High Voltage

REVIEW OPEN ACCESS

HVDC Cable System Testing

Giovanni Mazzanti

Department of Electrical, Electronic and Information Engineering, University of Bologna, Bologna, Italy

Correspondence: Giovanni Mazzanti (giovanni.mazzanti@unibo.it)

Received: 20 March 2025 | **Revised:** 27 May 2025 | **Accepted:** 3 June 2025

Associate Editor: Jin Li

ABSTRACT

This paper reviews the existing testing techniques for high voltage direct current (HVDC) cable systems, following as a backbone the structure of CIGRE Technical Brochure (TB) 852:2021 'Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 800 kV' because it has a fairly similar structure to CIGRE TB 853:2021 for lapped DC cables, and especially because of the impressive spread of HVDC extruded cables experienced worldwide in the last 25 years. The review considers development tests, pre-qualification tests, extension of qualification test, type tests (with hints at IEEE 1732-2017 for space charge measurements in the qualification of HVDC extruded cables), routine tests (with hints at IEEE 2862-2020 for routine tests of HVDC extruded cable system joints), sample tests and after installation tests. The review also analyses CIGRE TB 853 for lapped HVDC cable systems, as these cables remain unbeaten for submarine applications at the highest sea depths. The main novelties of CIGRE TB 852 and 853 with respect to previous standards for HVDC cable systems (mainly CIGRE TB 496 and IEC 62895 for extruded cables and CIGRE Electra 189:2000 for lapped cables) are put under the spotlight—with focus on the so-called temporary over-voltage tests—together with the limits and gaps of CIGRE TB 852. The main HVDC cable system testing equipment that is usually employed for electro-thermal tests is also treated. Emphasis is given to CIGRE TB 490 to treat the peculiarities of submarine cable systems, as well as to mechanical tests, having CIGRE TB 623 as a reference, with particular focus on the special sea trial tests. An example of an innovative sea trial testing procedure is shown, which is the outcome of a fruitful partnership between a cable manufacturer and the national Transmission System Operator in Italy.

1 | Introduction

High voltage direct current (HVDC) cable lines are impressively spreading worldwide, as they are often the best—or the only—way to integrate massive renewables from remote regions (oceans, deserts, mountains) into the grid to connect faraway islands to the mainland or to link different grids for providing cheap and reliable energy. Self-contained oil filled (SCOF) and mass-impregnated (MI)—also referred to as mass-impregnated nondraining (MIND)—cables, available for voltage levels up to about 600 kV, ruled the HVDC cable system market until the new millennium [1]. Later on, the novel voltage source converters (VSC), allowing power flow reversal at a given DC voltage polarity, and many successful scientific-technological developments have enabled a steadily broader use of HVDC extruded cables—mainly with cross-linked polyethylene (XLPE) insulation—at higher voltages and powers, thereby improving economics, logistics, accessory installation and transmission capacity due to higher maximum conductor temperatures [1–3]. Noteworthy examples of this trend are the following:

1. the ± 400 kV-DC/1 GW submarine Nemo Link with filled DC-XLPE insulation, commissioned in 2019 [4];
2. the three ± 525 kV-DC/2 GW land German Corridors [5], with different types of insulation selected for different parts of the corridors, namely filled DC-XLPE insulation,

---

https://doi.org/10.1049/hve2.70121

unfilled DC-XLPE insulation and novel polypropylene (PP)-based thermoplastic insulation [6];

3. the ± 525 kV-DC/1 GW submarine Adriatic Link in Italy, with unfilled DC-XLPE insulation in the submarine sections and novel PP-based thermoplastic insulation in the land sections [7].

The progress over the years of HVDC cable systems to attain such very high voltage and power ratings has also been made possible by thorough testing procedures to assess the performance of innovative designs, materials, manufacturing techniques of cable system components, that is, cables, joints, terminations, grounding connection etc. Testing procedures and techniques have evolved over time and are included in reference standards and recommendations issued by international bodies—mainly CIGRE and IEC—and periodically checked and reviewed for updating testing methods to state-of-the-art testing techniques.

Focusing on HVDC extruded cables because of their impressive spread worldwide hinted at above, the main standard documents in the technical-scientific literature that were explicitly devised for HVDC extruded cable system testing and are either still valid or still have effects on major ongoing HVDC cable projects are the following:

1. CIGRE Technical Brochure (TB) 852:2021, entitled 'Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 800 kV', issued in 2021 by CIGRE Working Group (WG) B1.62 [8];
2. former CIGRE TB 496:2012 (TB 496), entitled 'Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV', issued in 2012 by CIGRE WG 21.01 [9]. It was superseded by TB 852, but as a matter of fact many existing HVDC extruded cable systems in service to date were qualified from 2012 to 2021 according to TB 496. Among these existing cable systems qualified according to TB 496, let us cite the above mentioned 400 kV-DC Nemo Link—in fact the HVDC extruded cable system that is in service with the highest rated voltage at present [4]. Hence, TB 496 remains an important reference—also because TB 852 has kept the same structure and the vast majority of contents already present in TB 496, broadening the recommendations and particularly the appendices with respect to TB 496 [9, 10];
3. CIGRE TB 636:2015, entitled 'Diagnostics and accelerated life endurance testing of polymeric materials for HVDC application', issued in 2015 by CIGRE WG D1.23 [11];
4. IEC Standard 62895:2017, entitled 'HVDC power transmission cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications—Test methods and requirements' [12].

Other existing standards that—although not specifically conceived for HVDC cable systems—report mechanical or other special tests of great interest in particular for the critical submarine HVDC cable systems are the following:

1. CIGRE TB 490:2012, entitled 'Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30 (36) to 500 (550) kV', valid strictly speaking for AC extruded cables and accessories only, but in practice also serving as a very useful reference for DC cables and accessories, in particular as far as mechanical tests and/or water penetration tests are concerned [13];
2. CIGRE TB 623:2015, 'Recommendations for mechanical testing of submarine cables', valid for both AC and DC cables and accessories [14].

The analysis of the first four documents developed for HVDC cable systems shall commence with IEC 62895. This priority is justified by the fact that being the only IEC standard, it would be expected to be the most authoritative and worldwide agreed document. However, it must be observed that IEC 62895 is essentially the transposition of IEC 62067, Edition 2 [15] for DC extruded cables in the framework of the prescriptions by TB 496. Moreover, it is relevant to

- cables with rated voltage up to 320 kV, a level overcome by new HVDC extruded cable systems at a rated voltage of 525, 600 and even 640 kV [16], qualified according to ref. [8] or [9];
- land cables only, whereas submarine cables are also playing a key role in the HVDC cable market.

Hence, IEC 62895 can be deemed as 'born old'. Its review and update procedure will start in 2026; now IEC has formed a Task Force to prepare its revision starting from a better definition of long temporary overvoltage (TOV) testing in TB 852, which will be the subject of an IEC technical report.

As far as TB 636 is concerned, it is essentially qualitative and descriptive, not prescriptive. Indeed, it first examines electrical ageing of polymeric insulation under DC voltage focusing on space charges and diagnostic properties; then, it deals with R&D tests, adding more details to the general indications provided at Clause 3 of TB 852; later, it reviews briefly qualification tests, routine tests and 'online' diagnostic measurements with illustrative examples. Thus, here, TB 636 is treated in Section 2, focused on development tests.

In summary, TB 636 is mainly qualitative, IEC 62895 was 'born old', TB 496 was superseded by TB 852, and TB 490 and TB 623 are not peculiar to HVDC extruded cable systems. Therefore, it can be concluded that TB 852 is the reference for HVDC extruded cable system testing.

TB 852 follows the general structure of former TB 496:2012, but—as witnessed by the increase in the upper limit voltage from 500 to 800 kV—it is much broader, as it introduces new concepts and new tests to account for the technological developments of HVDC extruded cable systems in 2021 compared to the situation in 2012. First of all, the main novelty of TB 852 among the general definitions at Clause 1.5.1 is the distinction between [8]:

- HVDC cable systems, that is, cable systems with nominal (= rated continuous) voltage $U_0 \leq 400$ kV and design average electric stress (= field) of the cable ≤ 20 kV/mm, being the average electric stress equal to the ratio U_0 over nominal insulation thickness.

- Extra-high voltage direct current (EHVDC) cable systems, that is, cable systems with nominal voltage $U_0 > 400$ kV or design average electric stress of the cable > 20 kV/mm.

Moreover, TB 852 at Clause 1.4 confirms the following main tests to be performed in sequence on HVDC extruded cable systems as they already appeared in TB 496, that is,

1. development tests: to be carried out during the R&D activities of the HVDC extruded cable system [8, 9];
2. qualification tests: to be carried out to qualify the HVDC extruded cable system, thereby making it possible to deliver the cable system to the market. Qualification tests are in turn split into [8, 9]:
    a. pre-qualification test (PQT): to be carried out before delivering to the market a cable system type in order to prove 'satisfactory long-term performance of the complete cable system';
    b. type test (TT): to be carried out before delivering to the market a cable system type in order to prove 'satisfactory performance characteristics to meet the intended application';
3. routine tests: to be carried out in the factory on all manufactured cable system components—namely, transmission cables, accessories (joints and terminations) and return cables—to verify that each of them 'meets the specified requirements' [8, 9];
4. sample tests: to be carried out in the factory 'on samples of a complete cable or components taken from a complete cable or accessory'—at a given frequency—to check that 'the finished product meets the specified requirements' [8, 9];
5. tests after installation (= after laying tests): to be carried out on site to prove that the cable system has been correctly installed without any damage (i.e., cable lengths with no damage and high installation quality of accessories).

Nonetheless, in addition to these tests, TB 852 at Clause 1.4 introduces two major new tests at the qualification stage, that is,

- the extension of qualification test (EQT), see Clause 7 of TB 852, as a shorter alternative to the PQT for a cable system that has already been pre-qualified;
- the thermal stability test (TST), see Clause 6 of TB 852, for EHVDC cable systems only, to prove that the cable system is thermally stable in its operational conditions.

Coming to lapped HVDC cables, namely HVDC cables with paper insulation or polypropylene-paper laminated (PPL) insulation that is MI or oil-filled, the main standard document in the technical-scientific literature currently valid for these cables is CIGRE TB 853:2021, entitled 'Recommendations for testing DC lapped cable systems for power transmission at a rated voltage up to and including 800 kV', issued in 2021 by CIGRE WG B1.66 [17]; TB 853 has replaced the previous CIGRE 'Recommendations for tests of power transmission DC cables for a rated voltage up to 800 kV', published in Electra No. 189:2000 by WG 21.02 (see more details in Section 8), whereby lots of MI cables have been qualified. The name and the structure of TB 853 seem to indicate that this is the 'twin document' for HVDC lapped cable systems of TB 852 for HVDC extruded cable systems. However, some major differences can be found between TB 853 and TB 852 that account for the peculiar features of HVDC cable systems with lapped insulation versus extruded insulation.

In summary, due to the similar structure and major significance of TB 852 and TB 853 as general reference documents for testing extruded and lapped HVDC cable systems, respectively, as well as to the huge growth of extruded cables in the last 25 years, this paper reviews the existing HVDC cable system testing techniques and practices following the structure of CIGRE TB 852 as a backbone. In Section 2, focus is on development tests, taking CIGRE TB 636 as the reference for overall recommendations. Section 3 is devoted to PQT and to EQT after TB 852. Section 4 is dedicated to TT after TB 852, with hints at IEEE 1732-2017 for space charge (SC) measurements in the qualification of HVDC extruded cables [18]. Section 5 is concentrated on routine and sample tests after TB 852 on cable lengths and accessories, with hints at IEEE 2862-2020 for routine testing of HVDC cable system joints [19]. Section 6 is devoted to after installation tests. Section 7 highlights the main novelties of TB 852 with respect to previous standards for HVDC extruded cable systems (mainly TB 496 and IEC 62895), with focus on the so-called TOV tests. Section 8 analyses TB 853, reporting the main differences compared to TB 852 related to the peculiarities of lapped HVDC cable systems, as these cables remain unbeaten for submarine applications at the highest sea depths. Section 9 examines TB 852 critically, emphasising its limits and gaps. Section 10 summarises the main equipment that is usually employed for electro-thermal testing of HVDC cable systems. Section 11 deals with TB 490 to treat the peculiarities of submarine cable systems. Section 12 concentrates on mechanical tests, having TB 623 as a reference. Section 13 focuses on sea trial tests (reported also in TB 623), as these tests are very critical for the strategic long-length and high-depth submarine cable links, showing an example of an innovative testing procedure which is the outcome of a fruitful partnership between a cable manufacturer and the national Transmission System Operator (TSO) in Italy. Section 14 draws the main conclusions.

2 | Development Tests

According to TB 852, development tests are left to the discretion of the cable system manufacturer during the R&D stage before qualification. However, TB 852 at Clause 3 provides the following general suggestions for the assessments to be done during development tests:

- investigation of materials and processes by means of breakdown tests, electrical conductivity measurements and SC measurements;
- assessment of electric field distribution in the insulation of cable system components in common installation and loading conditions;
- ageing tests for assessing the long-term effects of electrical, thermal, environmental stresses etc.;

- evaluation of electric stress distribution sensitivity to expected changes of cable system size, materials and manufacturing processes.

TB 636 at Chapter 4 broadens these general indications, first of all singling out two stages for R&D tests [11, 20].

1. Research tests for material/design selection. This first stage requires tests on small specimens of different cable insulation materials/technologies, namely:
    - thin films and plaques, having thickness from 100 μm up to a few mm;
    - minicables, having conductor cross-section $\approx$ 5 mm^2 and insulation thickness $\approx$ 1 mm (the so-called 'model 1 cables' or 'model A cables');
    - medium voltage (MV) cables, having conductor cross-section $\approx$ 50–70 mm^2 and insulation thickness $\approx$ 5 mm (the so-called 'model 2' or 'model A cables').

    The goal of this stage is the study of key parameters for DC extruded cables, namely: SC storage properties, electrical conductivity and DC breakdown strength.

