Recommendations for Mechanical Tests on Submarine Cables

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ABSTRACT

"Recommendations for mechanical tests on submarine cables" is the title of the document published in the Electra No. 171 article in April 1997. Experience with submarine cable installation has since increased significantly with respect to the number of installations, depth, length and complexity. For this reason CIGRE SC B1 decided to start a new working group, B1.43, with the purpose of updating the Electra No. 171 article. This has resulted in a new Technical Brochure - Recommendations for Mechanical Tests on Submarine Cables - that will be published in 2015. This paper gives an overview of this new brochure.

INTRODUCTION

Background

Several documents concerning recommendations for tests on submarine cables have been issued over the years under the responsibility of the CIGRE Study Committee (SC) B1. In 1980 the document titled "Recommendations for mechanical tests on sub-marine cables" was published in Electra No. 68. The field of application was defined with a rated voltage U_0 higher than 36 kV AC or 100 kV DC. It was also stated that the recommendations were primarily meant for single or 3-core paper-insulated cables for AC voltages. For DC cables it was mentioned that the reader should refer to the CIGRE document published in Electra No. 32, 1974, which described the test procedures for DC cables. Reference to mechanical tests was very briefly confined in a note: "Note: in the case of submarine cables, special mechanical tests may be agreed upon."

After 1980, several deep and long submarine cable links were installed and, as a consequence, the experience with cable installations increased. At that time it was recognised that in some cases the computed test forces according to the Electra No. 68 document differed in some cases from the actual measured tension during laying and recovery. For these reasons SC 21 (as SC B1 was named at that time) decided in the Sydney meeting in 1993 to revise the recommendations. The work done by Working Group (WG) 21.02 resulted in the document published in the Electra No. 171 article in April 1997, titled "Recommendations for mechanical tests on sub-marine cables". The field of applications in terms of voltages remained the same, although the limitation to paper-insulated cables was removed in this version. The primary use of the recommendations for both AC and DC cables was also explicitly stated.

The number and scope of submarine cable installations has increased ever since and it is expected to increase even more in the future. It was also judged that the application areas are diversifying (offshore wind farms, floating platforms, etc.) and that the maximum installation depth is also increasing. These facts were recognised by SC B1 during the late 2000's, subsequently initiating preparation of terms of reference for a new WG to update the Electra No. 171 document. Preparation of the terms of reference for the new WG was carried out by a Task Force within WG B1.27 and resulted in WG B1.43 being set up.

Terms of reference for WG B1.43

The terms of reference for Working Group B1.43 to produce the new technical brochure (TB) were as listed below.

Terms of Reference:

- Cover both impregnated paper cables and extruded cables (AC and DC) including a review of cable

installation methods and cable protection for submarine cables
- Examination of relevant IEC standards, CIGRE recommendations and standards from the offshore industry (e.g. umbilical testing)
- Assess the risk for mechanical damage during installation and cable protection
- Assess the risk for mechanical damage after installation (anchoring, drag-net fishing, pile driving)
- Calculation of tensile tests to be updated and a more detailed background to be described to the selected factors (security factors and torsion as well as dynamic forces)
- Propose test methods to cover:
  - Dynamic cable system installations
  - Very deep sea installations (including extruded cables)
  - Impact tests
- Consider the heat cycling influence on the metallic sheath and evaluate possible test methods
- Update/introduce mechanical tests for rigid joints
- Consider tests for free-spans, strumming
- Consider tests for the cable interaction with J-tubes, bend restrictors, etc.

BROCHURE APPLICABILTY

The scope of the TB is submarine cable systems intended to be used in AC and DC power transmission systems with rated voltages above 30 (36) kV AC or 60 kV DC. It is the opinion of the WG B1.43 that the TB also can be used for voltages down to 6 (10) kV AC or 10 kV DC.

The TB is applicable for extruded cable systems, MI cable systems and fluid-filled cable systems. The brochure has not been written specifically for gas-filled cables, which are rarely used now, although it cannot be stated that all or certain parts of the brochure are non-applicable. The TB covers both shallow and deep water installations.

