

Development of submarine MV-AC power cable with aluminum conductor

Sven **MUELLER-SCHUETZE**, Heiner **OTTERSBERG**, Carsten **SUHR**, Ingo **KRUSCHE**, Norddeutsche Seekabelwerke GmbH/General Cable, Nordenham, Germany, sven.mueller-schuetze@nsw.com, heiner.ottersberg@nsw.com, carsten.suhr@nsw.com, ingo.krusche@nsw.com
Daniel **ISUS FEU**, General Cable, Manlleu, Spain, disus@generalcables.es

ABSTRACT

A single armored MV-AC submarine power cable with an aluminum conductor was developed for offshore renewable energy, interconnections between offshore platforms, islands and shore. For the cable design process an intended installation in water depths up to 300 m and the application of additional cable protection methods such as rock dumping for on-bottom stabilization were considered.

A type test has been successfully performed on 3x 800 mm² 19/33 (36) kV XLPE submarine power cable with an aluminum conductor. The qualification program was performed under consideration of the CIGRE Electra 171, CIGRE TB 490, IEC 60502-2 and CENELEC HD620-10C standards.

KEYWORDS

Submarine MV-AC power cable, subsea, offshore, aluminum conductor, XLPE insulation, type test, qualification, 300 m water depth, impact loads

INTRODUCTION

The reduction of construction cost is one of the biggest demands for today's offshore renewable energy sector. The need of cost reduction is not limited to the energy conversion system itself, it includes the interconnections between the single platforms and the connection to shore. Consequently cost of submarine power cable for infield- and export-connections needs to be reduced through the reduction of both production and material costs. Both the conductor material selection and the submarine power cable design play crucial roles and need to be reviewed under consideration of all relevant industrial standards such as IEC and Cenelec [1,2]. However, during that process all other major requirements have to be considered as well. Specifically, the cable design needs to be qualified to withstand high tensile loads and holding forces during cable installation as well as high impact forces during operation. The latter is a glaring need for all offshore renewable energy systems where scour formation or on-bottom stability are a major concern. In this case, additional cable protection methods such as rock dumping, concrete mattresses or others are required. In addition, the cable design is suitable for installations in water depths of up to 300 m.

The following sections outline the development considerations and qualification process for a MV-AC submarine power cable with aluminum conductor. The cable is developed for interconnections between offshore platforms, islands and shore.

MATERIALS SELECTION

Copper conductors are commonly used in submarine

cables due to its very good conductivity. However, the high demand of copper material results in a very high market value. This was set to above 6000 \$/ton at the beginning of April 2015.

Aluminum has lower conductivity compared to copper resulting in the need to select larger conductor cross sections. Despite the larger conductor cross section, cost reduction is achieved due to the lower material price of aluminum compared to copper. At the beginning of April 2015 the market value for aluminum was oscillating around 1770 \$/ton. Due to that market value difference aluminum is a cost-effective replacement for copper as conductor material. During the selection conductor material, both the electrical and mechanical material properties were reviewed for all aluminum alloy candidates to select the alloy which satisfies all specified requirements.

Submarine power cable costs are mainly driven by the conductor material selection. However, other submarine power cable components such as the armoring layer, bedding layer or outer serving concept would also have a significant impact on cable price.

Typical armor wire materials of submarine cables need to have good mechanical properties. Especially a high E-modulus and a high tensile strength are required given the fact that the armor layer shall support a mayor portion of the applied tensile load. Galvanized steel is the typical armor wire material used in submarine cables. Copper, nickel or titan are some of the possible replacement candidates although they share the drawback of limited mechanical properties and higher material acquisition costs compared to steel.

The bedding and outer serving layer shall damp external forces which act on the submarine cable such as impact and pressure forces during cable handling and operation. Two different bedding layer and outer serving concepts are used for submarine power cables: extruded polyethylene jackets or stranded polypropylene (PP) yarn layers. Extruded PE jackets exhibit slightly superior mechanical functionality than PP yarn. Though it requires at least two additional productions steps. On the other hand, both PP yarn layers can be applied during the armoring process. Consequently PP yarn would be the cost effective solution compared to extruded PE jackets as bedding and outer serving layers.

CABLE DESIGN

A schematic drawing of the submarine power cable is shown in Fig. 1. The MV-AC submarine power cable is a three core design combined with fibre optic cable elements and PE fillers. All elements are laid up with a periodically reversed lay direction, forming a round and circular cable assembly. Although the assembly is dimensionally stable, additional binder tapes and yarns



Fig. 1: Schematic drawing of the submarine power cable design.

are applied helically on the assembly to fix the shape of the cable.

