against the problem of space charge traps created by the by-products themselves, as proved by HPTE performances under high electrical gradient at high temperature. In fact, the new insulation allows to achieve superior thermo- mechanical properties for the cable at temperature significantly higher than other crosslinked materials; the high melting temperature of HPTE insulation opens the possibility to increase the actual temperature limitations of DC cables up to 90°C.

HPTE technology has also a very efficient manufacturing process, characterized by lower power consumption, with energetic benefits. The absence of any degassing treatments avoids emissions in the atmosphere, with a lower environmental impact of the whole process. Full recyclability of polymeric materials is a valuable property of this technology, with benefits in terms of low carbon footprint. Besides recovering metals such as in other HV cables, also all the polymeric layers of these cables can be fully recycled.

High Performance Thermoplastic Elastomer (HPTE) is a cable insulating material suitable for both AC and DC applications. It provides higher an HVDC systems power transmission capability and reliability while decreasing the environmental impact. Thanks to its intrinsic characteristics, mainly linked to the thermoplastic nature of the polypropylene based insulation, in recent years HPTE cable systems were successfully tested at 320 kV, 350 kV, 525kV and 600 kV DC voltage levels and always at high conductor temperature (90°C). HPTE insulated cables have been meanwhile successfully pre-qualified at 525kV in accordance with TB 496 and Customer specific testing requirements.
HPTE cables are already being used in several HVDC projects under construction, all of which using VSC converters in different configurations (symmetrical monopole and rigid bipole, see Figure 1). The following three major HVDC projects have been awarded using this insulating technology.

A-Nord

HPTE copper cables will be used in A-Nord project, which includes two ±525 kV HPTE poles and a separate insulated metallic return cable. The route, with a total length of around 300 km, runs from Emden in Lower Saxony to Osterath in Nordrhein-Westfalen.

SuedOst Link

HPTE copper cables will also be used in SuedOst Link, a ±525 kV underground cable system which will transmit power in excess of 2GW on a single system for the first time. The route, with a length of over 250 km, starts at the Southern Germany connection point at Isar, close to Landshut in Bavaria. HPTE cables will have optimised long delivery lengths, extending beyond 2 km.

SOFIA

HPTE very large aluminium cross section cables will be used in the land part of SOFIA export cable system. SOFIA is the largest windfarm under construction at the time of writing, which will operate a symmetrical monopole system connecting the offshore converter station with the onshore one. The project involves more than 440 km of ±320 kV submarine export cables with XLPE insulation and 15 km of ±320 kV land cables with HPTE insulation.