UPDATES COMPARED TO ELECTRA NO. 171 ARTICLE

The new brochure is divided into two parts; a descriptive part and a part describing the mechanical tests. The descriptive part aims to give the reader general background information and covers: submarine cable loading, transportation, laying, cable protection, operation, maintenance, cable repair and dynamic cables.

The basis for establishing the test tension for the tensile bending test and tensile test has been revised and the formulas have been updated compared to Electra No. 171. Recommended safety factors that should be applied when establishing the test tension have also been included. More details on this are given below.

The testing part of the brochure consists of two sections;

- Type Tests
- Project Specific Tests and Special Tests.

Readers familiar with Electra No. 171 will recognise the described Type Tests, consisting of for instance *Coiling Test*, *Tensile Bending Test*, etc. The described tests have been clarified and some additions have been made, for instance to also cover integrated optical fibres. One new test has been introduced within the type tests, which is the *Full Scale Fatigue Test* for dynamic cables.

The *Project Specific Tests and Special Tests* is a new chapter with additional tests that are considered to go beyond the Type Tests. These tests are further described below.

ESTABLISHING TEST FORCES

In the new brochure the basis for establishing test forces has been clarified compared to Electra No. 171. The tensile force used in the test of the cable shall be chosen on the basis that the test tension is higher than the tensile force that will be experienced during all steps of the installation (and repair if applicable).

A set of equations are provided in the brochure which can be used to estimate the maximum tensile force during installation. The overall aim has been to present a set of relatively simple equations that can be used to provide a conservative estimate of the expected tension during cable laying. The dynamic tension during cable laying is complex and affected by many parameters. Some are project specific such as weather conditions, vessel response characteristics and position of laying sheave/chute or wheel. It has therefore been a balance to present a set of equations that are conservative for a broad set of installation conditions but at the same time not overly conservative.

An important change with the new brochure is to permit the test tension to be established based on more advanced analysis. Dynamic installation analysis, where the vessel response and weather limitation of the operation are taken into account, can be used to provide a better estimate of the expected maximum tension during the installation.

In addition to the tensile forces experienced during laying, the tensile force required during pull-in operations in J-tubes or pipes at landings should also be analysed to ensure that the test tension also covers these situations.

Equations for calculating test tension

Water depth 0 - 500 m

The test tension, *T*, is calculated using the following equation:

$$T = 1.3 * w * d + H \qquad (1)$$

Where:

w – submerged weight of 1 m cable [N/m]

d – maximum laying depth, [m]

H – maximum expected bottom tension during installation. The value of *H* shall not be taken as less than $40 \cdot w$. [N]

The prerequisite for using equation (1) is that the weather conditions during the operation are restricted to a significant wave height, $H_s \leq 2$ m. The factor of 1.3, accounting for dynamic forces and safety factors, may not be sufficiently large in adverse weather. For these cases the test tension should be established based on taking the actual movement of the laying sheave into account. Equations (2)-(8), described in the next section, can then be used to calculate the test tension.

Water depth > 500 m or when dynamic vessel characteristics are known

For water depths greater than 500 m, or for applications at shallower water depths where the vessel characteristics and laying conditions are known, the expected maximum installation tension, T_E, can be derived through a detailed dynamic installation analysis or calculated according to the following equation:

$$T_E = w \cdot d + H + D \qquad (2)$$

Where,

w – submerged weight of 1 m cable, [N/m]

d – maximum laying depth, [m]

H – maximum expected bottom tension during installation. The value of *H* shall not be taken as less than $40 \cdot w$, [N]

The dynamic tension, *D*, is given by the force resulting from the cables inertia,D_I, and the drag force, D_D, acting on the cable according to the following equation:

$$D = \sqrt{D_I^2 + D_D^2} \qquad (3)$$

The force due to cable inertia, D_I, is calculated with the following formula:

$$D_I = 1.1 \cdot \frac{1}{2} \cdot b_h \cdot m \cdot L_0 \cdot \omega^2 \qquad (4)$$

Where,

b_h - the maximum vertical movement, crest to crest, of the laying sheave, [m]

m – mass of 1 m of cable, including the mass of sea water inside the cable during installation, [kg/m]

ω – $2\pi/t$, circular frequency of the movement of the laying sheave, [1/s]