The armor bedding is made of a PP yarn layer. One layer of galvanized steel wires is applied over the bedding layer and selected according to EN 10257-2 and EN 10244-2 [3,4]. The armoring is flushed with bitumen compound to improve corrosion resistance. To protect the armoring one layer of polypropylene yarn is applied as outer sheath around the armoring.

The power core design is based on Cenelec HD-620 10C and IEC 60502-2 standards [1,2].

Aluminum alloy wires were stranded into class 2 type conductor design with a circular shape as per IEC 60228 [5]. A semi-conducting sealing compound was applied in the interstices of the conductor strand to prevent longitudinal water penetration in case of cable damage. The semiconducting conductor screen, crosslinked polyethylene (XLPE) insulation and semiconducting insulation screen are applied around the conductor by a triple-extrusion process. The metallic screen is made out of helically applied copper wires and a contra helically applied copper tape. Underneath and on top of the metallic screen semiconducting swellable tapes are applied as longitudinal water barrier. The metallic screen is enclosed by a longitudinal applied Aluminum foil which is glued to the outer high density polyethylene (HDPE) jacket.

A 3x 800 mm² 19/33 (36) kV XLPE submarine power cable (for details see Tab. 1) was used to verify the cable performance by test and a full cable qualification.

Tab. 1: Design details of the 3x 800 mm² 19/33 (36) kV XLPE submarine power cable

Design Parameter	Value
Nominal overall diameter	171 mm
Nominal cable mass in air	38.8 kg/m
Nominal cable weight in water	15.1 daN/m
Maximum pulling force	195 kN

MECHANICAL CABLE PERFORMANCE

To evaluate the mechanical performance of the submarine power cable design development test were performed to verify the ability of the cable to withstand all mechanical forces during and after cable installation. All development test were performed on different cable samples from 3x 800 mm² 19/33 (36) kV XLPE submarine power cable. All samples were extracted from that cable after the FAT and the coiling test which is summarized below.

Crush load analysis

The crush test simulate the pressure forces which are exerted onto the cable during cable handling or installation by caterpillars. In order to simulate pressure force under realistic conditions original caterpillar track pads were utilized. To avoid deformations of the track pads, each element was placed in a metal form reproducing the installation on typical caterpillar designs. Fig. 2 shows an overview of the complete crush test setup including the cable sample placed between the two track pads and inside a hydraulic press.



Fig. 2: Crush test with original caterpillar track pads

The specimens were first subjected to different pressure loads and then electrically tested and dissected. No defects or an irreversible ovality were detected.

Impact load analysis

The objective of the impact resistance test is to confirm the cable ability to withstand high impact loads during cable handling, installation and operation. The impact test was performed by dropping a specific weight m from a defined height h , the resulting impact load is consequently defined by the equation:

$$E = m \cdot g \cdot h \quad [1]$$

The weight slides down on a hammer. It shaped as a wedge, i.e. two a 90° faces joined by a 2 mm radius fillet. The cable sample is placed on a steel base frame underneath the hammer (see Fig. 3). For each weight the impact was performed in succession at 3 different points along the cable sample. The impact loads, which were applied during the impact test, were selected on basis of typical rock sizes which could affect submarine power cables.



Fig. 3: Impact Test, the impact hammer had a curvature radius of 2 mm.

Both the impact test and the subsequent performed electrical test and dissections showed no defects or any other flaws for any of the selected impact loads on the power core or fibre optical elements.

The crush load and impact load analysis assess the performance of PP yarn, both as bedding and outer serving layer material.

Cable Stiffness Estimation

The number and extent of submarine cable installation as well as on-bottom stability studies increases from project to project. Consequently the number and level of detail of required cable properties is growing steadily as well. In addition to the cable properties specified in Tab. 1 more detailed mechanical cable properties are required including the cable bending stiffness.

An experimental method to determine the cable bending stiffness is summarized by Vaz et al. [6]. A straight cable specimen is bent to progressively increasing maximum curvature of interest. The cable bend is induced by a chain hoist which is attached close to both ends of the



Fig. 4: Test arrangement to measure the bending moment and curvature to investigate the bend stiffness.

