Close and Return

System performance and demonstration of 400kV-525kV DC-XLPE cable and accessories

Tsuyoshi Igi, Shoji Mashio, Masatoshi Sakamaki, Tatsuya Kazama, Kenichi Sasaki, Satoshi Nishikawa; Sumitomo Electric (Japan),
igi-tsuyoshi@sei.co.jp

ABSTRACT

DC400kV XLPE power cable system has been applied to the NEMO interconnector between UK and Belgium. The cable system was subject to the type test in accordance with CIGRE TB496 and relevant IEC standards followed by the additional type test with longer load cycles. In order to fulfil the requirements, design approach to controlling electrical stresses by ultra-high volume resistivity of DC XLPE insulation and material control with low space charge accumulation has been done with extensive research outcome. Based on this approach, DC 525kV system type test has been successfully completed with pre-molded one-piece joints, outdoor termination at polarity reversal conditions.

KEYWORDS

DC XLPE cable system, type test, volume resistivity, space charge accumulation

INTRODUCTION

Despite CIGRE TB496 "Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV" was established in 2012, industrial experience in commercial operational lines are still limited up to ±320kV for VSC converter system as of 2017, and also published IEC standard in 2017 covers only up to 320kV. On the other hand, Sumitomo Electric has supplied the world first DC250kV XLPE cable system in 2012. Before implementing the project, the main DC characteristics have already been evaluated in cable, which are DC breakdown strength, volume resistivity and space charge characteristics. We have manufactured a DC XLPE cable using own material and developed accessories for the cable system. The first 250kV DC-XLPE cable system has been successfully operated since 2012 in the Hokkaido-Honshu DC link in Japan with LCC converter with polarity reversal operation [1].

This fact reminds us the valuable experiences that previous approach to DC XLPE cable development for us was aiming LCC converter and test conditions were set more stringent than the current IEC standard. For example, the rest period during polarity change in the PQ and type test are now introduced in the sequence but actual operation may not fulfill this assumption in case of HVDC converter failure. Therefore, we aimed to demonstrate the higher performance than those required in current IEC standard when new 400kV and 525kV project are considered due to the lack of commercial experiences for these voltages.

This paper showed successful type test results demonstrated for 400kV project, and development results for 525kV cable system based on our design philosophy, material control and accessory design.

1. NEMO LINK, THE WORLD FIRST 400KV DC-XLPE CABLE SYSTEM IN ACTUAL SERVICE

NEMO link consists of 1050MW of symmetrical monopole 400kV HVDC converter and ±DC 400kV XLPE cable system with submarine and land cable accessories. There is no threat of lightning strike from overhead line. This HVDC converter is VSC, HVDC plus ® supplied by Siemens AG which does not require polarity reversal operation and cable conductor temperature was designed to operate continuously at 90 deg-C. In order to demonstrate the higher performance than the system requirement, additional LCC conditions were adopted for type test, and even higher temperature was adopted for additional load cycle test.

The main components of the cable system for NEMO link are submarine cable, land cable, factory joint of submarine cable, submarine joint, land joint, transition joint and air insulated termination. The features of the cable system are as follow:

- XLPE insulation cable system in accordance with CIGRE TB496 and relevant IEC/CIGRE standards/recommendations
- Transmission capacity of 1050MW at the rated voltage of DC400kV
- Maximum operating temperature of 90 deg-C.
- Symmetrical monopole with VSC converter
- Design life of 40 years

Submarine cable

The construction of submarine cable is illustrated in Fig.1 and the photo of the submarine cable is shown in Fig.2. The features of the submarine cable are as follow.