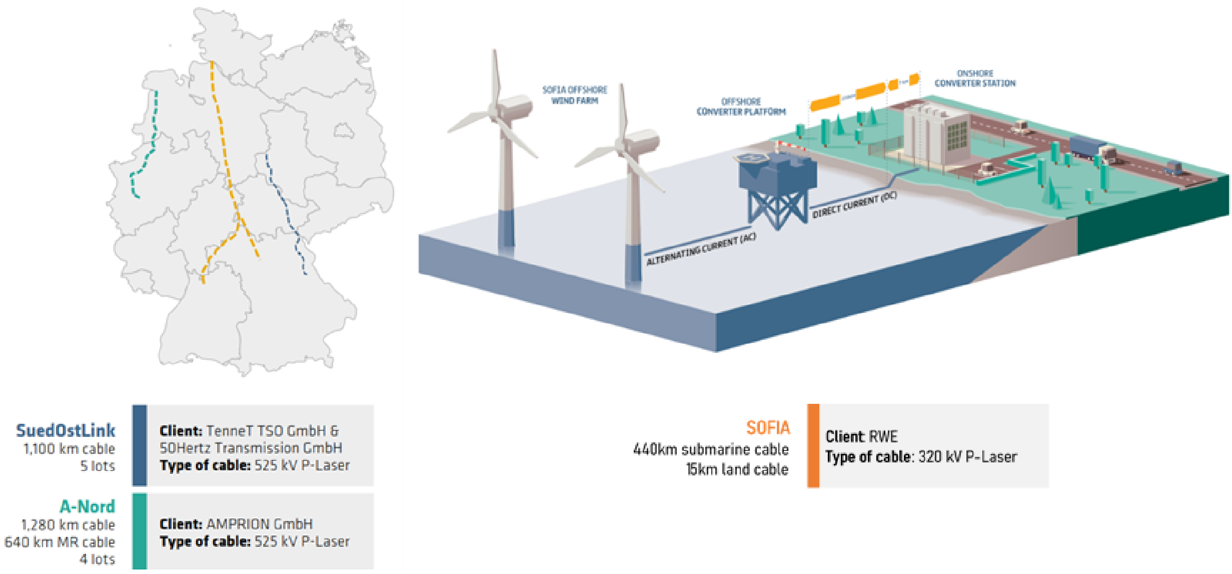

Figure 1 Visual representation of A-Nord, SuedOstLink and SOFIA HVDC projects

TEMPORARY OVER VOLTAGES

According to the work of CIGRE JWG B4/B1/C4.73 [11], two more overvoltages can be experienced on HVDC and EHVDC cable systems on top of conventional lightning and switching impulses: very slow front overvoltages with same polarity to actual DC voltage and oscillating voltage transient with opposite polarity peaks to actual DC voltage. To this day tests on full-size cable systems have been performed on XLPE insulation, tests on HVDC ±525 kV HPTE cable systems are planned for Q1-Q2 2022. The aim of the experiments described in this section was to test aged DC cable systems against TOV waveshapes, that reproduce the typical situation affecting balanced DC transmission systems when a fault occurs on one pole. With reference to Figure 4, this waveshape is experimented by the healthy pole, subjected to a steep increase of voltage that is slowly damped. Figure 6 shows an example of zero crossing damped temporary overvoltage occurring along the faulty cable during the cable discharge process. Parameters definition for both very slow and zero crossing damped TOVs is under discussion and different requests on values to be achieved during tests have been received. A summary of parameters and values is reported in Table 1.

Table 1 Main parameters for very slow and zero crossing damped TOVs

Very slow front TOV			**Zero crossing damped TOV**		
U_1	Peak voltage	$1.6U_0$ - $2.5\ U_0$	f_{LF}	Oscillation frequency LF	<400 Hz
U_2	Plateau voltage	90% U1	f_{HF}	Oscillation frequency HF	>5000 Hz
$t_1 - t_0$	Time to peak	60 us - 10 ms	U_{f1LF}	First peak amplitude	>90% U0
$t_2 - t_1$	Plateau time	30 ms - 150 ms	U_{f1HF}	First peak amplitude	>50% U0
$t_3 - t_2$	Cable discharging time	>10 ms	N_{HF}	Number of oscillations	>14
Second tail discharge: to ground or to U_0			N_{LF}	Number of oscillations	>15

VERY SLOW FRONT TOV TEST LOOP AND EXPERIMENTAL RESULTS

The very slow front TOV test loop adopted for tests on full-size ±320 kV XLPE cable system is shown in Figure 2 and Figure 3. It is characterized by: the cable system (test object) pre-polarized by an HVDC source (B), an Impulse Generator (C) charged by an external HVDC source (A), a front resistor to regulate $t_1 - t_0$, two triggered gaps SG1 (D) and SG2 (E), a voltage divider to measure the waveform, a discharging resistor to speed up the voltage decrease when, at the end of each voltage level test, pre-polarization needs to be removed.