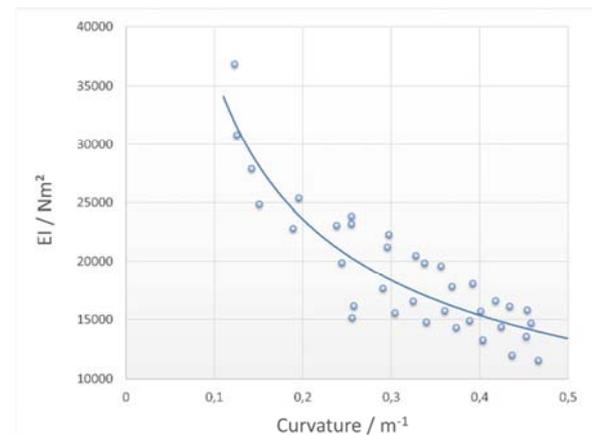


Fig. 5: Bend stiffness vs. curvature of the 3x 800 mm² 19/33 (36) kV XLPE submarine power cable

cable test specimen (see Fig. 4). To measure the applied bending forces a load cell instrument is integrated in the chain hoist. In addition to the bending force the geometrical configuration is measured through coordinates of lateral displacements as summarized by Vaz et al. [6]. The bend stiffness test has been done continuously in both directions with no waiting time in between the steps for several times.

In Fig. 5 the experimental estimated cable bending stiffness (EI) of 3x 800 mm² 19/33 (36) kV XLPE submarine power cable is represented as function of the applied cable curvature. An potential function as mean function is used to illustrate the change of the cable bending stiffness due to the change of the cable curvature.

TYPE TEST

A type test was performed on the 3x 800 mm² 19/33 (36) kV XLPE submarine power cable which was summarized above. The type test program was performed under consideration of the Cenelec HD620-10C and IEC 60502-2 in agreement with CIGRE Electra 171 and CIGRE TB 490 [1,2,7,8].

The qualification of submarine power cables by the type test program recommended by the CIGRE Electra 171 and CIGRE TB 490 is divided into three parts: a mechanical, an electrical and a non-electrical type test [7,8].

Part I: Mechanical Type Test

During the mechanical type test mechanical loads acting on submarine power cables during handling, installation and operation are simulated.

Coiling Test

MV-AC submarine power cables are commonly stored in static tanks during the single production steps as well as for transportation and cable installation. The coiling test as part of the type test simulates the torsional load applied to a coiled cable and validates the coiling ability of a submarine power cable.



Fig. 6: Coiling test of the 3x 800 mm² 19/33 (36) kV XLPE submarine power cable into a fixed static tank

The 3x 800 mm² 19/33 (36) kV XLPE submarine power cable was coiled into fixed static tanks after the stranding process as well as after the armoring process. A cable sample of about 700 m length was used for the coiling test. The test cable was wound from a turn table storage device and coiled into a static tank (see Fig. 6). Its end was fixed in the coiling core with a minimum of 4 layers on the bottom of the static tank. The cable was then rewound through a linear engine back into the turn table. The coiling and rewinding process was performed ten times.

After the coiling test, samples for the following tensile bending test and electrical type test were extracted from the coiled sample.

Tensile Bending Test

The tensile bending test simulates the mechanical loads acting on the cable during both installation and cable repair. The test was performed on a 30 m long 3x 800 mm² 19/33 (36) kV XLPE submarine power cable sample which was cut from the coiling test sample. Cable pulling heads were installed at both ends of cable samples ensuring that the resulting forces were equivalent to the



Fig. 7: Tensile bending test of the 3x 800 mm² 19/33 (36) kV XLPE submarine power cable around a 5.4 m sheave.

distribution of forces during laying operations.

The cable sample was bent around a sheave under tensile load as specified in the Cigre Electra 171 [7] (see Fig. 7). The test tension was calculated on basis of the Cigre Electra 171 recommendation assuming maximum installation water depth of 300 m and demanding weather conditions [7].

Part II: Electrical Type Test

During the electrical type test part the cable performance under both electrical and thermal load cycles is tested. The extent of the electrical type test is summarized in the Cigre TB 490 [8]. As specified in the Cigre TB 490 test was performed on the 30 m long 3x 800 mm² 19/33 (36) kV XLPE submarine power cable sample after it was subjected to the tensile bending test.

The sample was laid out on the floor of the test laboratory and heating transformers were applied at one end of the submarine power cable over each of the three power cores. A reference sample was also prepared exactly in the same arrangement to validate the conductor temperature during all tests where heating was required. The tested cable sample was equipped with outdoor terminations (a schematic drawing of the test loop setup is illustrated in Fig. 8).