2. Development tests for validation of material/design. This second stage requires tests on prototypes of full-size cables. Typical tests to be carried out in this stage are the following:
    - thermal stability, to exclude the chance of thermal instability of the cable as temperature and electric field are raised;
    - SC measurements, to check the possible electric field increase brought about by SC compared to the theoretical electric field;
    - load cycles with DC applied until breakdown;
    - voltage polarity reversal (PR) load cycles—if PR is required in the prospective cable system—until breakdown;
    - superimposed impulse voltage (DC plus impulse voltage) tests until breakdown.

3 | Pre-Qualification Test and Extension of Qualification Test

3.1 | Pre-Qualification Test

The PQT after TB 852, Clause 4, carried to prove satisfactory long-term performance of the whole cable system, consists of [8]:

1. the so-called long duration voltage test (Clause 4.4), a sequence of 360 '24-hour' load cycles where the cable system is alternatively heated via DC or AC conductor current—the most common is AC current induced in the conductor through heating transformers, see Figure 1—and naturally cooled under a proper test voltage;
2. the superimposed impulse voltage test (Clause 4.5);
3. the final examination (Clause 4.6).

FIGURE 1 | Heating transformers in the PQT loop of a 525-kV DC-XLPE cable system. Two loops are under test, one with a land cable (left), the other with a submarine cable (right) (Courtesy Hellenic Cables, Greece).

At Clause 4.2, TB 852 mentions mechanical preconditioning before the PQT as an option. Mechanical preconditioning is appropriate particularly for submarine cable systems, where mechanical stresses are very challenging (see Section 11).

The goal of the long duration voltage test is to reproduce the typical load cycles the cable system faces during service, with the relevant time-varying electro-thermal stress in the insulation layers—due to the combination of DC voltage and time-varying temperature—and time-varying thermo-mechanical stresses at the various polymer–metal interfaces in the cable and accessories—due to the differential expansion/compression of the various cable system component polymeric and metallic layers. The main prescriptions of TB 852 for the PQT can be summarised as follows [8].

1. The PQT loop is made of all cable system components to be pre-qualified, namely around 100 m of cable plus the relevant accessories (joints and terminations).
2. PQT is split in 3 periods of different heating currents:
    - the 'load cycle' (LC) period, lasting 160 days overall, where every daily cycle consists of at least 8 h heating—with such a current as to reach a conductor temperature $T_{\mathrm{cond}} \geq T_{\mathrm{cond,max}}$ = design temperature of cable conductor and a temperature drop across cable insulation $\Delta T \geq \Delta T_{\max}$ = design temperature drop across cable insulation during the last 2 h of heating—and at least 16 h cooling down to room temperature;
    - the 'high load' (HL) period, lasting 80 days overall, with such a current as to keep $T_{\mathrm{cond}} \geq T_{\mathrm{cond,max}}$ and $\Delta T \geq \Delta T_{\max}$ throughout the period;
    - the 'zero load' (ZL) period, lasting 120 days, where no heating current is applied to the cable.
3. For VSC cables, that is, cable systems designed to operate with VSC converters, test voltage is always $U_{\mathrm{TP1}} = 1.45 \times U_0$, higher than rated voltage U_0 to accelerate the ageing and

reduce test time from 40 years (design life of cables) to 360 days. As explained later, the voltage level and number of 24-h cycles of the PQT are based on the inverse power law model with life exponent $n = 10$, design life = 40 years and test time = 360 days ≈ 1 year, see Appendix A of TB 852. Test voltage polarity is always negative during the ZL period, whereas it is changed every 40 days during LC and HL periods.

4. For line commutated current source converter (LCC) cables, that is, cable systems designed to operate with LCCs, test voltage is $U_{TP1} = 1.45 \times U_0$ during the so-called voltage polarity reversal cycles (LC + PR), lasting 40 days overall; indeed, LCC cables, which can be subjected to voltage polarity reversal on duty, must also undergo LC + PR cycles, whereby voltage polarity is reversed every 8 h and a voltage $U_{TP2} = 1.25 \times U_0$ is applied instead of U_{TP1}. In addition, test voltage polarity is always negative during the ZL period; it is changed every 30 days during LC periods and every 40 days during HL periods.

The details of duration, polarity and applied voltage magnitude (in p.u. of U_0) during the PQT load cycles according to TB 852 are reported in Table 1 for VSC cables and in Table 2 for LCC cables. The technical basis for the test durations and voltages during the load cycles of the PQT—as well as of the EQT (Section 3.2) and of the electrical TT (Section 4.2)—is given in Appendix A of TB 852. It relies on the so-called inverse power model (IPM) or $V - t$ characteristic [8, 9, 21–24], which—as witnessed by these names—expresses insulation life t (or t_F, or L) as an inverse power of applied voltage V or U—or of electric field E—as follows:

$$U^n t = \text{constant}, \tag{1}$$

where n is the so-called life exponent.

Equation (1) can be recast in terms of design life L_0 at rated voltage U_0 of HVDC cables, as well as of duration t_1 of qualification load cycle tests at voltage U_1, obtaining [24]

TABLE 1 | Duration, polarity and applied voltage (p.u. of U_0) during the PQT load cycles for VSC cables according to TB 852, Clause 4.4 [8].

Period→	LC	LC	HL	HL	ZL	LC	LC
Cycles	40	40	40	40	120	40	40
Polarity	+	−	+	−	−	+	−
Voltage (× U_0)	1.45	1.45	1.45	1.45	1.45	1.45	1.45
Total days	40	80	120	160	280	320	360

$$t_1 = L_0 (U_1/U_0)^{-n}. \tag{2}$$

From Equation (2), the test voltage factor K_1 by which rated voltage U_0 must be multiplied to attain the load cycle test voltage U_1 is derived as follows (see Appendix A of TB 852):

$$K_1 = \sqrt[n]{L_0/t_1}. \tag{3}$$

From Equation (3), with $n = 10$ and $L_0 = 40$ years at U_0 [8], the following values of test factor K_1 and load cycle test voltage U_1 are obtained (see Table 8 of TB 852 and Figure 2):

- for PQT with $t_1 = 360$ days, $K_1 = 1.45$, $U_1 = U_{TP1} = 1.45 \times U_0$;
- for EQT with $t_1 = 82$ days, $K_1 = 1.68$, $U_1 = U_{EQ1} = 1.68 \times U_0$;
- for TT with $t_1 = 30$ days, $K_1 = 1.85$, $U_1 = U_T = 1.85 \times U_0$.

The duration t_1 of PQT, EQT and TT load cycles comes from the testing experience as a compromise between the contrasting needs of studying the cable system long-term behaviour at voltages not too far from rated voltage and keeping test times within acceptable limits as test voltage decreases.

After the long duration voltage test, Clause 4.5 of TB 852 requires the superimposed impulse voltage test, essentially as a check that no substantial thermo-mechanical changes have

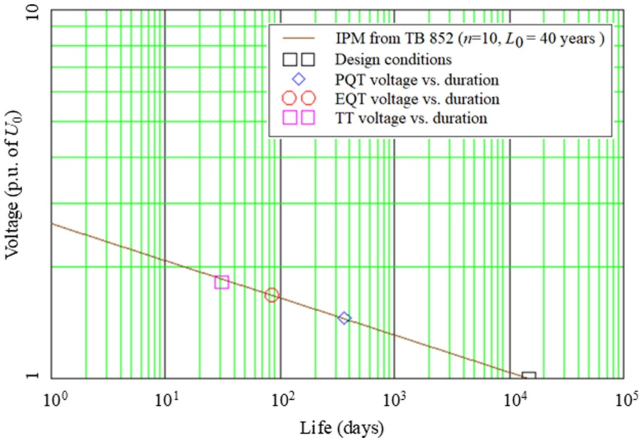

FIGURE 2 | Log–log plot of test voltage U_1 versus test duration t_1 for the IPM of Equation (2) with $n = 10$ and design life $L_0 = 40$ years at rated voltage U_0 (brown solid line) and test voltage versus duration for PQT ($t_1 = 360$ days, $U_1 = U_{TP1} = 1.45 \times U_0$, blue diamond), EQT ($t_1 = 82$ days, $U_1 = U_{EQ1} = 1.68 \times U_0$, red circle), TT (30 days, $U_1 = U_T = 1.85 \times U_0$, magenta box).

TABLE 2 | Duration, polarity and applied voltage (p.u. of U_0) during PQT load cycles for LCC cables according to TB 852, Clause 4.4 [8].

Period→	LC	LC	LC + PR	HL	HL	ZL	LC	LC	LC + PR
Cycles	30	30	20	40	40	120	30	30	20
Polarity	+	−	±	+	−	−	+	−	±
Voltage (× U_0)	1.45	1.45	1.25	1.45	1.45	1.45	1.45	1.45	1.25
Total days	30	60	80	120	160	280	310	340	360

taken place during the long-term testing and the pre-qualified cable loop is still healthy enough to withstand superimposed voltage impulses of the switching type and lightning type—if the cable system installation is exposed to lightning. About this test, in line with TB 496, TB 852 establishes that [8]:

- superimposed voltage impulses are applied after heating the PQT loop at a DC voltage U_0 (of the relevant polarity) so that $T_{\mathrm{cond}} \geq T_{\mathrm{cond,max}}$ and $\Delta T \geq \Delta T_{\mathrm{max}}$ are achieved for ≥ 10 h;
- based on available specifications for HVDC cable projects, the recommended impulse voltage values are $U_{\mathrm{P2,O}} = 1.2 \times U_0$, $U_{\mathrm{P1}} = 2.1 \times U_0$, where (see Clause 1.5.3 of TB 852) $U_{\mathrm{P2,O}} = 1.15 \times$ maximum absolute peak of the switching impulse voltage experienced by the cable system for impulses with the opposite polarity to the DC voltage, $U_{\mathrm{P1}} = 1.15 \times$ maximum absolute peak of the lightning impulse voltage experienced by the cable system for impulses with the opposite polarity to the DC voltage. $U_{\mathrm{P2,S}} = 1.15 \times$ maximum absolute peak of the switching impulse voltage experienced by the cable system for impulses with the same polarity as the DC voltage is not considered in the PQT, whereas it is encompassed in the type test (see Section 4.2);
- cable and accessories must withstand without failure 10 positive and 10 negative superimposed switching impulses at $U_{\mathrm{P2,O}}$, plus—for systems exposed to lightning—10 positive and 10 negative superimposed lightning impulses at U_{P1}.

Moreover, TB 852 refers to IEC 60230 for the various impulse shapes allowed, specifies that they can be obtained using two different dividing/blocking devices—that is, either capacitor or spark gap—and establishes that impulse voltage characteristics shall be in accordance with IEC 60060-1 [25, 26].

According to Clause 4.6 of TB 852, the final examination performed according to Appendix I closes the PQT. Details about success criteria, re-testing and interruptions are given at Clause 4.7.

Miscellaneous but very interesting notes to the PQT at Clause 4 are the following [8].

- It is recommended to carry out a PQT on a cable of a large conductor cross-section in order to cover thermo-mechanical aspects.
- PQTs successfully performed according to TB 219 [27], TB 496 and IEC 62895 are valid, on condition that they were carried out within the voltage scope of TB 219, TB 496 and IEC 62895.
- The impulse test at the end of a PQT does not qualify the cable system for the applied impulse level. Project-specific impulse levels are qualified during the type test.

TB 852 states that a cable system qualified—that is, passing the PQT (or EQT, Section 3.2) and the type test (Section 4)—for LCC is also qualified for VSC, whereas a cable system qualified for VSC is not qualified for LCC [8]; this is due to the more challenging load cycles for LCC cables (including LC + PR) than VSC cables. Similarly, TB 852 states that an armoured cable type qualified does qualify an unarmoured cable, whereas an unarmoured cable type qualified does not qualify an armoured cable [8]; this is due to the more complex design and manufacture, as well as to the more stressful operating conditions of armoured versus unarmoured cables.

3.2 | Extension of Qualification Test

As hinted at above, a novelty of TB 852 is the introduction at Clause 7 of the EQT, to be carried out at the qualification stage 'to verify the long-term performance of a previously qualified cable system when substantial changes are implemented on [such] system' [8].

Similar to the PQT, the EQT consists of a load cycle test, followed by a superimposed impulse voltage test, a subsequent DC test and a final examination. As for the load cycle tests, the main prescriptions at Clauses 7.2 and 7.3 of TB 852 are as follows.

1. The EQT loop is made of at least 30 m cable, with at least one accessory of each type to be qualified.
2. The EQT is split in the same three periods—LC, HL and ZL—as the PQT; but in the EQT, the LC period lasts overall 40 days (instead of 160), the HL period lasts 36 days (instead of 80), and the ZL period lasts 6 days (instead of 120), for a total of 82 days (instead of 360).
3. The test voltage is mostly set at $U_{\mathrm{EQ1}} = 1.68 \times U_0$, higher than $U_{\mathrm{TP1}} = 1.45 \times U_0$ to further accelerate the ageing and reduce test time from 360 to 82 days. Additionally, the voltage level and number of 24-h cycles of the EQT are based on the inverse power law model with life exponent $n = 10$ and design life = 40 years, but test time is now 82 days, see Appendix A of TB 852 and Figure 2 at Section 3.1. As in PQT, test voltage polarity is changed at regular intervals, and applied voltage differs for LCC versus VSC cables during the LC + PR cycles, lasting 24 days overall; indeed, in the case of LCC cables which can be subjected to voltage polarity reversal on duty, LC + PR cycles are carried out whereby voltage polarity is reversed every 8 h and a voltage value of $U_{\mathrm{EQ2}} = 1.37 \times U_0$ is applied instead of $U_{\mathrm{EQ1}} = 1.68 \times U_0$.

The details of duration, polarity and applied voltage magnitude (in p.u. of U_0) during the extension of qualification load cycle test according to Clause 7.3 of TB 852 are reported in Table 3 for VSC cables and in Table 4 for LCC cables.