L_0 - is the length of the catenary, and is given by $L_0 = d\sqrt{1 + 2\frac{H}{w \cdot d}}$, [m]

t – movement period, [s]

The drag force onto the cable catenary is calculated based on a semi-empirical relationship according to the following equation:

$$D_D = 500 \cdot OD \cdot R^{0.9} \cdot (b_h \cdot \omega)^{1.8} \qquad (5)$$

Where,

OD – outer diameter of cable [m]

R – Bending radius at touch down point given by $R = \frac{H}{w}$ [m]

Vertical movement of the sheave and the period should be established based on the actual installation vessel and the worst weather conditions (maximum significant wave height, H_s) allowed during the operation. The maximum vertical displacement of the sheave, b_h, should be based on the maximum expected wave height $H_{max.}$ The following relationship can be used to estimate the maximum wave height $H_{max} = H_s$*1.9.

Safety factors

A safety factor should be added when establishing the test tension (only for the case where the equations for water depths > 500 m are used). This is regardless of whether the maximum expected tension is calculated based on the equations provided in the brochure, or if a dynamic installation analysis is performed.

The test tension, *T*, is established by applying a safety factor on the derived expected maximum installation tension, according to:

$$T = 1.1\, T_S + 1.3 \cdot T_D \qquad (6)$$

Where

T_s – is the static tension

T_D – dynamic tension

If the expected installation tension, T_E is calculated based on equation (2) the static and dynamic tensions are defined according to:

$$T_S = w \cdot d + H \qquad (7)$$

$$T_D = D \qquad (8)$$

Background to revised formulas

To investigate the suitability of the Electra No. 171 formulas the initial plan was to compare the formulas with measurements from installations or sea trials. However, only two measurements of cable top tension were made available for the WG:

- SAPEI cable, installation at 1600 m water depth
- Installation of cable in Japan at 190 m water depth

To provide additional input and investigate the influence of different parameters on the top tension, an extensive set of dynamic analyses were performed with a commercially available FE software for dynamic analysis of offshore marine systems.

Based on experience from the group, the two sea trials and the dynamic analyses the following observations were made:

Water depth 0 – 500 m

- For Electra No. 171, the factor of 1.3 to account for dynamic forces (including drag force) would be too low in case of large vertical movements of the laying sheave, i.e. adverse weather conditions.
- The relative contribution from hydrodynamic drag force increases with decreasing water depth and lower mass to diameter ratio. The drag force is related to cable diameter and is independent of the cable mass. This is not captured with the existing Electra No. 171 formula.

Water depth > 500 m

- Electra No. 171 predictions of static tension are very accurate
- Electra No. 171 dynamic tension is underestimated with increasing bottom tension
- Electra No. 171 formula can overestimate bottom tension for large water depths. The bottom tension is normally chosen independently of the water depth.

Based on these findings some modifications of the Electra No. 171 formula were therefore introduced.

The largest modification has been for the formulas for *Water depth > 500 m or when dynamic vessel characteristics are known*. The dynamic tension in equation (2) is calculated based on a simplified model where the cable departure point is assumed to follow a simple harmonic motion with amplitude given by the vertical movement of the lay sheave, b_h, and the angular frequency, ω. Based on this assumption the maximum velocity, v_{max} and maximum acceleration, a_{max}, of the cable departure point can be computed as the first and second time derivatives of the displacement according to:

$$v_{max} = \frac{b_h}{2} \cdot \omega \quad (9)$$

$$a_{max} = \frac{b_h}{2} \cdot \omega^2 \quad (10)$$

Equations (9) and (10) are unchanged compared to Electra No. 171.

Equation (4) is used to calculate the maximum dynamic force resulting from inertia, D_I, which is given by the inertial mass of the suspended catenary times the maximum acceleration at the cable departure point. The inertial mass of the suspended cable is computed based on the mass of the cable per meter and the length of the suspended catenary, L_0. To account for the added mass from the surrounding water that moves with the cable a factor of 1.1 has been included. This gives the following expression for dynamic tension resulting from cable inertia:

$$D_I = 1.1 \cdot m \cdot L_0 \cdot a_{max} \quad (11)$$

Combining equation (10) and equation (11) gives the same expression as in equation (4).