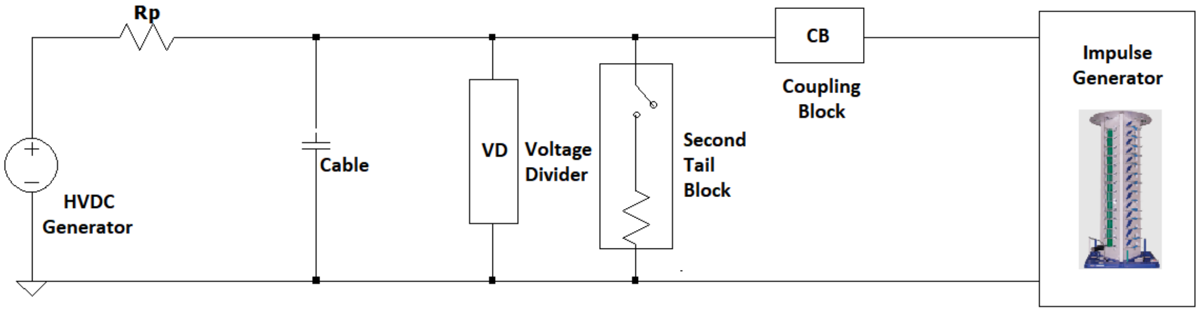

Figure 2 Very slow front TOV test loop scheme

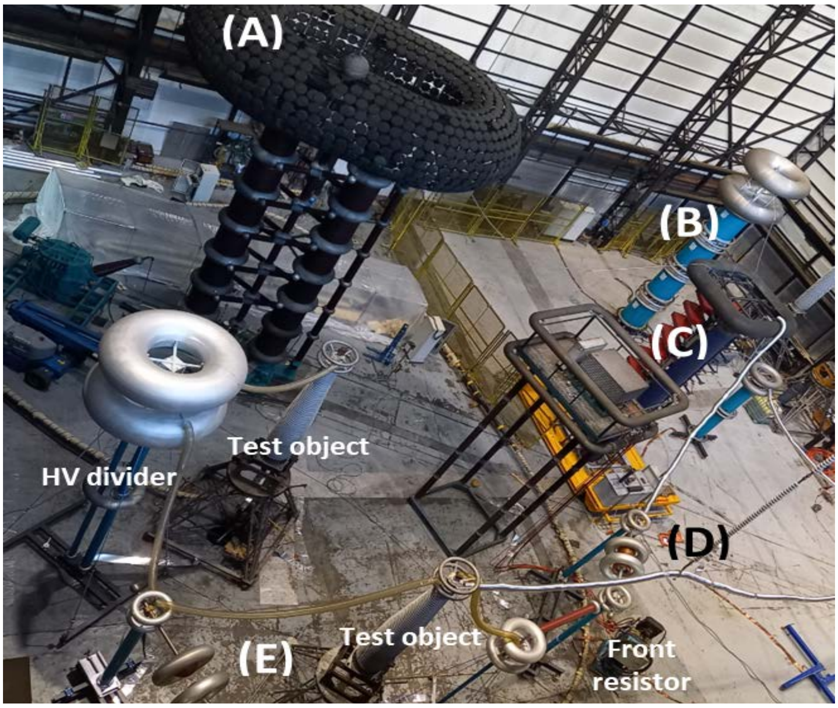

Figure 3 Very slow front TOV ±320 kV XLPE cable system test loop

As stated above an HVDC ±320 kV cable system joints and outdoor terminations, previously subjected to thermal cycles, has been tested for very slow front TOV impulses. Superimposed impulses with same polarity (negative and positive) have been applied to the system starting from 640 kV, increasing the voltage by 50 kV each step. The test was stopped at U1 = 800 kV since the testing equipment limit was achieved. For each step 5 impulses of both polarities were applied. These tests showed that the cable, previously subjected to thermal cycles, is able to withstand TOVs up to at least an in-field withstand level of the 480 kV (corresponding to a laboratory voltage of 800 kV). An example of very slow front TOV achieved during the tests is shown in Figure 4.

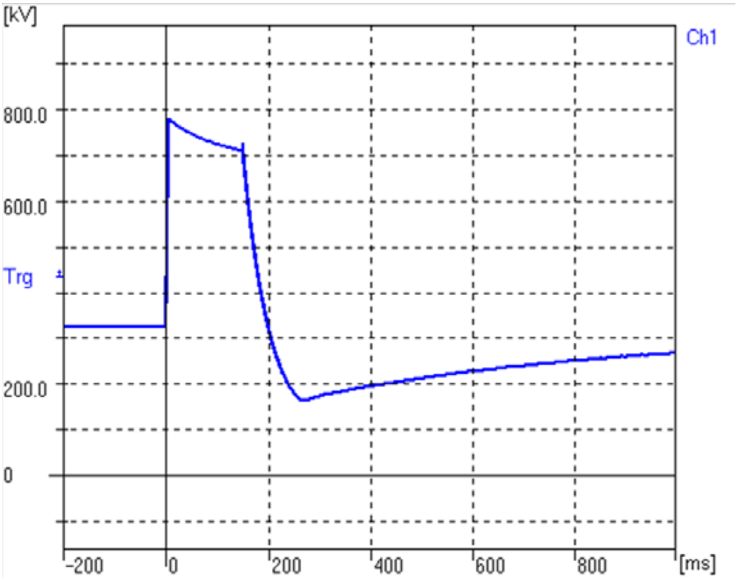

Figure 4 Example of very slow front temporary overvoltage applied to a HVDC ±320 kV cable system with one sectionalized pre-moulded joint, one straight pre-moulded joint and two outdoor terminations.