- 1100mm2 watertight copper conductor
- Mechanical design for 100m sea depth installation
- 16 composite single-mode optical fibres for data communication and 16 composite multi-mode optical fibres for DTS measurement

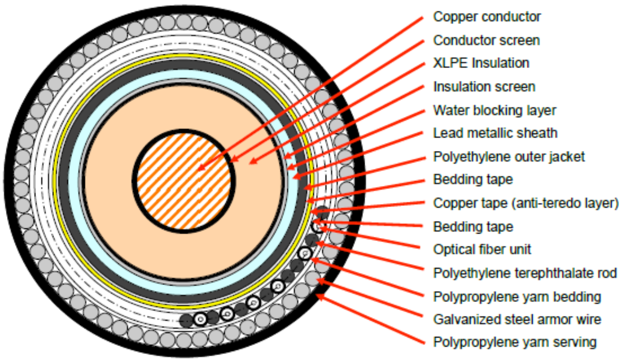

Fig. 1: Construction of submarine cable

Fig. 2: Photo of submarine cable

Land cable

The construction of land cable is illustrated in Fig.3 and the photo of the land cable is shown in Fig.4. The features of the land cable are as follow.

- 1600mm2 segmental copper conductor
- 16 composite single-mode optical fibres for data communication and 16 composite multi-mode optical fibres for DTS measurement

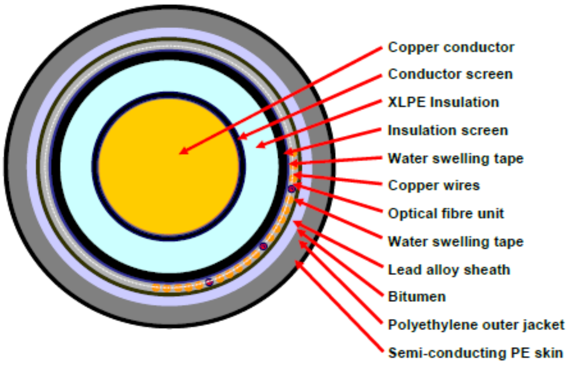

Fig. 3: Construction of land cable

Fig. 4: Photo of land cable

Accessories

Both the submarine joint and the land joint are pre-molded one-piece type. Fig. 5 shows the construction of the land joint. The land joint is encased in the FRP protection casing. The submarine joint is encased in the steel protection casing.

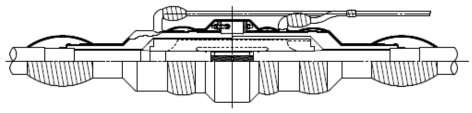

Fig. 5: Construction of land joint

The transition joint between the submarine and the land cable is pre-fabricated composite type. Fig. 6 shows the construction of the transition joint.

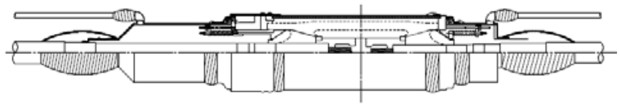

Fig. 6: Construction of transition joint

The cable termination is polymer bushing type with rubber insulatior. Fig. 7 shows the construction of cable termination.

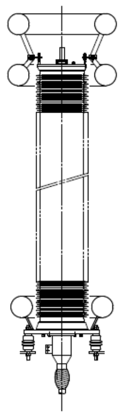

Fig. 7: Construction of cable termination

TYPE TEST

The cable system components were subject to type test summarized below in accordance with CIGRE TB 496 and relevant IEC/CIGRE standards/recommendations.

- Mechanical tests
  - Coiling test on submarine cable (CIGRE TB623)
  - Tensile bending test on submarine cable (CIGRE TB623)
  - Tensile test on submarine cable and joint (CIGRE TB623)
  - Bending test on land cable (IEC62067)
  - Test on integrated optical fibres

- o Mechanical loading test on land and transition joints
- o Impact test on submarine cable
- o Crush resistance test on submarine cable

- Electrical tests
  - o Load cycle test for cable system to be qualified for LCC (CIGRE TB496)
  - o Super imposed impulse voltage test (CIGRE TB496)
  - o Additional load cycle and impulse test
  - o Tests of outer protection for land and transition joints (IEC62067)