The drag force, F_D, onto an object moving in water is given by:

$$F_D = \frac{1}{2} \cdot \rho \cdot C_D \cdot A_p \cdot v_r^2 \quad (12)$$

Where ρ is the density of the fluid, C_D is drag coefficient, A_p is the projected area of the object and v_r is the velocity between water and the object. The drag force acting on a cable catenary will thus depend on:

- The diameter of the cable
- The shape of the catenary, where an increase in lay back distance results in an increased projected area.
- The relative velocity between cable and water.

The relative velocity between cable and water will vary along the catenary. In addition, the shape of the catenary changes due to the induced drag load. Numerical integration along the catenary would therefore be required to calculate the total drag force effecting the top tension. This can for instance be performed in special purpose software for dynamic analysis.

To provide an empirical expression that can be used to estimate the tensile force induced by drag, a set of parametric studies has been performed in a FE software for dynamic analysis to investigate how the drag induced tension is affected by influential parameters. The following parameters were investigated:

- Cable diameter
- Cable mass
- Bottom tension
- Installation depth
- Wave height and period

The simulations were performed assuming a simplified vessel where the cable departure point follows the surface elevation of the waves, where the waves are modelled as regular Airy waves. This implies that the cable departure point follows a simple harmonic motion in line with the assumption made in the calculations of the dynamic force in equation (4), (9) and (10). In the simulations a constant drag coefficient of $C_D = 1.2$ has been used. This will provide conservative estimates of the drag force for non-bundled cables.

The shape of the catenary is governed by the depth, cable mass in water and the bottom tension. The study showed that the depth had very little influence on the drag force. Instead good correlation was found between the drag force and the mean bending radius at touch down, *R*. Increasing the bending radius results in a longer lay back distance and thereby a longer cable length moving through the water perpendicular to the cable axis.

Based on the parametric study the semi-empirical expression in equation (5) was established for the maximum induced drag force.

Equation (5) has large similarities to equation (12);

- The force is linearly related to cable diameter
- The bending radius at touch down is almost linearly related to the projected length of the catenary moving perpendicular to the cable axis through the water.
- Since $v \propto b_h \cdot \omega$, the maximum drag force is thus close to proportional to the square of the maximum vertical velocity of the sheave. The reason for the not fully quadratic relationship is believed to be due to the velocity varying along the catenary.

The three constants in equation (5) (500, 0.9 and 1.8) were empirically determined to ensure that the prediction of drag force is on the conservative side for a large set of parameter variations.

Equation (3) is used to combine the contribution from equation (4) and equation (5). The time varying dynamic tension is the sum of the time varying forces resulting from cable inertia and drag. The force due to cable inertia is proportional to the vertical acceleration of the sheave and the drag force to the velocity. Since the velocity and the acceleration are 90 degrees out of phase the maximum total dynamic force can be calculated based on superposition of the two force components according to equation (3).

The TB gives a more detailed background to the new formulas and also compares the result from the formulas with measured tension during sea trials and the result from dynamic analysis in special purpose software.

SUMMARY OF TYPE TESTS

Type tests are the tests made before supplying a cable system on a general commercial basis in order to demonstrate satisfactory performance characteristics to meet the intended application.

The Type tests for submarine cable systems and their accessories comprise the appropriate mechanical and electrical tests on the complete cable and accessories. In addition suitable pressure related tests are performed in order to guarantee the water tightness and pressure withstand capabilities of the cable system.

The new TB describes the mechanical preconditioning tests and the water pressure tests. The electrical tests, performed after the mechanical preconditioning tests, will depend on the cable type and are performed according to CIGRE TB 490, TB 496, Electra No. 189 or similar. The new TB also describes specific type tests that can be performed to verify the performance of dynamic cables.

Type tests, overview

The Type tests described in the new TB are similar to the tests described in Electra No. 171. Fig. 1 shows the flow chart of the mechanical and electrical Type tests for static cables.