All electrical type test were performed according to the test parameters specified in Cenelec HD620 10C and IEC 60502-2 [1,2]. For each test the more severe test conditions specified in both standards were selected:

1. Partial discharge test at ambient temperature: The test voltage was gradually raised to and held at $2.4 \times U_0$ for ≥ 60 s and then slowly reduced to $2.0 U_0$. At a test

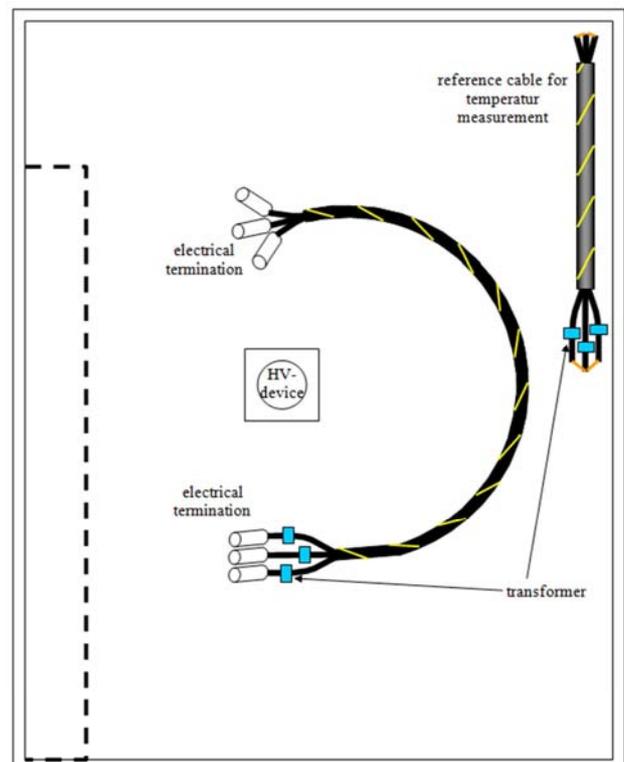


Fig. 8: Schematic drawing of the test loop setup for the electrical type test.

Tab. 2: Non-electrical type test sequence.

Test Description	IEC, DIN EN 60811
Test on inner semi-conductive layer	
Thickness	IEC 60811 - 201
Irregularity	IEC 60811 - 100
Test on the insulation	
Measurement of thickness of insulation	IEC 60811 - 201
Irregularity	IEC 60811 - 100
Determination of the mechanical properties of insulation before and after ageing	IEC 60811 - 401, 501
Hot set test	IEC 60811 - 507
Water absorption test on insulation	IEC 60811 - 402
Shrinkage test	IEC 60811 - 502
Strippability test for insulation screen	IEC 60811 - 503
Test on outer semi-conductive layer	
Thickness	IEC 60811 - 201
Irregularity	IEC 60811 - 100
Test on the outer sheath	
Measurement of thickness of non-metall sheaths	IEC 60811 - 202
Determination of the mechanical properties of the outersheath before and after ageing	IEC 60811 - 401, 501 and HD 620
Shrinkage test for PE oversheaths	IEC 60811 - 503
Measurement of carbon black content of black PE oversheaths	IEC 60811 - 605
Pressure test at high temperature	IEC 60811 - 508
Shore D hardness	HD 605 clause 2.2.1
Test of the complete cable	
Additional ageing test on pieces of completed cables	EN 60811 - 401 and HD 620 table 2a, 4B

voltage of $2 \times U_0$ the maximum partial discharge level should be ≤ 2 pC.

- Tan δ measurement at ambient temperature: ≤ 0.004 at a test voltage of U_0 .
- Tan δ measurement at maximum conductor temperature in normal operation: ≤ 0.008 at a test voltage of U_0 .
- Heat Cycle Test followed by partial discharge test: 20 heating cycle with a heating duration of at least 8 h at the maximum conductor temperature were executed on that sample.
- Partial discharge test at maximum conductor temperature in normal operation: The test voltage was gradually raised to and held at $2.4 \times U_0$ for ≥ 60 s and then slowly reduced to $2.0 U_0$. At a test voltage of $2 \times U_0$ the maximum partial discharge level should be ≤ 2 pC.
- Impulse Withstand Test: The sample was heated to a conductor temperature of 95 to 100 °C. Ten positive as well as ten negative impulses were applied on the test sample with an impulse voltage of 170 kV.
- High Voltage Test at ambient temperature: An AC test voltage of $4 \times U_0$ was applied on the test sample for a duration of 4 h. During that time no breakdown was observed.