After the EQT load cycles, Clause 7.3 of TB 852 requires that the cable system withstands the same superimposed impulse

TABLE 3 | Duration, polarity and applied voltage (p.u. of U_0) during EQT load cycles for VSC cables according to TB 852, Clause 7.3 [8].

Period→	**LC**	**LC**	**HL**	**HL**	**ZL**	**LC**	**LC**
Cycles	10	10	18	18	6	10	10
Polarity	+	−	+	−	−	+	−
Voltage (× U_0)	1.68	1.68	1.68	1.68	1.68	1.68	1.68
Total days	10	20	38	56	62	72	82

voltage test as that after the PQT, described above at Section 3.1 [8]. In addition, Clause 7.3 of TB 852 also prescribes a subsequent DC test whereby a negative DC voltage $-U_T$ is applied to the cable loop at room temperature for 2 h [8]. According to Clause 7.4 of TB 852, the final examination based on Appendix I closes the EQT [8].

4 | Type Tests

The TTs after TB 852, Clause 5, must prove the satisfactory performance of the HVDC extruded cable system for the intended application [8]. First of all, TB 852 states that, if a cable system passes TTs, this holds for cable systems with the same design, materials, manufacturing processes, service conditions and having the same or lower values of:

- service voltages U_0, U_M (= maximum DC voltage peak including ripples, harmonics and measuring tolerances), U_{P1}, $U_{P2,S}$ and $U_{P2,O}$;
- preconditioning mechanical stresses;
- $T_{cond,max}$ and ΔT_{max};
- conductor cross-section;
- calculated average electric field in the insulation;
- calculated Laplace electric field at the cable conductor and insulation screen.

Type tests according to TB 852 are essentially split into

1. nonelectrical TTs, see TB 852, Clause 5.3;
2. electrical TTs, see TB 852, Clause 5.4.

4.1 | Nonelectrical Type Tests

As for nonelectrical TTs, TB 852 refers first to IEC 62895, specifying that the test programme shall be agreed between the manufacturer and utility, discussing also if additional testing is necessary. However, aiming at a more complete characterisation of the performances of novel HVDC extruded cable technologies, TB 852 introduces additional tests compared to former TB 496, namely [8]

- at Clause 5.3.1, the by-product content in insulation material test for EHVDC cables, measured via either Thermogravimetric analysis (TGA) as per Appendix G.1 or chromatography as per Appendix G.2;
- at Clause 5.3.2, the pressure test of thermoplastic insulation, to be carried out as per Appendix G.6;
- at Clause 5.3.3, the hot set test of cross-linked insulation, to be carried out on XLPE and low cross-linked polyethylene (LXLPE, an XLPE with a lower amount of crosslink density than XLPE) as per Appendix G.7.

TB 852 confirms at Clause 5.3 that land cables with water blocking systems must pass the water penetration test after IEC 62895 (instead of IEC 62067, Ed. 2 [15], as in ref. [9]), whereas submarine cables must pass a water integrity test after TB 623 [14] (instead of Electra 189:2000 for AC extruded cables [28], as in ref. [9]) and cables with metal earthing leads through plastic sheaths must pass the relevant test after TB 623 [14] (instead of Electra 189:2000 for lapped DC cables [29], as in ref. [9]). Section 12, devoted to TB 623, tells more on these tests.

4.2 | Electrical Type Tests

For electrical TTs, TB 852 confirms the same sequence as in TB 496, reported hereafter and sketched in Figure 3.

1. Mechanical preconditioning at Clause 5.4.1 of TB 852, aiming at applying to the cable system the maximum mechanical stress during handling, installation and recovery on site. Thus, mechanical preconditioning for land cables consists of a bending test after IEC 62895, with proper bending radius, and does not include field joints, whereas mechanical preconditioning for submarine cables

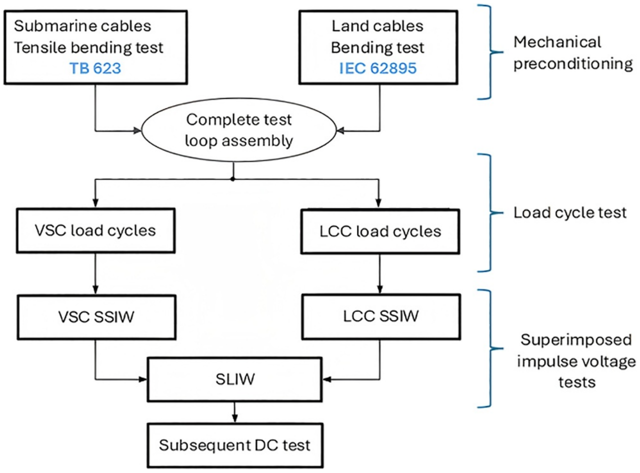

FIGURE 3 | Overview of electrical type tests. *Source:* Reprocessed after ref. [8].

TABLE 4 | Duration, polarity and applied voltage (p.u. of U_0) during EQT load cycles for LCC cables according to TB 852, Clause 7.3 [8].

Period→	**LC**	**LC**	**LC + PR**	**HL**	**HL**	**ZL**	**LC**	**LC**	**LC + PR**
Cycles	4	4	12	18	18	6	4	4	12
Polarity	+	–	+/–	+	–	–	+	–	+/–
Voltage (× U_0)	1.68	1.37	1.25	1.68	1.68	1.68	1.68	1.68	1.37
Total days	4	8	20	38	56	62	66	70	82

includes factory and repair joints and consists of a coiling test after Clause 5.1 of TB 623 (if applicable), a tensile bending test after Clause 5.2 of TB 623, and a tensile test after Clause 5.5 of TB 623 (if applicable). Mechanical preconditioning is followed by visual examination after Clause 2.2.1.1 of TB 446 [30] for land cables and after Clause 5.1.4 of TB 623 for submarine cables.

2. Load cycle test at Clause 5.4.2 of TB 852, carried out on the electrical TT loop obtained assembling both those cable system components subjected to mechanical preconditioning and those accessories that do not require mechanical preconditioning. The TT load cycles are analogous to the PQT and EQT load cycles but feature higher voltage and shorter duration. They basically consist of 24 '24-h' load cycles that are 'thermally'-identical to those of the LC period of PQT, plus 3 '48-h' load cycles (with at least 18 h at $T_{\mathrm{cond}} \geq T_{\mathrm{cond,max}}$, $\Delta T \geq \Delta T_{\max}$ and at least 24 h natural cooling). Test voltage is set to $U_{\mathrm{T}} = 1.85U_0$, apart from 8 '24-h' LC + PR load cycles at $U_{\mathrm{TP1}} = 1.45U_0$ carried out only for LCC cables. More details are found in Tables 5 and 6.
3. Superimposed impulse voltage test at Clause 5.4.3 of TB 852 for which TB 852 confirms the same sequence as the TB 496, namely:
   - Superimposed Switching Impulse Voltage Withstand (SSIW) test for the LCC cable system:
     - DC voltage $+ U_0$ plus 10 impulses at $- U_{\mathrm{P2,O}}$
     - DC voltage $- U_0$ plus 10 impulses at $+ U_{\mathrm{P2,O}}$
   - SSIW test for the VSC cable system:
     - DC voltage $+ U_0$ plus 10 impulses at $+ U_{\mathrm{P2,S}}$
     - DC voltage $+ U_0$ plus 10 impulses at $- U_{\mathrm{P2,O}}$
     - DC voltage $- U_0$ plus 10 impulses at $- U_{\mathrm{P2,S}}$
     - DC voltage $- U_0$ plus 10 impulses at $+ U_{\mathrm{P2,O}}$
   - Superimposed Lightning Impulse Voltage Withstand (SLIW) test, only for cable systems directly or indirectly exposed to lightning:
     - DC voltage $+ U_0$ plus 10 impulses at $-U_{\mathrm{P1}}$
     - DC voltage $-U_0$ plus 10 impulses at $+ U_{\mathrm{P1}}$

   In line with TB 496, TB 852 states that the superimposed voltage impulses are applied after heating the TT loop up to $T_{\mathrm{cond}} \geq T_{\mathrm{cond,max}}$ and $\Delta T \geq \Delta T_{\max}$ at a DC voltage U_0 for ≥ 10 h. Contrary to TB 496, TB 852—after pointing out that the values of U_{P1}, $U_{\mathrm{P2,S}}$ and $U_{\mathrm{P2,O}}$ are typically project-specific—recommends, for cases where the TT is not project-specific, the following impulse voltage values: $U_{\mathrm{P2,O}} = 1.2\ U_0$, $U_{\mathrm{P2,S}} = 2.1\ U_0$ and $U_{\mathrm{P1}} = 2.1\ U_0$.
4. Subsequent DC test: 2 h at $-U_{\mathrm{T}}$, no heating.

TABLE 5 | Duration, polarity and applied voltage (p.u. of U_0) during TT load cycles for VSC cables according to TB 852, Clause 5.4.2.3 (LC48 = '48 h' load cycle) [8].

Period→	**LC**	**LC**	**LC48**
Cycles	12	12	3
Polarity	−	+	+
Voltage (× U_0)	1.85	1.85	1.85
Total days	12	24	30

TABLE 6 | Duration, polarity and applied voltage (p.u. of U_0) during TT load cycles for LCC cables according to TB 852, Clause 5.4.2.2 [8].

Period→	**LC**	**LC**	**LC + PR**	**LC48**
Cycles	8	8	8	3
Polarity	−	+	+/−	+
Voltage (× U_0)	1.85	1.85	1.45	1.85
Total days	8	16	24	30

The electrical TT loop consists of all cable system components to be type-tested, including a minimum of 10 m of continuous noninterrupted cable plus accessories.

In line with TB 496, TB 852 at Clause 5.5 prescribes TTs also for return cables, namely 'the low/medium/high voltage DC cable used for the return current in a monopolar operation of HVDC schemes' [8]. These tests include mechanical preconditioning, thermo-mechanical preconditioning, AC voltage test at power frequency and lightning impulse withstand test (if applicable). Details are skipped here for brevity.

4.3 | SC Measurements: IEEE 1732-2017

IEEE 1732-2017, entitled 'IEEE recommended practice for space charge measurements in high voltage direct current extruded cables for rated voltages up to 550 kV', is the 1st standard document worldwide establishing a protocol for the measurement of SC in qualification tests (PQT and TT) for full-size HVDC extruded cable systems. Such measurements are recommended at the beginning and at the end of load cycle qualification tests (either the long-duration voltage test of PQT or the load cycle test of electrical TTs). In IEEE 1732-2017, the various steps of the protocol for SC measurement in HVDC extruded cables are carefully described. Details are given about the procedure for applying and switching off the voltage, the preparation and conditioning of specimens, the measurement times during poling and depolarisation and the calculations for checking electric field stabilisation. The ultimate goal of this recommended practice is not verifying the compliance with any maximum acceptable limit of either SC or electric field but rather assessing that the maximum variation of the electric field profile in the cable insulation wall before and after the load cycles of qualification tests is moderate, thus indicating that the SC dynamics in cable insulation are under control and not harmful for the cable [18].

Hence, although IEEE 1732-2017 does not include a pass/fail test, it does provide a very useful engineering information on the SC dynamics behaviour of the measured cable. This information can be greatly useful to manufacturers and utilities, especially when considering that HVDC extruded cables are not so well established as lapped cables, particularly at the state-of-the-art voltage level of DC-XLPE cables, that is, 525 kV. Anyway, the reliability and accuracy of SC measurements, especially with the pulsed electro-acoustic (PEA) technique, have improved greatly over the years, particularly in the last decade. And, as a matter of fact, many SC measurements have been satisfactorily performed on full-size HVDC extruded cables with quite good calibration and signal-to-noise ratio, obtaining SC profiles and especially electric field profiles in the insulation that are meaningful and consistent with the composition and behaviour of the dielectric (see e.g., [31–35]).

The measurement protocol recommended in IEEE 1732-2017 was devised by the IEEE Dielectrics and Electrical Insulation Society (DEIS) Technical Committee (TC) on HVDC cable systems in 2015 [31] and relies on the experience gained in successful SC measurements done during the qualification tests of the Italy–France 320-kV HVDC extruded cable line [32]. It was also successfully applied for the qualification of the IFA-2320 kV HVDC extruded cable line between the United Kingdom and France, and quite recently on a full-size 525-kV HVDC extruded cable [33]. In ref. [33], the measurements were successful, showing meaningful charge and field profiles all over the insulation thickness. The application of the procedure was also successful, as the stabilisation of the field profile was clearly observed during the measurements, indicating the satisfactory behaviour of the cable as for SC dynamics.

The recommendations after IEEE 1732-2017 are summarised in ref. [34]. It should be emphasised that the recommended SC measurement methods in IEEE 1732-2017 are the PEA [35] and the thermal step method (TSM) [36].

5 | Routine and Sample Tests

5.1 | Routine Tests on Cables

At Clause 8, TB 852 establishes the routine tests to prove the integrity of the delivery lengths of HVDC extruded cable systems. In particular, at Clause 8.1, the routine tests to be carried out on all lengths of transmission (= pole) cables can be found [8]. Contrary to TB 496—but following a comment reported in TB 496 about the scarce experience on routine DC voltage test of extruded cables, thereby suggesting also AC tests—first of all, at Clause 8.1.1, TB 852 prescribes that every delivery length of the transmission cable must undergo an AC voltage test aiming at controlling the quality of the material and processes employed for manufacturing cable insulation [8].

There must be an agreement between the supplier and utility about the AC voltage level and duration—TB 852 suggests 20 kV/mm applied for 30 min to HVDC cables and 23 kV/mm for 60 min to EHVDC cables as the maximum AC Laplace field stress—whereas the AC voltage frequency must range from 10 to 500 Hz for submarine cables (referring to ref. [13]) and from 49 to 61 Hz for land cables (referring to ref. [15]). If a complete delivery length of submarine cable cannot be tested under AC voltage in one run, the single manufacturing lengths must be AC-voltage tested before joining them with factory joints [8].