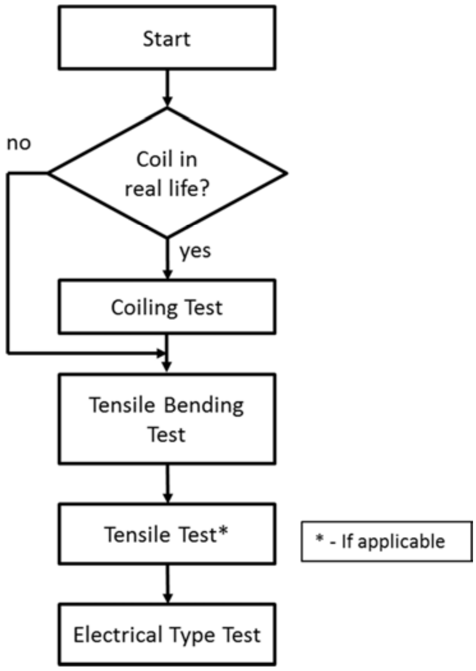

Figure 1: Flow chart of the test sequence of mechanical and electrical type test

Some clarifications and improvements have been introduced compared to Electra No. 171, for instance:

- *Coiling Test* – Distinction between 3-core cables and 1-core cables to determine the requirements for number and distances between joints. The minimum required number of complete turns of the coil has been reduced from eight to six for test cables including less than two joints.
- *Tensile Bending Test* – Calculation of test forces updated. Requirements on conductor and armouring bonding more clearly specified.
- *Tensile test* - Part of type test regime for rigid joints and for situations where the expected tensile forces are larger compared to the tensile force in the tensile bending test (e.g. pull in through long HDD).
- Fibre optic cables have been included in the mechanical preconditioning tests.

A flow chart for the pressure related tests on the paper lapped cable types is showed in Fig. 2.

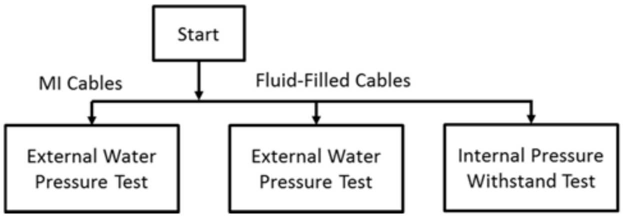

Figure 2: Test flow for pressure related test for paper lapped cable types

This is similar to Electra No. 171.

A clarification has been introduced for the external water pressure test regarding why flexible joints are not included in the test and aspects of verifying the water tightness of soldering and PE jacket are discussed. The background for not performing metallic sheath and conductor penetration tests on paper lapped cable types is also given in the TB. For the *Internal Pressure Withstand Test* the new TB recommends a *Tensile Bending test* to be performed as a preconditioning test for single armoured cables.

The new brochure also specifies pressure and water penetration tests for extruded cable types. The tests are in accordance with the tests specified in TB 490.

Dynamic Cables

A full scale fatigue test has been included as part of the Type tests for dynamic cables.

Submarine cables are categorised as dynamic when they experience continuous dynamic loads throughout their service life. Dynamic cables are primarily used for connections to floating platforms. Since dynamic power cables are permanent installations, the cable must survive the environmental loads resulting from extreme weather conditions. Dynamic cables will also be exposed to fatigue loading due to waves, currents and movements of the floating platform. Additional mechanical testing, primarily with regards to fatigue, is therefore performed to qualify a dynamic cable.

Full Scale Fatigue Test – Dynamic Cables

The main purpose of the fatigue test is to verify that the dynamic cable can withstand the expected fatigue loads experienced during service life.

The test is performed by cyclic bending of the cable. A constant tensile force, representative of the tensile force experienced during operation, is applied onto the cable during the bending cycles. The bending cycles are divided into a number of blocks, typical 5-7, each with different bending radius and number of cycles. The total number of cycles in all blocks should be at least $1.5x10^6$ for a test representing 20 years of dynamic operation.

After completion of the fatigue loading the cable test length shall be submitted to an electrical routine test. After the electrical test the cable shall be dissected and subjected to visual inspection where all components are checked for signs of fatigue damage, which could affect the system in service operation. The metallic sheath from one core shall be subjected to a dye penetration examination. The test shall not reveal any cracks or holes through the metallic sheath.