ZERO-CROSSING DAMPED TOV TEST LOOP AND EXPERIMENTAL RESULTS

The zero-crossing damped TOV test can be described as an oscillating discharge of a pre-charged capacitor. Achieving this waveform in laboratory is easier than very slow TOV since less components are required. The scheme of the loop adopted for the test is shown in Figure 5. It is characterized by the cable system (test object) pre-polarized by an HVDC source, a voltage divider to record the waveform, an inductor (with two different values for low and high frequency respectively), a damping resistor; a suitable circuit-breaker to avoid the problem of sphere gap self-extinguishing arc during zero-crossings.
Experiments have been performed on a 12 nF ideal capacitor up to 600 kV with excellent results. An example of the waveform achieved is shown in Figure 6.

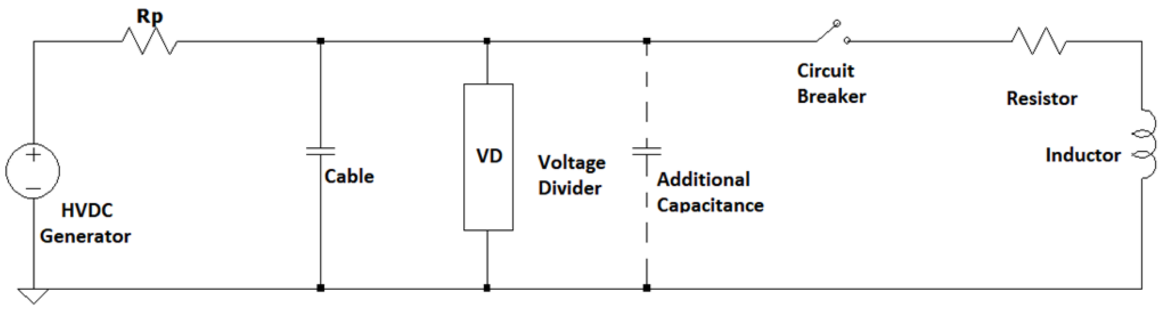

Figure 5 Zero crossing damped TOV test loop scheme

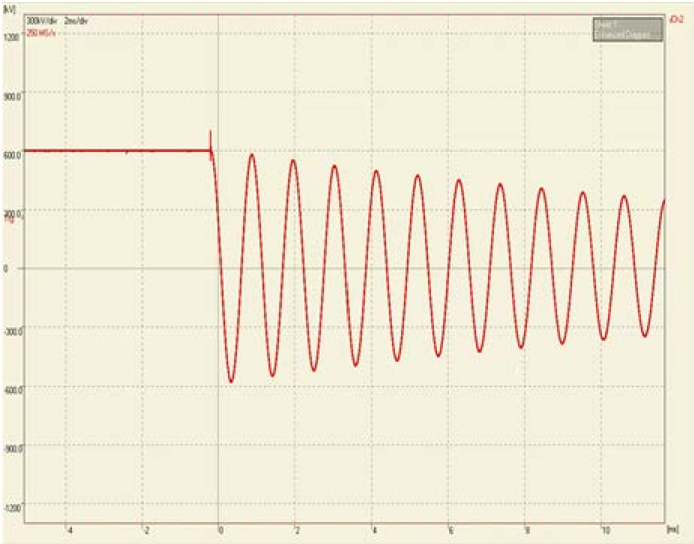

Figure 6 Example of zero crossing damped temporary overvoltage applied to an ideal capacitor of C = 12 nF.

NEW MATERIAL TESTS PERFORMED ON CABLE SYSTEMS WITH HTPE INSULATION

To guarantee a stable quality of the materials supplied, a specific Quality Plan was prepared, applied to TT prototypes and pilot productions and implemented during the execution of the different projects employing HPTE. One of the focal points of this plan was to address the new types of material tests to be performed on HPTE.
The HPTE insulation is not crosslinked and so Hot Set tests and TGA are not applicable and/or relevant. The following non-electrical tests are recommended to be carried out as part of the quality controls on manufactured HPTE cables.

1. Fourier Transform Infrared Spectroscopy (FTIR) analysis

Using a FTIR instrument it is possible to obtain a fingerprint of the chemical bounds present in HPTE material. No samples preparation is required since the sample is place on the ATR crystal and a force is applied to obtain a good contact between the sample and the crystal (see Figure 7).
An example of FTIR test is provided in Figure 8 showing 3 peaks between 3000cm^{-1} and 2750cm^{-1} and 2 peaks between 1500cm^{-1} e 1250cm^{-1}.
This test has been included as fingerprint test in CIGRE Technical Brochure 852 [5].