After the AC voltage test, at Clause 8.1.2, TB 852 prescribes the DC voltage test at a DC voltage $-U_T = -1.85U_0$ for 1 h—same values as in TB 496—but further specifying that the test shall be at room temperature. TB 852 also recommends that the that AC voltage test is carried out before the DC voltage test for safety reasons related to the polarisation phenomenon taking place under DC voltage [8].

In addition to TB 496, TB 852 points out at Clause 8.1.3 that the over-sheath may undergo routine electrical tests after IEC 60229 [37], as well as at Clause 8.1.4 that a time domain reflectometry (TDR) measurement could be performed for engineering information, in line with Clause 11.3 of TB 852 for after installation tests (see Section 6 hereafter).

At Clause 8.3, TB 852, consistently with TB 496, prescribes that every delivery length of return cable must undergo a voltage test, preferring the AC voltage test—voltage and duration of the test to be agreed between the counterparts. If AC voltage testing is unfeasible due to long lengths and high voltages, the counterparts may agree on a proper level of DC test voltage for which TB 852 recommends at least the highest between $2.5U_{\mathrm{RC,DC}}$ (= maximum DC voltage of return cable in service) and 25 kV to be applied for 1 h [8].

5.2 | Routine Tests on Cable Accessories

At Clause 8.2, TB 852 establishes the routine tests to be performed on cable accessories. In particular, at Clause 8.2.1, the routine tests to be carried out on all prefabricated joints and terminations are described, establishing that 'The main insulation of prefabricated accessories shall undergo voltage routine tests as in §8.1.1' (see Section 5.1) '(if applicable)'; later at Clause 8.2.1, it is further stated that 'An AC test combined with PD' (Partial Discharge) 'measurement is recommended'. Similarly, at Clause 8.2.2, the routine tests to be carried out on all factory joints of submarine cables are described, listing four possible methods 'for checking the quality of the factory joint insulation system: (1) AC voltage test, if applicable; (2) PD measurement, if applicable; (3) DC voltage test; (4) X-ray inspection' and further stating: 'A screening AC voltage test … directly after jointing would reduce the time delay in case the joint were to fail at a later stage … The AC voltage test and the PD measurement may be carried out if possible on the complete delivery length' [8].

Thus, in TB 852, the AC voltage test with PD measurement is recommended as a routine test of prefabricated joints and terminations and clearly suggested as a routine test of factory joints of submarine cables. These concepts will be resumed later in Section 9 when treating the issues not addressed in TB 852 [10].

5.3 | Routine Tests on Joints: IEEE 2862-2020

IEEE 2862-2020, entitled 'Recommended Practice for Partial Discharge Measurements under AC Voltage with VHF/UHF Sensors during Routine Tests on Factory and Pre-moulded Joints of HVDC Extruded Cable Systems up to 800 kV', is the 1st standard document worldwide recommending a good practice for PD measurement under AC voltage with wireless sensors in tests for HVDC extruded cable system joints [19, 38]. It was developed by the same IEEE DEIS TC on HVDC cable systems which issued IEEE 1732-2017 (see Section 4.3). IEEE 2862-2020 comes from a new protocol for quality control in routine tests on factory and pre-moulded joints for HVDC extruded cable systems [38–40], based on PD measurements under AC voltage via VHF/UHF sensors, as well as on good and agreed manufacturers' practices for these kind of measurements on joints.

In summary, IEEE 2862-2020 describes [19, 38]:

- at Clause 4.2 the performance check to control the functionality of the sensor;
- at Clause 4.3 the test set-up arrangement to raise the acquired signal;
- at Clause 4.4 the whole measurement procedure.

Key statements to be considered for the correct application of IEEE 2862-2020 are as follows [19, 38]:

- IEEE 2862-2020 is applicable if the cable system design allows AC testing;
- test acceptance is based not only on PD amplitude but on whole PD phenomenon (pattern, pulse waveshape, etc.), looking for 'critical PDs', namely for PDs within the body of the insulation of the joint.

5.4 | Sample Tests

At Clause 9, TB 852 establishes the sample tests that must be performed on cables and some types of cable accessories. General reference is made to IEC 62895 . Thereafter, the following sample tests are listed in TB 852, referring to the relevant Appendixes of TB 852 when needed:

- conductor examination;
- measurement of electrical resistance of the conductor and of the metallic screen/sheath;
- measurement of capacitance;
- measurement of thickness of insulation and nonmetallic sheath;
- measurement of thickness of metallic sheath and/or dimension of screen wires;
- measurement of diameters, if required;
- by-product content on the insulation material. This test, not found in ref. [12] and mentioned above at Section 4.1 among nonelectrical TTs, is a novelty of TB 852, applies to EHVDC cables—it can be discussed between the supplier and client for HVDC cables—and must be performed via TGA as per Appendix G.1 or chromatography as per Appendix G.2;
- volume resistivity of semiconductive screens. This test is a novelty of TB 852 and must be carried out as per Appendix G.4;
- pressure test of thermoplastic insulation. This test is a novelty of TB 852 and must be carried out as per Appendix G.6;
- hot set test of cross-linked insulation;
- impulse voltage test;
- water penetration test. For land cables, the procedure of Clause 10.13 in IEC 62895 must be accomplished. For submarine cables, the procedure of Clause 8.7.2 in TB 490 must be accomplished, but with no need of mechanical preconditioning;
- adhesion and peel strength of the laminated metal foil of cables with longitudinally applied metal tape or foil, bonded to the oversheath, if applicable.

At Clause 9.3 for factory joints of submarine cables, TB 852 recommends the following sample tests on 1 factory core joint only (with $\geq$ 10 m of cable) prior to joints manufacturing [8]:

- tensile test;
- PD measurement and AC voltage test;
- impulse voltage test;
- hot set test for insulation where applicable.

At Clause 9.4, TB 852 points out that repair joints (of submarine cables)—as well as terminations, mentioned at Clause 8.2.1—can only be routine-tested (see Section 5.2); hence, sample tests are not applicable to them [8].

At Clause 9.5 for field moulded joints, TB 852 recommends the sample test sequence with the frequency and procedure after IEC 62895, stating also that the same tests as prescribed in Clause 8.2.2 of TB 852 are applicable.

6 | After Installation Tests

In line with former TB 496 and with IEC 62895 for land cables, the after installation tests—treated in detail in CIGRE TB 841 [41], where they are referred to as 'after laying tests'—recommended in TB 852 are as follows [8]:

- the high voltage test at Clause 11.1, whereby the HVDC extruded cable system after laying undergoes a DC voltage test at $-U_{\mathrm{TP1}} = -1.45U_0$ for 1 h;
- the test on polymeric sheaths for land cable systems at Clause 11.2, carried out—if appropriate—following the prescriptions of IEC 60229;
- TDR measurement at Clause 11.3, possible for engineering purposes.

TDR measurement on healthy cables is suggested to acquire the so-called cable 'fingerprint' of wave propagation. This is particularly useful to locate a cable fault—especially in long HVDC submarine links—by comparing the fingerprint of the healthy cable with wave propagation and reflection in the presence of the fault. Indeed, TDR pulse propagation depends on cable resistance, capacitance and inductance; it is unaffected by coiling on a turntable or after installation, but it is affected by the low impedance at a cable faulted point [8, 42].

Additional after installation tests can be agreed between the supplier and client making reference to CIGRE TB 841.

7 | Main Novelties of TB 852 With Focus on TOV Tests

As hinted at in the previous sections, TB 852:2021 has essentially kept the same structure as TB 496:2012, but it has also introduced several updates and novelties, the most noteworthy of which are listed here below [8, 9].

- Voltage range has been extended up to 800 kV.
- The text has been updated to account for IEC 60840, Ed. 5 [43] plus corrigendum Feb. 2021, IEC 62895 and IEC 62067, Ed. 2 (in 2021, when TB 852 was issued, only Edition 2 of IEC 62067 was available, since Edition 3 was published later in 2022 [44]).
- The requirements are differentiated as a function of the cable design and performance by defining [8]:
  - HVDC cables = cables of voltage $\leq$ 400 kV and designed with an average stress $\leq$ 20 kV/mm;
  - EHVDC cables = cables of voltage $>$ 400 kV or designed with an average stress $>$ 20 kV/mm.
- The PQT and TTs have been revised and integrated for details of the heating method, temperature control and thermal test parameters (see novel Appendixes D and E of ref. [8]).
- In addition to $T_{\text{cond,max}}$ and ΔT_{max}, at Clause 1.5.4, TB 852 introduces for EHVDC systems a novel thermal cable design parameter to be computed and declared by the manufacturer, that is, ΔT_{min} = minimum temperature difference over cable insulation in a steady state at $T_{\text{cond,max}}$ at which the cable is designed to operate. A note points out that ΔT_{min} is defined in relation to $T_{\text{cond,max}}$ to emphasise the minimum outgoing thermal flux needed to prevent cable insulation overheating [8].
- Related to ΔT_{min}, at Clause 6, TB 852 introduces a thermal stability test in the qualification of EHVDC cable systems due to the increased electrical stress, aimed at singling/ruling out a thermal runaway.
- At Clause 7, TB 852 introduces a new EQT, claimed to reduce the duration and avoid repetitions of PQT while ensuring the reliability of tested cable systems, see Section 3.2 above.
- TB 852 gives more allowance for some test methods, for example, impulse test with blocking capacitors or sphere gaps (also referred to simply as 'spark gaps' in ref. [8]).
- In TB 852 test criteria, regimes and methods are revised for routine and sample tests on cables and accessories, to be consistent with IEC 62895. In particular, sample tests are broadened to introduce new fingerprint methods and extend testing to new insulations available in the market—for example, LXLPE, nano-filled insulations and thermoplastic dielectrics—whose properties are outlined in the novel Appendix G of ref. [8].
- At Clause 10, TB 852 provides an extremely detailed guide for the selection of test procedures in case of changes in a qualified cable system.
- At Clause 12, TB 852 devises special TOV tests for the new waveshapes from VSC HVDC modular multilevel converter (MMC) schemes, studied by CIGRE Joint Working Group (JWG) B4/B1/C4.73 [8, 45].

Among these novelties, let us focus on TOV tests as follows:

1. they appear also at Clause 8 of TB 853 for lapped HVDC cables [13], treated hereafter at Section 8;
2. they are still debated, as they need a complex test set-up.

These tests started from the extensive studies of the JWG B4/B1/C4.73, which showed that HVDC VSC cable systems can experience unconventional long TOVs on top of conventional lightning and switching impulses [45–51]. These studies emphasised that, in particular, two new TOVs can occur on HVDC and EHVDC cable systems in the presence of faults:

1. Very slow front overvoltages with the same polarity as actual DC voltage of two different types depending on the type of fault that caused them:
   a. phase-to-ground faults on the AC side;
   b. DC pole-to-ground faults on the DC side, these latter found to generate overvoltages leading to the highest peak values, particularly for HVDC VSC MMC cable systems in asymmetric monopolar scheme.
2. Zero crossing damped TOVs. This latter TOV occurs along the faulty cable during the cable discharge process and manifests itself as a sequence of damped oscillations with the first and highest peak never overcoming the rated DC voltage.

Preliminary studies about the severity of the most critical long TOVs—type (1.b) above—on HVDC extruded cable insulation did not show any evidence that these long TOVs have an impact on any HVDC VSC extruded cable technology, although they could not rule out that potentially harmful space charge effects are triggered by the combination of time scale and field intensity of these TOVs [52–54]. All this considered, TB 852 has introduced special TOV tests at Clause 12, which are split into:

- very slow front TOV test, see Clause 12.3 of TB 852, to assess for development purposes the HVDC cable system withstand level to TOVs of type 1 above;
- chopped very slow front TOV test, see Clause 12.4 of TB 852, to assess for development purposes the HVDC cable system withstand level to TOVs of type 1 above when the cable is abruptly grounded after the fault—as done in some types of converter operations—only if the system is operated in such manner;
- zero crossing damped TOV test, see Clause 12.5 of TB 852, to assess for development purposes the HVDC cable system withstand level to TOVs of type 2 above.

Generalities and definitions of waveshape parameters are found in TB 852 at Clause 12.1 and Clause 12.2, whereas details of the waveshapes to be applied and the possible test circuits to be used in each of these TOV tests are found at Clause 12.3, Clause 12.4 and Clause 12.5, respectively.

As hinted at above, the TOV test has also been added for lapped HVDC cables at Clause 8 of TB 853, with the same structure and Clauses as for extruded cables in TB 852. One minor difference is Clause numbering: Clauses 8.x in TB 853 correspond to Clauses 12.x in TB 852. As shown in next Section 8, a few more significant differences concern some test details.

The scope of TOV tests is to check that the cable system design is acceptable under these special waveforms. As long TOVs are related to faults and their number is expected to be limited during cable system lifetime, TOV tests are intended only to investigate the system limits; therefore, voltage, time and number of applied TOVs must not be regarded as design parameters for the insulation coordination interface between the converter and cable system, which can be better estimated by the cable system supplier. On the other hand, some utilities think that these tests are very important, also because of the limited experience on HVDC extruded cable systems and VSC converters; therefore, they have inserted these tests in their HVDC extruded cable system specifications [55].

However, since TOV test waveshapes deviate significantly from superimposed impulse voltage tests according to Clause 13.2.5 of IEC 62895:2017, IEC TC 20 WG 16 has started a Task Force (TF) to evaluate if these tests are significant and needed to be included into the scope of the new issue of IEC 62895. Since first tests have already been carried out according to TB 852 and TB 853 and/or client's specification, first experiences with the set-up are already available on which the IEC TC20 WG 16 TF will rely for its work.

8 | Hints at the Peculiarities of Lapped HVDC Cable Systems: TB 853

Cables with lapped insulation have been commissioned since 1954 to date for HVDC cable systems at the highest voltage levels [17]. As hinted at in Section 1, for a long time until 2021, the reference document for lapped HVDC cable system testing was ‘Recommendations for tests of power transmission DC cables for a rated voltage up to 800 kV’, published in Electra No. 189:2000 [29] (plus the addendum published in Electra No. 218:2005 [56]). To account for the subsequent significant development of HVDC technology—including VSCs, which changed cable system stresses in normal and transient conditions—WG B1.66 was formed to merge and update the recommendations in refs. [29, 56] into TB 853:2021. TB 853 applies to lapped insulation cables in general—apart from gas-pressurised cables, which have been excluded with respect to ref. [29]—for example, to kraft paper or PPL insulated cables, either oil-filled or MI [17].