PROJECT SPECIFIC TESTS AND SPECIAL TESTS

Type tests are normally sufficient to verify the design of a cable system. However, if there are changes in the conditions related to, for instance, handling, installation or operation, then special tests may be required. In most cases these items are covered by proper engineering. In specific cases one or more project-specific test(s) for engineering or development purposes and/or qualification may be needed.

Examples of specific issues that may need to be considered either by engineering means or by project specific tests are for example:

- Increased water depth, different climate or different environment
- New type of cable storage, roller ways, pulling or breaking devices or other equipment
- New type of laying, installation, protection or repair method or configuration

The new TB has added a chapter with examples of additional tests, called *Project Specific Tests and Special Tests,* which are considered to go beyond the Type tests. It is not the intention that all tests described in the brochure are automatically part of testing regime for all submarine cable systems. These tests are more the exception to study and are performed to address project specific issues, or for engineering information.

The list of *Project specific tests and special test* included in the brochure are the following:

- *Bending test without tension* – Performed to verify the integrity of the cable when being bent to a small bending radius without tension.
- *Crush test* – The purpose of the test is to verify that the cable can withstand the expected crush loads during installation or repair. This test replicates the crush loads experienced by the cable during installation with a linear tensioner system where traction is achieved by squeezing the cable between two or more tracks.
- *Crush test for long term stacking* – Performed to verify that the cable can withstand long term crush loads representative of the stacking during storage, transportation or operation.
- *Sidewall force test* – The purpose of the test is to verify that the cable can withstand the sidewall forces that the cable will be exposed to during installation or operation. Sidewall forces are radial forces that arise when a cable is in tension simultaneously as it is bent against another object. This may for instance occur when pulling the cable over rollers, or pulling the cable over a fixed metallic curve like a chute or J-tube, or winding the cable around a laying capstan.

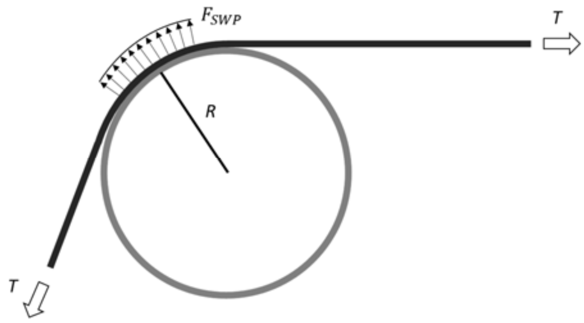

Figure 3: Illustration of sidewall force from distributed contact force per unit length

- *Impact test* – Primarily performed for information to establish the impact capacity of the cable and to give an indication of the effect of a typical impact. Impact damage may for instance result from accidentally dropped objects.
- *Pulling stocking test* - This test is performed to verify the integrity of the cable after being held by a pulling stocking. The test procedure is also applicable for other cable holding devices that grip the cable through friction by applying a radial force onto the cable.
- *Handling test for rigid joint* – The purpose of the handling test is to verify the ability of the rigid joint, together with cable, to withstand the expected handling during off-shore installation. If mechanical supports such as bend stiffeners or bend restrictors are used, these should be included in the test.
- *Sea trial* - The sea trial test is performed to study the interaction between the submarine cable and the installation equipment. Sea trials may be considered in special cases where for example installation conditions are close to the operational limits of the laying spread, if the protection techniques utilised significantly differ from established practice, etc.
- *Tensile characterisation test* - The test is performed for engineering information to establish axial stiffness, torsional balance and rotational characteristics of the cable.
- *Friction Coefficient Test* – Test is performed for engineering information to establish the friction coefficient between the cable and different surfaces.

CONCLUSIONS

The working group B1.43 has been active for a little more than 3 years, resulting in a new Technical Brochure - *Recommendations for Mechanical Tests on Sub-marine Cables* - that will be published in 2015. In addition to the more or less well-known tests under the Type test regime a set of new tests; *Project specific and special tests*, have been described and are to be consideration in special cases.

The basis for establishing the test tension has been revised and the formulas have been updated based on analyses using analytical methods, FEM based calculations and some measured forces from actual installations.

All parts in the submarine cable system were considered. Tests were defined reflecting mechanical aspects during the whole life cycle of the cable system.