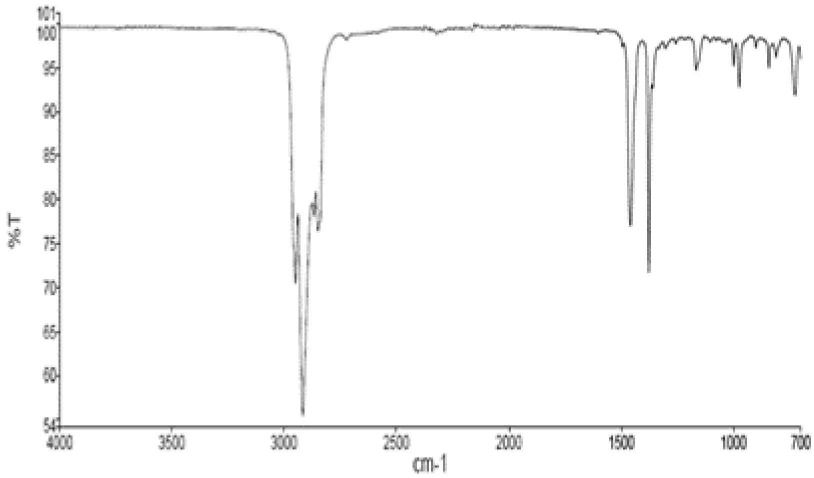

Figure 8 Example of HPTE FTIR test plot

2. Differential Scanning Calorimetry (DSC) analysis

Another way to obtain a fingerprint of the chemical bounds present in HPTE material is to perform a DSC analysis. As an example, the test on HPTE material was carried out in accordance with EN 61074, where a sample is heated with a rate of 10°C/m and two scanning cycles are executed. The results recorded during the second heating are:

- Melting temperature: 160°C
- Melting heat: 24.5 J/g

However, the sensitivity of this test to the process parameters is low and therefore it was discarded as fingerprint test in CIGRE Technical Brochure 852 [5].

3. Thermopressure test

To provide information related to the functionally of the cable system and applicable to all the new HVDC compounds, a new test method has been defined with the aim to reproduce the thermo-mechanical conditions to which the cable will undergo during its operating life .
The test can be performed from 90°C up to 130°C, with a load corresponding to 0.3 bar.
Test is based on UL1581 [12] and it is performed on flat samples (10x20x1 mm) realized from plate or, better, directly from a cable. The presser foot has a flat, round face with a diameter of 6.4±0.2mm. Test is performed at different time with load applied 1h + 1h for thermal conditioning.
Thermo-pressure deformation is measured with the following formula:

$$D_{\%} = 100 \cdot \frac{T_1 - T_2}{T_1}$$

where:

$D_{\%}$ is the deformation in percentage
T_1 is the original thickness
T_2 is thickness measured at the end of the test

.

Figure 9 Example of deformation test apparatus with specimens in place

Maximum deformation should be < 50% as required in the recently published CIGRE Technical Brochure 852 Appendix G.6 [5] which recommends this test to be performed as part of type and sample tests. It is applicable to thermoplastic insulation materials, but it is also a good method to test thermosetting insulations as it represents the calculated clamping pressure and the pressure developed by the joints and terminations. The thermopressure test results on different insulation materials are here presented in Table 2 for comparison purposes at 90°C and 100°C. It results that HPTE behaves equally or better than Low Cross-Linked Polyethylene (LXLPE), especially at increased operating temperature.

Table 2 Percentage deformation after thermopressure test for different extruded insulation materials

	HPTE	**XLPE**	**LXLPE**
90°C	2.0	2.6	1.9
100°C	3.0	4.1	2.6

CONCLUSIONS

The big demand for transmission of high electrical power over long distances has fostered the fast and successful development in the recent years of HVDC Transmission Systems at increasing current and voltage levels, pushing the evolution of both traditional and new technologies and materials. The recent development demonstrated the suitability of ±525 kV HTPE DC cables to withstand the stressful overvoltages induced by both VSC and LCC systems. As HPTE is a thermoplastic material, new material tests had to be developed and reference values to be measured: part of these tests are now included in CIGRE Technical Brochure 852 as part of the testing protocol for thermoplastic insulation materials.

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