The structure of TB 853 is fairly similar to that of TB 852 for HVDC extruded cables but features some major novelties compared to refs. [29, 56], namely

- Development tests at Clause 2, not included in ref. [29].
- PQT at Clause 3, introduced with respect to ref. [29] for new insulating materials—suppliers with previous service experience on MI cables can skip this PQT.
- EQT at Clause 4, introduced with respect to ref. [29] for substantial changes to kraft paper insulated MI cables.
- Sample tests at Clause 7, not included in ref. [29].
- Special TOV tests at Clause 8, introduced in TB 853 as in TB 852 to check the cable system's ability to bear TOVs in VSC HVDC systems, see Section 7.
- Appendix D, which reports the addendum published in ref. [56] focusing on electric field profiles in cable insulation during energisation due to long polarisation time under different test conditions.

Another major change compared to ref. [29] concerns the updated test sequences to reflect testing for HVDC systems with VSCs. For load cycles test, at Clause 1.5.4, the values of $U_T = 1.8U_0$, $U_{TP1} = 1.4U_0$, $U_{TP2} = 1.2U_0$ are defined, in line with the experience and testing procedures on lapped DC cables after ref. [29], but slightly smaller than $U_T = 1.85U_0$, $U_{TP1} = 1.45U_0$ and $U_{TP2} = 1.25U_0$ for extruded cables in TB 852. Apart from this, the same schemes as in TB 852 are adopted in TB 853 for:

- the long duration voltage test of the PQT at Clause 3.4 (compare it with Tables 1 and 2 above);
- the switching impulse withstand test for LCC cable systems at Clause 5.7.2.1 (compare it with Clause 5.4.3.2 of TB 852) and for VSC cable systems at Clause 5.7.2.2 (compare it with Clause 5.4.3.3 of TB 852).

Apart from the values of U_T, U_{TP1} and U_{TP2}, the main differences of TB 853 with respect to TB 852 reflect some peculiarities of lapped versus extruded cable systems. They are listed and discussed hereafter.

At Clause 1.5.4 of TB 853, the following thermal cable design parameters have been added to those in TB 852 [17]:

- ΔT_{cold} = temperature drop in a steady state using rated current I_0 at cold ambient conditions;
- $T_{cond,cold,max}$ = maximum conductor temperature for the cable as installed in the cold ambient.

At the new Clause 1.5.5 (= thermal and pressure conditions for tests) of TB 853, it is stated that the thermal conditions of the cable route must be used as the basis when selecting the ambient temperature during TTs; in case a small difference exists between maximum and minimum temperature along the cable route and the cable behaviour is the same within this range, one temperature may be used as the basis for TTs (see

Appendix C of TB 853). This is because HVDC cable systems with lapped insulation are mostly used for long submarine links where the thermal conditions along the cable route may change significantly: this must be accounted for in thermal testing conditions. For this reason, more details—omitted here for brevity—are given for thermal testing conditions of land cables (separately for MI and pressurised cables), submarine cables, joints and sealing ends. Thermal testing conditions of MI cables are emphasised for which the following cable sections are considered to be important in line with Appendix D of TB 853:

- low ambient temperature and surrounded by water;
- high ambient temperature at the specified burial depth.

Clause 1.5.5 of TB 853 establishes LCs consisting of a heating and a cooling period as in TB 852, but differently from TB 852, it specifies two LC types [17]:

- LCs for warm ambient conditions. They are identical to LCs in TB 852 apart from the fact that during at least the last 1 h—instead of 2 h of TB 852—of the heating period, a conductor temperature $T_{\mathrm{cond,max}}$ and a temperature drop across the insulation $\Delta T_{\max}$ shall be maintained;
- LCs for cold ambient conditions, added to consider the cold laying ambient of submarine cables in deep sea. They are identical to LC for warm ambient conditions apart from the fact that during at least the last 1 h of the heating period, a conductor temperature $\geq T_{\mathrm{cond,cold,max}}$ must be attained; the tolerance on the cable surface temperature must be within $\pm$ 5 K for pressurised cables and $\pm$ 2.5 K for MI cables.

As pointed out above, at Clause 3.4.1 of TB 853, the same scheme for the PQT load cycles of the long duration voltage test is given as in TB 852, specifying that conductor temperature and temperature difference across the insulation shall both be controlled by the maximum design temperatures, which implicitly means that LCs for warm ambient conditions as defined above will be performed. However, an important note is added stating that, if the insulation system is sensitive to low ambient temperature, some of the LCs might be carried out for cold ambient conditions as defined above.

Furthermore, Clause 3.4.1 of TB 853 sets, for the superimposed lightning impulse voltage test (if required) after PQT load cycles, $U_{\mathrm{P1}} = 1.8 \times U_0$ instead of $U_{\mathrm{P1}} = 2.1 \times U_0$ for extruded cables in TB 852, on the basis of the recorded experience in various HVDC lapped cable projects.

At Clause 4 of TB 853, an extension of qualification is given which differs substantially from the EQT at Clause 7 of TB 852. Indeed, Clause 4 of TB 853 first of all states that substantial changes to MI cables must not result in a PQT, but in an extended TT. Such extended TT is applicable only if service conditions differ significantly from previous ones, for example, conductor temperature > 5°C above the previous experience (for more details see Clause 4 of TB 853). As usual, the extended TT differs for LCC versus VSC cables, as Clause 4 of TB 853 prescribes:

- for LCC cables, a TT as in Clause 5 of TB 853 (with load cycles as in Clause 5.6.2 of TB 853, see Table 7), followed by 84 daily load cycles for warm ambient conditions at $1.25U_0$ with 1000 polarity reversals every 2 h;
- for VSC cables, a TT as in Clause 5 of TB 853 (with load cycles as in Clause 5.6.3 of TB 853, see Table 8), followed by 84 daily load cycles for warm ambient conditions at 1.4 U_0.

At Clause 5.6.2 of TB 853, a slightly different scheme for the load cycle test of electrical TTs for LCC cable systems is given with respect to Clause 5.4.2.2 of TB 852: compare Table 7 with Table 6. At Clause 5.6.3 of TB 853, a slightly different scheme for the load cycle test of electrical TTs for VSC cable systems is given with respect to TB 852, Clause 5.4.2.3: compare Table 8 with Table 5. At Clause 5.7.3 of TB 853, slightly different test details for the lightning impulse withstand test (if needed) are given with respect to Clause 5.4.3.4 of TB 852.

As a final peculiarity involving lapped HVDC cable systems, let us mention the transition joints between lapped and extruded cables. Such critical accessory of HVDC cable systems is found especially in submarine HVDC cable links where the land section is extruded and the subsea section is lapped or in cases where extruded cables have replaced lapped cables, as occurred recently in the Kontek link [57]. A fundamental document that can be mentioned for testing transition joints is CIGRE TB 622:2015, entitled 'Recommendations for testing DC transition joints for power transmission at a rated voltage up to 500 kV', published by CIGRE WG B1.42 [58]. As noted explicitly both in TB 853, Clause 1.5.2 and in TB 852, Clause 1.5.2, the tests on transition joints between extruded and lapped HVDC cables must be performed following TB 622. Details are skipped here for the sake of brevity.

9 | Gaps and Issues Not Addressed in TB 852

As highlighted in Section 7, the efforts done in TB 852:2021 to update the testing procedures of HVDC extruded cables are really noteworthy and many novelties have been introduced compared to former TB 496:2021, see Section 8. The same holds

TABLE 7 | Duration, polarity and applied voltage (p.u. of U_0) during TT load cycles for LCC cables according to TB 853, Clause 5.6.2 [17].

Period→	LC	LC	LC + PR
Cycles	10	10	10
Polarity	−	+	±
Voltage (× U_0)	1.8	1.8	1.4
Total days	10	20	30

TABLE 8 | Duration, polarity and applied voltage (p.u. of U_0) during TT load cycles for VSC cables according to TB 853, Clause 5.6.3 [17].

Period→	LC	LC
Cycles	15	15
Polarity	−	+
Voltage (× U_0)	1.8	1.8
Total days	15	30

for TB 853:2021 relevant to HVDC lapped cables with respect to former Electra 189:2000. However—focusing for brevity on TB 852 devoted to the fast-growing extruded cables—as broadly shown in ref. [10], TB 852:2021 still has several gaps and issues not addressed relevant to PQT, TT, TOV, routine and sample tests. Below, they are briefly discussed.

9.1 | Issues Not Addressed in the PQT

First of all, the enlargement of insulation volume in long HVDC links (say, significantly longer than 100 km) versus the ≈100-m long test loops in the PQT is not considered, which statistically entails the introduction of a greater number of defects—possibly also of greater size—in the unavoidably nonuniform insulation of HVDC cable systems. The so-called enlargement law exists to account for these effects for cable length and insulation radii [59], as well as for terminations and joints in the cable line [60], but it is omitted in TB 852 [8, 10].

It is worth pointing out that the enlargement law has a semi-empirical approach, whereby—using the Weibull distribution of breakdown voltages/field strengths of the tested insulation—one estimates the reduction of such breakdown voltages/strengths in the installed cable line compared to those obtained from laboratory tests. Resorting to ad hoc testing strategies, the effect of various inhomogeneities and defects (like voids, semicon protrusions, contaminants and, possibly also, scorch marks), whose number and size increase with the insulation volume, can be accounted for. As a matter of fact, the estimates obtained using the enlargement law in a proper way are well aligned with the experience of cable line failures obtained from the field compared with the evidence coming from laboratory tests [21, 59].

Secondly, the same voltage levels and durations of PQT (and TT) load cycles are kept as in former TB 219:2003 and TB 496:2012, based—for PQT, EQT and TT, as explained above in Section 3.1—on the IPM with $n = 10$, this latter estimated by WG B1.62 as a lower limit for n and left unchanged over 20 years, despite new compounds with n up to 26 have emerged in the market [11, 61, 62]. More investigation on possible new tests to highlight the improved voltage endurance of these new materials is clearly needed [10].

Moreover, PQT, EQT and electrical TTs in TB 852 do not analyse SC effects on long-term reliability of full-size HVDC extruded cables, whereas these effects have been clearly demonstrated in many studies, see, for example, refs. [31, 33, 35, 62–70]. Space charge effects are disregarded also in routine and sample tests. This is apparently not justified now, as CIGRE TB 636:2015 pointed out at Chapter 4 and Appendix 1 that SC measurements on full-size cables are feasible since 2015 at least [11], and recommended at Chapter 4 'to prove that no significant space charge accumulation took place during or after a type test (= TT) or long-term test (= PQT)'. In fact, SC measurements on full-size extruded cables have been done since the 1990s and 2000s [63–66], and great improvements have been achieved in the last 5 years in particular for the PEA technique [35, 67, 68] so that now SC measurements are feasible for insulation thickness up to 88 mm [35], as well as for flexible factory joints [70] and prototypes of premoulded joints for HVDC extruded cables [35, 69]. IEEE 1732-2017 for SC measurements in the qualification of HVDC extruded cables [18], illustrated above at Section 4.3, was already available while WG B1.62 was writing TB 852:2021, but surprisingly, it is not even mentioned among the references of TB 852; this is not in line with CIGRE TB 636:2015 and clearly against what is stated in TB 852, Clause 1.1: 'wherever possible, the tests are based on existing recommendations, standards and practices'. This gap is really puzzling [10].

9.2 | Issues Not Addressed in the TTs and TOV Test

A first issue not fully addressed in TB 852 as for TTs is that more attention to water penetration would be required. Indeed—as pointed out above at Section 4.1 for nonelectrical TTs—in TB 852, Clause 5.3 [8], it is stated that land cables with water blocking systems must undergo the water penetration test per IEC 62895, whereas submarine cables must undergo the water integrity test per CIGRE TB 623. As a matter of fact, the ingress of water along the conductor is much more critical for extruded than for lapped cables, in particular, for the most popular MI type [71]. Indeed, many years of satisfactory service prove that MI insulation, being a mixture containing highly viscous impregnating oil, is self-watertight, thereby strongly limiting water penetration along the conductor even for damages in the deep sea. Although the water performance of extruded cable systems is uncertain and unassessed in the field, particularly in the deep sea, such systems are planned to be installed in HVDC subsea lines at remarkable sea depths [10].

A check is also needed on the manufacturer's method to assess water along the conductor and remove damaged cables. As an example, to prove the efficacy of the suppliers' technique to evaluate water penetration along the conductor, the HVDC extruded cable specification of Terna, the Italian TSO [55], requires that the TT loop includes

- for land cables, 1 earthed joint;
- for submarine cables, 1 field/repair joint.

They are both prepared via the so-called 'assess and remove' method—adapted from Annex E of IEC 62067 [15, 44]—as follows. According to the supplier's procedure to assess water penetration along the conductor, a proper length of cable must be chosen, and a ring ≈50 mm wide must be removed from the centre of the chosen length to expose the conductor. A pipe of diameter ≥ 10 mm sealed to the outer cable surface (Figure E.1 of refs. [15, 44]) must be placed vertically over the exposed conductor, filled with tap water at a temperature of (20 ± 10)°C so that the height of the water in the tube is 2 m above the cable and allowed to stand for 24 h. Thereafter, the sample must undergo 10 heating (≥ 8 h)/cooling (≥ 16 h) cycles. Subsequently, the chosen length must be taken outside the test cell and a cable section must be cut on both sides of the exposed conductor of length according to the supplier's procedure to assess water penetration along the conductor. In this way, the original chosen length is split in two different cable lengths, each supposed to be water-free. In the end, a joint must be manufactured to link these two different cable lengths into one single cable, which must be eventually included in the TT cable loop. As this procedure was shown to be practical and feasible, it could become part of the revision of TB 852 and/or of forthcoming standards on HVDC extruded cables [10].