After completion of all electrical tests the test loop was dismantled. The construction of the cable was visually inspected and did not reveal any sign of deterioration e.g. leakage, corrosion or harmful shrinkage and electrical degradation which could affect the system in service operation.

A cable sample of approximately 0.5 m was selected for more detailed analysis. The conductor was inspected and the measurement of the insulation, outer sheath, and metallic sheath thickness were performed without any sign of deterioration.

Part III: Non Electrical Type Test

The International Standard IEC 60811 and the national Standard DIN EN 60811 specifies a non-electrical test sequence (see Tab. 2) on insulation, on the conductor



Fig. 9: Longitudinal water penetration test setup on the metallic screen of the power core.

and insulation screen as well as the outer sheath [9]. During those test the different material qualities were analyzed by hot set test, shrinkage test, aging test, pressure test and purity test. All test were done on an additional $3 \times 800 \text{ mm}^2$ 19/33 (36) kV XLPE submarine power cable sample taken from the coiling test sample.

Both Cigre Electra 171 and Cigre TB 490 recommend the implementation of longitudinal water penetration test on conductor and on the metallic screen of the power core as part of the non-electrical type test sequence [7,8]. For that purpose the selected samples were pre-treated by mechanical tests¹ as per CIGRE ELECTRA 171 clause 2.2 and consecutively 3 heating cycles as specified in the Cigre recommendations [7,8]. The pre-treated test samples were place inside the water pressure test chambers according to the test setup specified in Cigre TB 490 (see Fig. 9) [8].

The water penetration test on the conductor and the metallic screen were performed with a test pressure of 30 bar for a duration of ten days. The applied test pressure corresponds to a maximum considered installation water depth of 300 m for submarine power cable design. The cable sample of the water penetration test on the metallic screen test sample was treated by 10 heating cycles while the test pressure of 30 bar was applied on the sample and the water temperature was equal to the ambient temperature.

The test reveals a water penetration depth below 0.3 m inside the Aluminum conductor of the $1 \times 800 \text{ mm}^2$ 19/33 (36) kV XLPE power core after a test duration of ten days. Inside the metallic screen a water penetration depth below 1.5 m was measured after the same time duration.

SUMMARY

The reduction of submarine power cable cost is achieved by utilization of Aluminum as conductor material instead of copper.

A MV-AC submarine power cable design with an Aluminum conductor was developed and qualified as per Cigre Electra 171 and Cigre TB 490 for a maximum water

¹ As recommended in the Cigre TB 490 the mechanical pre-treatment was not performed on the sample used for the water penetration test on the metallic screen.

depth of 300 m. In addition it could be presented that this cable design can withstand required impact loads as well as high crush forces.

REFERENCES

- [1] Cenelec, 2010, "Distribution cables with extruded insulation for rated voltages from 3.6 / 6 (7.2) kV up to and including 20.8 / 36 (42) kV", Cenelec HD620 10C / DIN VDE 0276-620 S2
- [2] IEC, 2014, "Power cables with extruded insulation and their accessories for rated voltages from 1 kV ($U_m = 1,2$ kV) up to 30 kV ($U_m = 36$ kV) - Part 2: Cables for rated voltages from 6 kV ($U_m = 7,2$ kV) up to 30 kV ($U_m = 36$ kV)", IEC 60502-2 edition 3.0
- [3] EN, 2012, "Zinc or zinc alloy coated non-alloy steel wire for armouring either power cables or telecommunication cables - Part 2: Submarine cables", EN 10257-2:2012-02
- [4] EN, 2009, "Steel wire and wire products - Non-ferrous metallic coatings on steel wire - Part 2: Zinc or zinc alloy coatings", EN 10244-2:2009-08
- [5] IEC, 2004, "Conductors of insulated cables" IEC 60228 edition 3.0
- [6] M. A. Vaz, L. A. D. Agular, S. F. Estefen, and M. Brack, "Experimental determination of axial, torsional and bending stiffness of umbilical cables", presented at the OMAE98, 1998.
- [7] Cigre, 1997 "Recommendations for Mechanical tests on submarine cables" Electra no. 171, 59-65"
- [8] Cigre, 2012 "Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30 (36) to 500 (550) kV", TB 490
- [9] IEC, 2012 "Electric and optical fibre cables - Test methods for non-metallic materials - Part 100: General", IEC 60811