Gaps are also found as far as the superimposed impulse voltage test of electrical TTs is concerned, see Clause 5.4.3 of TB 852. Indeed, only superimposed lightning impulses of opposite polarity (SLIOP) to DC voltage U_0 are prescribed at Clause 5.4.3.4; similarly, for LCC cables, only superimposed switching impulses of opposite polarity (SSIOP) to U_0 are prescribed at Clause 5.4.3.2, whereas for VSC cables, both superimposed switching impulses of the same polarity (SSISP) as U_0 and of the opposite polarity (SSIOP) to U_0 are prescribed at Clause 5.4.3.3. In this respect, it is worth noting that on the one hand, it makes sense to apply different test schemes for VSC versus LCC cables, particularly, because the transient performance of VSC systems is not completely assessed, but on the other hand such different test schemes should be employed not only for superimposed switching but also for superimposed lightning impulses. Indeed, if a shielding failure happens in a DC overhead plus cable line with VSC, then lightning impulses of the same polarity as DC voltage U_0 might also take place [10]. To scan also these events and the overall performance of VSC systems under voltage impulses, the HVDC extruded cable system specifications issued by a few main TSOs in the world include lightning impulses of the same polarity as and of the opposite polarity to U_0, see, for example, ref. [55].

More focus is needed also on TOV tests, which in Clause 12 of TB 852 are conceived as special tests to be performed for engineering purposes only to verify that long TOVs associated in particular with VSC in novel grid schemes for some projects are acceptable for the HVDC extruded cable system [8]. On the other hand, VSC HVDC cable systems are becoming more and more widespread with a scarcity of operational records [10]. For this reason, long TOV tests have been included among electrical TTs in the HVDC extruded cable specifications of a few utilities [55], and the same solution might be considered in future standard documents on HVDC extruded cable systems.

9.3 | Issues Not Addressed in Routine and Sample Tests

As highlighted above at Sections 5.2, in TB 852, the AC voltage test with PD measurement (if applicable) is [8]:

- recommended as a routine test on pre-moulded joints (PMJ) and terminations at Clause 8.2.1;
- suggested as a routine test on flexible factory joints (FFJ) of submarine cables at Clause 8.2.2;
- prescribed as a sample test on FFJ for submarine cables at Clause 9.3.2.

IEEE 2862-2020 for PD measurement under AC voltage with wireless sensors in routine tests for HVDC extruded cable system joints [19, 38], illustrated above at Section 5.3, was issued a year before TB 852:2021, and it still represents to date the only standard document recommending a procedure—with solid grounds based on suppliers' practices—for PD measurements under AC voltage during routine tests on FFJ and PMJ of HVDC extruded cables. Nevertheless—once more surprisingly against the commitment in TB 852, Clause 1.1, to base the tests on existing recommendations, standards and practices—IEEE 2862-2020 is not even included among the references of TB 852. Also this gap is really puzzling, exactly in the same way as noted above for IEEE 1732 during PQT and TT. Maybe in this case, the missing reference to IEEE 2862-2020 is even more critical, as it concerns a prescribed/recommended/suggested routine/sample test on joints, a critical component of HVDC extruded cable systems [10].

As a final remark to the above gaps and issues not addressed in the reference standard for HVDC extruded cable systems testing, that is, TB 852, this might also be due to the scarce involvement of the academy not only in the R&D process of HVDC cable systems but also in the development of CIGRE and IEC documents. The wider interest of utilities in new domestic and cross border HVDC interties might hopefully pave the way towards a stronger synergy between the academy and industry in the development of future HVDC cable system standards [10].

10 | HVDC Cable System Testing Equipment

This section briefly illustrates the main equipment that is used for electro-thermal tests on HVDC cable systems, with focus on qualification tests of full-size cable loops.

As made clear in the previous sections, HVDC cable system testing at all stages—R&D, qualification, routine and sample and after installation—requires of course, first of all, a constant high DC test voltage, U_{DC}. To generate high values of U_{DC}, the so-called Cocroft–Walton scheme generator—or other cascade type circuits—is usually employed, whereby the AC voltage of an HV transformer is rectified and multiplied via diodes and capacitors. The HVDC test generator must have a robust mechanical, electrical and thermal design for a reliable operation in HV test bays, as well as a low PD level. The generated U_{DC} has to comply with the requirements of IEC 60060-1—among which voltage ripple $\delta = (U_{max} - U_{min})/2 \leq \pm 3\%$ of U_{DC} for tests longer than 60 s [20]—and the voltage measurement dividers with those of IEC 60060-2 [72].

HVDC test generators are generally provided as single modular units—a common module size has 400 kV-DC voltage rating and current rating in the range 20–40 mA [73]—that can be combined to raise the total DC output voltage. For example, Figure 4 shows a modular HVDC test generator consisting of 3 modules of 400 kV-DC each, providing a total output voltage of 1200 kV-DC. Some generators may allow either stationary or movable applications using an air cushion system. Modularity and mobility of HVDC test generators are desirable to enable different test conditions, series/parallel connection and ease of transport, with short times required for generator reconfiguration when the load is changed [73].

The HVDC generator must enable voltage PR with a recommended time duration ≤ 2 min [8, 12]. Thus, the generator must provide a high-enough DC charging current to quickly recharge the test object; if one generator is used, PR time is mostly due to the PR of the diodes within the generator (see details in ref. [20]). PRs are required for both test periods at different polarity and LC + PR cycles of PQT, EQT and TT after TB 852/853, see Sections 3.1, 3.2, 4.2, 8 and Tables 1–8.

The block diagram of Figure 5 shows a commercially available HVDC test generator system. The generator (No. 3) is fed by a switch (No. 1) and a regulating transformer (No. 2), which adjusts the test voltage. The voltage measurement system consists of an internal resistive voltage divider and a peak voltmeter (No. 14), whereas the current measurement system consists of a current shunt (No. 7) and a current metre (No. 13). A proper control system (Nos. 8–12) manages and regulates the test system, recording the measured data. The test object (= cable loop) is connected via an external damping (blocking or protective) resistor (No. 5), which protects the DC generator against overvoltages. Typically, the resistor can be switched between high-ohmic and low-ohmic position, respectively, for testing and discharging purposes, as it consists of two parallel branches [20, 73]:

- a high resistance branch (= high-ohmic position) steadily connected in parallel to the source;
- a low resistance branch (low-ohmic position) triggered when the cable has to be discharged.

FIGURE 4 | Modular HVDC test generator system providing a total output voltage of 1.2 MV-DC (Courtesy HIGHVOLT Prüftechnik Dresden GmbH, Germany) [72].

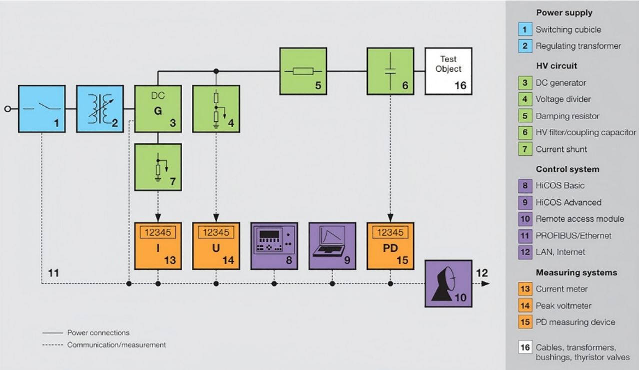

FIGURE 5 | Block diagram of a modular HVDC test system (Courtesy HIGHVOLT Prüftechnik Dresden GmbH, Germany) [73].

As reported in Sections 2–4, R&D and qualification tests on HVDC cable systems also require the superimposed impulse voltage test, that is, the application of switching or lightning (for cable lines exposed to lightning) voltage impulses overlapped onto the DC voltage. Two voltage sources are needed for this test, creating a technical challenge for the setup preparation (Figure 6). The main needs of this test are isolation of the HVDC generator from the impulse generator via the above-mentioned protective resistor and a voltage divider to measure the superimposed impulse voltage [20, 74]. Thus, the test set-up must combine different elements allowing all these functions.

In particular, as mentioned in Section 3.1, TB 852 and TB 853 allow the HVDC generator and the impulse generator to be connected via two possible means [20, 75]:

1. the so-called 'blocking capacitor', acting as an open circuit to the DC voltage—thus decoupling the HVDC generator from the impulse generator—but with low enough impedance to voltage impulses so as to transfer them to the test object. Because the capacitor is a permanent connection, it has to withstand the full DC voltage;
2. a spark gap. Then, the impulse generator is connected to the cable as soon as the spark gap is triggered.

The blocking capacitor and the spark gap have pros and cons, which are treated in detail in ref. [20].

Particularly challenging is the slow front TOV test facility, see Clause 12.3 of TB 852 and Clause 8.3 of TB 853, as it requires the combination and synchronised triggering of DC and impulse voltage sources, as well as of multiple switching/coupling devices, see the schemes of Figures 9 and 10 in TB 852. A practical implementation of Figure 9 in TB 852 is reported in Figure 7.

As a closing remark to testing facilities, let us emphasise that major technical issues that have to be faced in the design of

FIGURE 6 | Combined DC and impulse voltage test system (Courtesy HIGHVOLT Prüftechnik Dresden GmbH, Germany).

FIGURE 7 | TOV system with an extra large capacitance impulse system and spark gap (Courtesy HIGHVOLT Prüftechnik Dresden GmbH, Germany).

HVDC test systems are the different voltage stresses that give rise to the overall field distribution. For example, when a flashover or breakdown of the test object happens, the HVDC test system must bear high voltage transients, often followed by swift polarity reversals; then, the DC electric field, which is mainly resistive, is overlaid by a fast capacitive field [20, 76].

11 | Peculiarities of Submarine Cables: TB 490

A document which can also be useful for HVDC cable system testing to account for the peculiarities of submarine cables is CIGRE TB 490:2012, entitled 'Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30 (36) to 500 (550) kV' [13]. As hinted at in Section 1, TB 490 is valid, strictly speaking, for AC extruded cables and accessories only, but in practice it is a useful reference also for testing HVDC cables and accessories, in particular, as far as mechanical tests and/or water penetration tests are concerned. The aim of the work by CIGRE WG B1.27, which developed TB 490, was to assess how extruded AC submarine cable systems should be tested mechanically and electrically (with special focus on repair joints) and to include the improvements in PD techniques and AC resonant test techniques to revise earlier recommendations—first and foremost after the former document for AC extruded submarine cables published in Electra No. 189:2000 [28]. This was done by introducing and modifying various tests of which the following are also interesting for HVDC cable systems:

- tests for a stricter quality check of factory joints;
- AC-tests on delivery lengths with frequency in the range 10—500 Hz after IEC 60060-3 [77] (see AC voltage test at Clause 8.1.1 of TB 852);
- a radial water penetration test of rigid repair joints;
- a mechanical testing scheme for different types of repair joints;
- a test set for visual inspection of submarine cables;
- a test set for volume resistivity of conductive polymeric sheaths.

A detailed analysis of TB 490 would take too much space and would also be out of scope for this paper. In summary, let us highlight that TB 490 can be divided ideally into two parts:

1. a descriptive part. This part includes an introductory background, the main relevant definitions and experiences on extruded HVAC/EHVAC subsea cables, the current technologies for subsea cable designs (focusing on general aspects about water tightness, conductors, insulation system, metal screen/sheath, amour, outer protection, all of which applicable also to HVDC cables apart those for the insulation system) and for submarine joint designs (focusing on factory, repair, sea/land transition joints);
2. a test part, basically structured as follows:
   - Routine tests
     - Test on manufactured length
     - Test on factory installed joints
     - Tests on complete delivery length (which may be deemed as a factory acceptance test for the delivery length, see TB 490, Clause 6.5)
   - Sample tests
     - Sample tests on the cable
     - Sample tests on the joint
   - Type tests
     - Mechanical tests on a complete cable
     - Electrical tests on a complete cable
     - Nonelectrical tests on cable components and on the complete cable
   - Pre-qualification tests (not relevant for HVDC cable systems)
   - Extension of qualification tests (not relevant for HVDC cable systems).

As for the direct relationship between TB 490 and TB 852, the latter refers straightforwardly to the former as for the frequency of the AC voltage routine test on transmission cables at Clause 8.1.1—for which a frequency in the range 10–500 Hz is recommended after TB 490, see Clauses 5.2.2 and 6.1—as well as for the water penetration sample test on submarine transmission cables at Clause 9.1.13—for which the procedure at Clause 8.7.2 of TB 490 is recommended apart from the fact that no mechanical preconditioning is required [8, 13].

12 | Mechanical Tests: TB 623

Within the same CIGRE WG B1.27 which issued TB 490, the WG B1.43 was formed that eventually prepared CIGRE TB 623:2015 entitled 'Recommendations for mechanical testing of submarine cables' [14], and in fact some direct relationships are found between TB 490 and TB 623. Differently from the former, the latter is applicable to both extruded and lapped (MI and oil-filled) cable systems with rated voltages above 30 (36) kV-AC or 60 kV-DC, covering both shallow and deep sea installations [14]. When preparing TB 623, WG B1.43 aimed at improving the recommendations for mechanical tests on submarine cables after former Electra 171:1997 [78] relying on the increase of experience, maximum installation depth and number of applications of subsea cable systems, also in a consistent manner with the closer in time TB 490:2012 [13, 14].

TB 623 is divided in two parts as follows:

1. description of the background of mechanical handling of cables all over their life cycle and of the generalities of the relevant tests (chapters 3 and 4);
2. description of the tests that are recommended or may be performed (chapters 5 and 6).

As outlined at Clause 1.2 of TB 623, the main issues covered by TB 623 are as follows:

- a review of cable installation methods and cable protection for submarine cables including both AC and DC lapped and extruded cables;
- analysis of relevant standard documents from IEC and CIGRE, as well as from the offshore industry;
- risk assessment of mechanical damage during installation—and relevant cable protection—as well as after installation (anchoring, drag-net fishing, etc.);
- updated computation of tensile tests and a more detailed background description for the chosen factors (security factors, torsion, dynamic forces);
- test methods for
    - installation of dynamic cable systems
    - very deep sea installation—for extruded cables too
    - impact tests
- heat cycling effects on the metallic sheath and prospective test methods;
- updated/new mechanical tests for rigid joints;
- special tests for free-span, strumming, cable interaction with J-tubes, bend restrictors etc.

As for the relationship between TB 623 and TB 852, the latter refers directly to the former for nonelectrical type tests at Clause 5.3, where (see Section 4.1) [8, 14]

- the water integrity testing as specified in TB 623 (see Pressure and Water Penetration Tests on Paper Lapped Cable Types at Clause 5.3 and Pressure and Water Penetration Tests on Extruded Cable Types at Clause 5.4 of TB 623, which in turn refers to Clauses 8.7.1 and 8.7.4 of ref. [13]) is prescribed for cable systems meant to be installed as submarine cables, pointing out that such test also qualifies the tested water-blocking technology for underground installation;
- the test for cables with metallic earthing connections through plastic sheaths in TB 623 (see Clauses 5.3.1 and 5.3.2 of TB 623 within the Pressure and Water Penetration Tests on Paper Lapped Cable Types, and Clause 5.4.2 of TB 623 within the Pressure and Water Penetration Tests on Extruded Cable Types; these clauses are not explicitly mentioned in TB 852) is prescribed for such kind of cables.

Furthermore, TB 852 also refers directly to TB 623 as for mechanical preconditioning for submarine cable systems before electrical TTs at Clause 5.4.1, prescribing the coiling test after TB 623, Clause 5.1 (if applicable), the tensile bending test after TB 623, Clause 5.2, and a tensile test after TB 623, Clause 5.5 (if applicable), as well as for the visual examination after mechanical preconditioning, prescribing the visual inspection according to Clause 5.1.4 of TB 623 [8, 14].

Beside these TTs recommended at Chapter 5, TB 623 was added in Chapter 6—entitled 'Project specific tests and special tests'—some additional tests that can be selected for engineering purposes in case common design values are exceeded, or major differences are found for loading, installation, operation, repair, cable handling, for example, crush test, sidewall force test, impact test, pulling stocking test, handling test for rigid joint and sea trial.

Details on such tests are skipped here apart from the sea trial test on which, for its significance, Section 13 is focused.

13 | Focus on the Sea Trial Tests

The sea trial test is described in Clause 6.9 of TB 623. In summary, according to Clause 6.9.1, the purpose of this test is to check [14]

- the ability of the submarine cable system to be laid, installed and repaired both in shallow waters and up to the maximum target burial depth, that is, the maximum depth of installation expected;
- the validity of the cable installation and recovery equipment;
- the operation of the equipment for installation of the mechanical protection of the cables at the maximum depths at which this protection is expected;
- the behaviour of the joints during the various stages of the installation.

The sea trial is not meant as a qualification test of the cable system design; hence, changes in the mechanical construction of the cable system will not normally motivate a sea trial. The focus of the sea trial test is on the interaction between submarine cable and installation equipment. Particularly, in special situations—for example, installation is close to operation limits of laying spread, installation and protection techniques differ a lot from common practical cases etc.—the sea trial may be needed to prove the installation capability of the equipment. The sea trial can include the laying vessel, but it can also focus on other aspects, for example, post lay protection; it includes mechanical tests to reproduce real installation as closely as possible, but also laboratory tests are suggested to control loads during installation in advance and to introduce safety factors. Overall, the sea trial is in practice a very costly test, typically asked by utilities in quite peculiar cases [14].

More details about the sea trial test are given at Clauses 6.9.2, 6.9.3 and 6.9.4 of TB 623 in particular [14]:

- as for the preparations and conditions, Clause 6.9.2 states that the object under test depends on the issues to be tested during the sea trial. Accessories like repair joints, field joints, factory joints and earthing connections between metallic sheath and armour are only included if relevant for the issues addressed;
- as for the test itself, Clause 6.9.3 states that the laying spread, the equipment used, the laying conditions and the tested cable system must be representative of the actual conditions for the cable installation on site;
- as for the discussion of requirements, Clause 6.9.4 emphasises that the tests to be performed after the sea trial test depend on the issues to be analysed and recommends the following tests:
    - Electrical test: after the sea trial test, the cable test length must undergo an electrical test at a minimum voltage level corresponding to an after laying test (= test after installation of TB 852, Clause 11.1). Additional/alternative electric tests can be agreed between the supplier and utility.
    - Visual inspection: after the electrical test, the tested sample must undergo a visual inspection aiming at checking the presence of significant damage and water leaks.
    - Optical fibre (OF): if the sample contains an OF, the integrity of the OF must be checked after the sea trial test. Acceptance criteria and other additional tests can be agreed between the supplier and utility: for example, during the sea trial, one optical time domain reflectometry (OTDR) monitoring via OF could be conducted.

As a noteworthy and recent example of a sea trial test, let us consider the sea trial performed for the Tyrrhenian Link [79], a ± 500 kV-DC MI VSC bipolar cable line that is being realised by Terna to connect the Italian mainland with the two largest islands in Italy, namely Sicily and Sardegna. As shown in Figure 8, the Tyrrhenian Link consists of two separate lines: the East Tyrrhenian Link (ETL) linking Italian mainland to Sicily via 33 km of the land cable plus 484 km of the submarine cable and the West Tyrrhenian Link (WTL) linking Sicily to Sardegna via 42 km of the land cable plus 482 km of the submarine cable, this latter reaching the worldwide record laying a depth of 2150 m [79].

Marine surveys for this project showed a very harsh cable route, with high sea depths reached for both the ETL and the WTL, as well as slopes locally > 40° in canyons. Moreover, protection performance was deemed opportune up to 800 m depth due to anthropic activities related to fishing with nets and trawlers. For this reason, a sea trial test based on TB 623, Clause 6.9, was requested by Terna and planned together with the supplier (Prysmian Cables and Systems).

FIGURE 8 | Route of the HVDC Tyrrhenian link. *Source:* Reprocessed from ref. [80].

Due to the great significance and challenges of this project, testing the repair and installation procedure of the cable and accessories under the worst conditions at the maximum expected mechanical stress for each component was deemed as the first and foremost priority. For this reason, three dedicated sea installation sea trial tests were planned—each at the maximum water depth foreseen for the cable—as follows [79]:

1. shallow water installation sea trial with shallow water cable plus 1 repair joint and 1 transition joint with the deep water cable;
2. deep water installation sea trial with the deep water cable plus 1 repair joint and 1 factory joint;
3. ultra-deep water installation sea trial with the ultra-deep water cable with 1 repair joint plus 1 flexible factory joint plus 1 transition joint with a deep water cable.

The deep water installation sea trial test was done on a ≈4.5-km long deep water cable plus 1 deep water in-field/repair joint. Similar procedures were adopted for shallow water and ultra deep water installation sea trial tests. In summary, the test procedure was as follows:

1. installation of a portion of the deep cable at the maximum expected water depth in the project;
2. manufacturing of the deep in-field/repair joint on the cable laying vessel while the cable is tensioned on the ship (like in a real in-field/repair joint activity);
3. installation of the deep repair joint at the maximum expected water depth in the project;
4. recovery of whole installed cable sample and accessories after ≥ 30 min with cable sample installed and tensioned on the ship;
5. whole cable sample downloaded in the factory and submitted to a voltage test at $-1.4 \times U_{\mathrm{DC}} = -700$ kV for ≥ 15 min (see ref. [8], Clause 11.1);
6. visual examination of the cable sample and accessories.

Moreover, a burial installation test was also requested with both trenching and jetting using the deep water cable at a water depth ≥ 300 m. The burial installation test was done on a submarine deep water cable sample ≈1 km long. In summary, the test procedure was as follows:

1. cable sample installation with the laying vessel at sea depth > 300 m;
2. bury ≥ 200 m of the cable with the trenching tool;
3. bury ≥ 200 m of the cable with the jetting tool;
4. check of the burial depth of the whole cable sample;
5. recover the cable sample with the cable laying vessel;
6. cable sample downloaded in the factory and submitted to a voltage test at $-1.4 \times U_{DC} = -700$ kV for ≥ 15 min (see ref. [8], Clause 11.1);
7. visual examination of the cable sample and accessories;
8. if the seabed was not suitable for both burial tools, the cable sample is installed in a different location to test the tool that could not be tested.

Let us emphasise that the installation and the burial tests for the Tyrrhenian Link were all successful, with no breakdown during the voltage test and no visible damage during the visual examination of cable lengths and joints [79], thereby proving the ability of the cable system to withstand the challenges set by the harsh marine environment during installation and burial.

14 | Conclusions

This paper has reviewed the existing HVDC cable system testing techniques, following as a backbone the structure of CIGRE TB 852:2021 because it has a fairly similar structure to CIGRE TB 853:2021 for lapped DC cables, and especially because of the impressive spread of HVDC extruded cables experienced worldwide in the last 25 years. Development, qualification, extension of qualification, type, routine, sample and after installation tests after TB 852 have been reviewed, highlighting the main novelties of TB 852 with respect to previous standards—with focus on the so-called TOV tests—together with the limits and gaps of TB 852. The review has also analysed some details of TB 853 for lapped HVDC cable systems, as these cables remain unbeaten for submarine applications at the highest sea depths. The main HVDC cable system electrothermal testing equipment that is usually employed has also been treated. Emphasis has been given to TB 490 to highlight the peculiarities of submarine cable systems, as well as to mechanical tests, having TB 623 as a reference, with particular focus on the special sea trial tests. An example of an innovative sea trial testing procedure has been shown, which is the outcome of a fruitful partnership between a cable manufacturer and the national TSO in Italy.

The paper has shown that a big deal of tests has been implemented in order to check the quality and the performance of developed, designed, manufactured and installed HVDC cable systems. These tests have been essential to reach the high level of voltage and power ratings of state-of-the-art HVDC cable technology. If on the one hand lapped HVDC cable systems, being in use since long time with very good performance, are perhaps close to a 'full maturity' and the relevant testing procedures are close to an asymptote, on the other hand, tests still need to be continuously refined and—if deemed necessary—enhanced for HVDC extruded cable systems. Indeed, these latter are still being further developed to attain higher ratings, and their service experience and records are much less—and date back to a much shorter time—than for HVDC lapped cables, especially for submarine cable systems at high sea depths. In these respects, if it is true that manufacturers have attained a great experience and knowledge on such cable systems, it seems that the scientific-technologic in-depth theoretical and empirical studies being carried out at research institutions and universities can still be useful for improving testing techniques of HVDC extruded cable systems. Hence, let us hope that a stricter synergy and cooperation can be pursued and followed between suppliers, utilities, research institutions and universities in the next years.

Here, it follows a very synthetic set of guiding principles on how to select appropriate testing standards for the various types of HVDC cables and application scenarios of the cable line. The starting point is a check of the cable insulation type:

1. if cable insulation is extruded, refer to TB 852, plus
    a. for land cables, IEC 62895 (check for latest issue);
    b. for submarine cables, TB 623 and TB 490 (this latter as far as applicable);
2. if cable insulation is lapped, refer to TB 853;
3. if cable line includes both extruded and lapped lengths
    a. for extruded lengths, go to point 1 above;
    b. for lapped lengths, go to point 2 above;
    c. for the transition joint, refer to TB 622.

Acknowledgements

The author greatly acknowledges Hellenic Cables, Greece, which provided a precious picture of qualification loops of 525 kV HVDC extruded submarine and land cable systems. The author greatly acknowledges HIGHVOLT Prüftechnik Dresden GmbH, Germany, which provided helpful and interesting pictures of HVDC cable testing set-ups.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

Data sharing not applicable—no new data generated, or the article describes entirely theoretical research.

References

1. G. Mazzanti, "Issues and Challenges for HVDC Extruded Cable Systems," *Energies*, paper no. 4504 14, no. 15 (2021): 1–34.

2. J. C. Fothergill, "The Coming of Age of HVDC Extruded Power Cables," in *2014 IEEE Electrical Insulation Conference (EIC)* (2014), 124–137.

3. M. Jeroense, "Editorial," *IEEE Electrical Insulation Magazine* 36, no. 1 (2020): 3–5.

4. Y. Ohki, "News From Japan—World's First DC 400-kV XLPE Cable System," *IEEE Electrical Insulation Magazine* 36, no. 2 (2020): 50–52.

5. 50Hertz Transmission GmbH, Amprion GmbH, Tennet TSO GmbH, and TransentBw GmbH, "Grid Development Plan (GDP) 2030, 2nd Draft, German TSOs, Berlin, Germany," Tech. Rep. (2019).

6. G. Mazzanti, "High Voltage Direct Current Transmission Cables to Help Decarbonisation in Europe: Recent Achievements and Issues," *High Voltage* 7, no. 4 (2022): 633–644.

7. "Adriatic Link: The New Centre-South and Centre-North Connection," Terna Driving Energy, accessed March 17, 2025.

8. Brochure CIGRE 852: Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 800 kV, CIGRE WG B1.62, (2021).

9. Brochure CIGRE 496: Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV, CIGRE WG B1.32, (2012).

10. G. Mazzanti, M. Marzinotto, and A. Battaglia, "Critical Review of Cigrè Technical Brochure 852," in *2023 AEIT HVDC International Conference (AEIT HVDC 2023)* (2023), 1–6.

11. Brochure CIGRE 636: Diagnostic and Accelerated Life Endurance Testing of Polymeric Materials for HVDC Application, CIGRE WG D1.23, (2015).

12. High Voltage Direct Current (HVDC) Power Transmission Cables With Extruded Insulation and Their Accessories for Rated Voltages up to 320 kV for Land Applications—Test Methods and Requirements, IEC 62895, (2017).

13. Brochure CIGRE 490: Recommendations for Testing of Long AC Submarine Cables With Extruded Insulation for System Voltage Above 30 (36) to 500 (550) kV, WG B1.27, (2012).

14. Brochure CIGRE 623: Recommendations for Mechanical Testing of Submarine Cables, WG B1.43, (2015).

15. Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 150 kV (U_m = 170 kV) up to 500 kV (U_m = 550 kV)—Test Methods and Requirements, IEC 62067, Ed. 2.0, (2011).

16. M. Jeroense, P. Bergelin, T. Quist, A. Abbasi, H. Rapp, and L. Wang, "Fully Qualified 640 kV Underground Extruded DC Cable System," Paper B1-309 in *CIGRE Session* (2018).

17. Brochure CIGRE 853: Recommendations for Testing DC Lapped Cable Systems for Power Transmission at a Rated Voltage up to and Including 800 kV, CIGRE WG B1.66, (2021).

18. IEEE Recommended Practice for Space Charge Measurements in HVDC Extruded Cables for Rated Voltages up to 550 kV, IEEE Standard 1732-2017, (2017).

19. IEEE Recommended Practice for Partial Discharge Measurements Under AC Voltage With VHF/UHF Sensors During Routine Tests on Factory and Pre-Molded Joints of HVDC Extruded Cable Systems up to 800 kV, IEEE Standard 2862-2020, (IEEE, 2021).

20. M. Albertini, S. F. Bononi, S. Giannini, G. Mazzanti, and N. Guerrini, "Testing Challenges in the Development of Innovative Extruded Insulation for HVDC Cables," *IEEE Electrical Insulation Magazine* 37, no. 6 (2021): 21–32.

21. G. Mazzanti and M. Marzinotto, "Extruded Cables for High Voltage Direct Current Transmission: Advances in Research and Development," in *IEEE Press Series on Power Engineering* (Wiley-IEEE Press, 2013).

22. G. Mazzanti, "What Have We Still to Learn About the Inverse Power Model?," in *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (IEEE CEIDP 2016)* (2016), 959–962.

23. G. Mazzanti, "Life and Reliability Models for High Voltage DC Extruded Cables," *IEEE Electrical Insulation Magazine* 33, no. 4 (2017): 42–52.

24. G. Mazzanti, "Updated Review of the Life and Reliability Models for HVDC Cables," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 4 (2023): 1371–1390.

25. Impulse Tests on Cables and Their Accessories, IEC 60230, Ed. 2.0, (2018).

26. High-Voltage Test Techniques. Part 1: General Definitions and Test Requirements, IEC 60060-1, Ed. 3.0, (2010).

27. Brochure CIGRE 219: Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 250 kV, CIGRE WG 21-01, (2003).

28. ELECTRA n. 189: Recommendations for Testing of Long AC Submarine Cables With Extruded Insulation for System Voltage Above 30 (36) to 150(170), CIGRE WG 21.02, (2000).

29. ELECTRA n. 189: Recommendations for Tests of Power Transmission DC Cables for a Rated Voltage up to 800 kV (ELECTRA 72, 1980—Revision), CIGRE WG B1.16,(2000).

30. Brochure CIGRE 446: Advanced Design of Metal Laminated Coverings: Recommendation for Tests, Guide to Use, Operational Feed Back, CIGRE WG B1.25, (2011).

31. G. Mazzanti, G. Chen, J. Fothergill, et al., "A Protocol for Space Charge Measurements in Full-Size HVDC Extruded Cables," *IEEE Transactions on Dielectrics and Electrical Insulation* 22, no. 1 (2015): 21–34.

32. M. Marzinotto, Albertini, M., Benard, L., Charles, F., and Hondaâ, P., "Cable System Qualification Process for the Italy—France HVDC Intertie," Paper B1-109 in *CIGRE Session* (2016), 1–11.

33. P. Romano, A. Di Fatta, A. Imburgia et al., "PEA Measurement on 525 kV HVDC Cable Compliant With IEEE 1732 Recommendation," in *2024 IEEE Conference on Electrical Insulation and Dielectric Phenomena* (2024), 1–4.

34. G. Mazzanti, "Space Charge Measurements in High Voltage DC Extruded Cables in IEEE Standard 1732," *IEEE Electrical Insulation Magazine* 33, no. 4 (2017): 9–15.

35. N. Hozumi, "Space Charge Measurement Techniques for Practical Insulation Systems," in *2023 4th IEEE International Conference on Electrical Materials and Power Equipment (IEEE ICEMPE)* (2023), 1–8.

36. J. Castellon, P. Notingher, S. Agnel, et al., "Electric Field and Space Charge Measurements in Thick Power Cable Insulation," *IEEE Electrical Insulation Magazine* 25, no. 3 (2009): 30–42.

37. Tests on Cable Oversheaths Which Have a Special Protective Function and Are Applied by Extrusion, IEC 60229, Ed. 3, (2007).

38. G. Mazzanti, "Bulletin Board: Activities of the DEIS Technical Committee on 'HVDC Cable Systems (Cables, Joints and Terminations)' for the Development of IEEE Std. 2862-2020," *IEEE Electrical Insulation Magazine* 37, no. 5 (2021): 48–50.

39. G. Mazzanti, J. Castellon, G. Chen, et al., "The Insulation of HVDC Extruded Cable System Joints. Part 1: Review of Materials, Design and Testing Procedures," *IEEE Transactions on Dielectrics and Electrical Insulation* 26, no. 3 (2019): 964–972.

40. G. Mazzanti, J. Castellon, G. Chen, et al., "The Insulation of HVDC Extruded Cable System Joints. Part 2: Proposal of a New AC Voltage PD Measurement Protocol for Quality Control During Routine Tests," *IEEE Transactions on Dielectrics and Electrical Insulation* 26, no. 3 (2019): 973–980.

41. Brochure CIGRE 841: After Laying Tests on AC and DC Cable Systems With New Technologies, WG B1.38, (2021).

42. M. Bawart, M. Marzinotto, and G. Mazzanti, "Diagnosis and Location of Faults in Submarine Power Cables," *IEEE Electrical Insulation Magazine* 32, no. 4 (2016): 24–37.

43. Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV (U_m = 36 kV) up to 150 kV (U_m = 170 kV)—Test Methods and Requirements, IEC 60840, Ed. 5.0 (2020).

44. Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 150 kV (U_m = 170 kV) up to 500 kV (U_m = 550 kV)—Test Methods and Requirements, IEC 62067, Ed. 3.0, (2022).

45. Brochure CIGRE: Surge and Extended Overvoltage Testing of HVDC Cable Systems, CIGRE JWG B4/B1/C4.73, (2025).

46. T. Karmokar, M. Saltzer, S. Nyberg, S. Mukherjee, and P. Lundberg, "Evaluation of 320 kV Extruded DC Cable System for Temporary Overvoltages by Testing With Very Long Impulse Waveform," Paper B1-123 in *CIGRE Session* (2018), 1–11.

47. M. Saltzer, M. Goertz, S. Wenig, et al., "Overvoltages Experienced by DC Cables Within an HVDC Transmission System in a Rigid Bipolar Configuration," Paper C5.1 in *10th International Conference on Insulated Power Cables (Jicable'19)* (2019), 1–6.

48. H. Saad, P. Rault, and S. Dennetière, "Study on Transient Overvoltages in Converter Station of MMC-HVDC Links," *Electric Power Systems Research* 160 (2018): 397–403.

49. S. Dennetière, H. Saad, A. Naud, and P. Hondaa, "Transients on DC Cables Connected to VSC Converters," Paper A10.4 in *9th Jicable* (2015).

50. M. Goertz, S. Wenig, S. Beckler, C. Hirsching, M. Suriyah, and T. Leibfried, "Analysis of Cable Overvoltages in Symmetrical Monopolar and Rigid Bipolar HVDC Configuration," *IEEE Transactions on Power Delivery* 35, no. 4 (2019): 2097–2107.

51. M. Goertz, S. Wenig, S. Beckler, C. Hirsching, M. Suriyah, T. Leibfried, "Overvoltage Characteristics in Symmetrical Monopolar HB MMC-HVDC Configuration Comprising Long Cable Systems," in *Proceedings of the International Conference on Power Systems Transients* (2019), 1–6.

52. G. Mazzanti and B. Diban, "The Effects of Transient Overvoltages on the Reliability of HVDC Extruded Cables. Part 1: Long Temporary Overvoltages," *IEEE Transactions on Power Delivery* 36, no. 6 (2021): 3784–3794.

53. G. Mazzanti and B. Diban, "The Effects of Transient Overvoltages on the Reliability of HVDC Extruded Cables. Part 2: Superimposed Switching Impulses," *IEEE Transactions on Power Delivery* 36, no. 6 (2021): 3795–3804.

54. G. Mazzanti, "Improved Evaluation of the Life Lost by HVDC Extruded Cables due to Long TOVs," *IEEE Transactions on Power Delivery* 37, no. 3 (2022): 1906–1915.

55. Terna Specification PRHM0711, Technical Specification for Construction and Testing of HVDC MIND Cable, (2022).

56. ELECTRA n. 218: Addendum to 'Recommendations for Tests of Power Transmission DC Cables for a Rated Voltage up to 800 kV', Task Force B1.16, (2005).

57. Y. Ohki, "News From Japan," *IEEE Electrical Insulation Magazine* 40, no. 6 (2024): 23–26.

58. Brochure CIGRE 622: Recommendations for Testing DC Transition Joints for Power Transmission at a Rated Voltage up to 500 kV, CIGRE WG B1.42, (2015).

59. M. Marzinotto and G. Mazzanti, "The Statistical Enlargement Law for HVDC Cable Lines. Part 1: Theory and Application to the Enlargement in Length," *IEEE Transactions on Dielectrics and Electrical Insulation* 22, no. 1 (2015): 192–201.

60. G. Mazzanti and M. Marzinotto, "Advanced Electro-Thermal Life and Reliability Model for High Voltage Cable Systems Including Accessories," *IEEE Electrical Insulation Magazine* 33, no. 3 (2017): 17–25.

61. Y. Ohki, "News From Japan—Development of XLPE-Insulated Cable for High-Voltage DC Submarine Transmission Line (1)," *IEEE Electrical Insulation Magazine* 29, no. 4 (2013): 65–67.

62. C. Watanabe, Y. Itou, H. Sasaki, et al., "Practical Application of ±250 kV DC-XLPE Cable for Hokkaido-Honshu HVDC Link," Paper B1-110 in *CIGRE Session* (2014).

63. N. Hozumi, H. Suzuki, T. Okamoto, K. Wakanabe, and A. Watanabe, "Direct Observation of Time Dependent Space Charge Profiles in XLPE Cable Under High Electric Field," *IEEE Transactions on Dielectrics and Electrical Insulation* 1, no. 6 (1994): 1068–1076.

64. T. Takeda, N. Hozumi, H. Suzuki, et al., "Space Charge Behavior in Full Size 250 kV DC XLPE Cables," *IEEE Transactions on Power Delivery* 13, no. 1 (1998): 28–39.

65. T. Yamanaka, S. Maruyama, and T. Tanaka, "The Development of DC +/−500 kV XLPE Cable in Consideration of the Space Charge Accumulation," in *IEEE 7th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)* (2003), 689–694.

66. H. Mori, H. Niinobe, and Y. Yagi, "Space Charge Measurements and Characteristics of HVDC XLPE Cable," in *Paper P05, European Seminar on Materials for HVDC Cables and Accessories: Performance, Modelling, Testing, Qualification (Jicable-HVDC'13)* (2013).

67. S. Zahra, S. Morita, M. Utagawa, et al., "Space Charge Measurement Equipment for Full-Scale HVDC Cables Using Electrically Insulating Polymeric Acoustic Coupler," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 3 (2022): 1053–1061.

68. S. Morita, N. Fuse, T. Takahashi, et al., "Space Charge Measurement of Full-Size 23-mm-thick XLPE Cables in Load Cycle Condition," in *Jicable HVDC'21* (2021), 1–8.

69. Y. Kim, Y. Cho, S. Kim, W. Lee, N. Hozumi, and P. Morshuis, "Space Charge Measurement on Full-Sized HVDC Joint With Voltage Class up to 150 kV," in *2022 IEEE 4th International Conference on Dielectrics (ICD)* (2022), 78–81.

70. G. Mazzanti and Z. Lv, "Technical Committees: Recent Activities of the DEIS Technical committee on 'HVDC Cable Systems': Two New Study Groups for Novel IEEE Standards on Space Charge Measurement," *IEEE Electrical Insulation Magazine* 40, no. 6 (2024): 30–33.

71. T. Worzyk, *Submarine Power Cables* (Spinger-Verlag, 2009).

72. High-Voltage Test Techniques—Part 2: Measuring Systems, IEC 60060-2, Ed. 3.0, (2011).

73. *Modular HVDC Test System*, (HIGHVOLT Prüftechnik Dresden GmbH, 2020/11).

74. M. Gamlin, P. Treyer, and U. Hammer, "Superimposed Voltage Tests on DC Cables," Paper A10-1 in *Jicable'19* (2019).

75. H. He, C. Beverwijk, P. Kuijpers, and W. Sloot, "Cost-Effective and Practical Solutions for Testing HVDC Cable Systems," Paper A10-2 in *Jicable'19* (2019).

76. T. Steiner, R. Pietsch, U. Kaltenborn, and M. Hensel, "Modular DC Test System," in *2019 IEEE PES GTD* (2019), 336–340.

77. High-Voltage Test Techniques—Part 3: Definitions and Requirements for on-site Testing, IEC 60060-3, Ed. 1.0, (2006).

78. ELECTRA n. 171: Recommendations for Mechanical Tests on Submarine Cables, CIGRE WG 21.02, (1997).

79. A. Battaglia, A. Cavaliere, L. Biotto, M. Fontana, M. Canova, and G. Mazzanti, "Qualification and Sea Trial Tests for the 500 kV Tyrrhenian Link HVDC Cable System," in *2023 AEIT HVDC International Conference (AEIT HVDC 2023)* (2023), 1–6.

80. "The Tyrrhenian Link: the Double Underwater Connection Between Sicily, Sardinia and the Italian Peninsula," Terna Driving Energy, accessed March 17, 2025.