- Longitudinal / radial water penetration tests
  - o Radial water penetration tests for factory joint and submarine joint (CIGRE TB490)
  - o Conductor water penetration test on submarine cable (CIGRE TB490)
  - o Metal sheath water penetration test on submarine cable (CIGRE TB490)
  - o Water penetration test on integrated fibre optic cable (CIGRE TB490)
  - o Longitudinal /radial water penetration test on land cable (IEC62067)

- Non-electrical tests
  - o Check of cable construction (IEC62067)
  - o Tests for determining the mechanical properties of insulation before and after aging (IEC62067)
  - o Tests for determining the mechanical properties of oversheaths before and after aging (IEC62067)
  - o Aging tests on pieces of complete cable to check compatibility of materials.
  - o Pressure test at high temperature on oversheaths (IEC62067)
  - o Hot set test for XLPE insulation (IEC62067)
  - o Measurement of carbon black content of black PE sheaths (IEC62067)
  - o Abrasion test on oversheath (NBN HD632)
  - o Shore D test on anti-corrosion sheath (ISO868)

Design Approach to 400kV and 525kV system

In order to demonstrate a stringent type test conditions for 400kV and above, not only initial performance of cable insulation at high temperature, but also long-term stability against high temperature operation including abnormal voltage is crucially important. For example, the volume resistivity of DC-XLPE cable compound is already very high, approximately 100 times higher than that of the conventional XLPE cable compound and DC breakdown strength at high temperature is rather high as reported in [2]. According to our material control scheme, not only the high volume resistivity of insulations and the breakdown strength, space charge accumulation characteristics is an important role to consider the tendency of stability for cable system.

Field Enhancement Factor (FEF) is defined by the following equation:

$$FEF = \frac{\text{Maximum electric field in specimen[kV/mm]}}{\text{Applied Voltage[kV]} / \text{Thickness of specimen[mm]}}$$

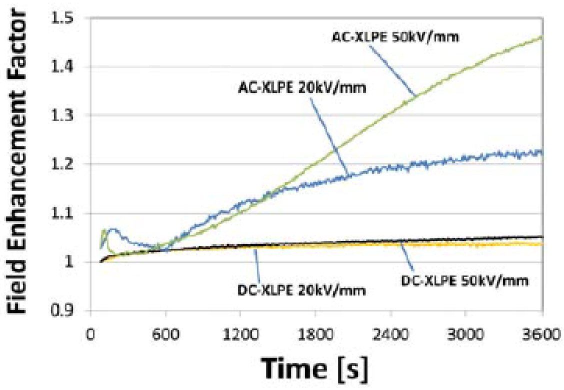

Fig 8. Field Enhancement Factor for DC-XLPE cable at 20kV/mm and 50kV/mm at 30 deg-C

Sampling results of FEF is shown in Fig 8, and FEF is now introduced in some country in Asia, but authors have kept the design basis to monitor FEF at 50kV/mm (elevated stress) instead of 20kV/mm (operational stress). This is due to a concern that material test at the operational electrical stress is not enough to confirm the long term stability and in order to accelerate space charge accumulation, higher electrical stress is more effective.

Stress control of Accessories

When considering accessories design, if space charge accumulation is very low, distortion of electrical field can be neglected. Therefore, design stress can be analyzed by Laplace stress which is given by insulation permittivity, and also DC stress which is given by resistivity. The latter case shall be analyzed by transient analysis against temperature rise/drop with time. However, both phenomena are well known for paper insulated cable.

In addition to this traditional approach to analysis of Laplace /DC field stress, we have analyzed electrical stress on accessories by combination of different material component (cable and rubber, oil) and a simple explanation is given that if the DC resistivity of cable is higher than that of accessories design, the electrical stresses on DC is not higher than that of Laplace stress. Fig 9 and Fig 10 show example of electrical stress of 525kV joint with Laplace stress distribution and DC stress distribution at thermal equilibrium conditions at conductor of 90 deg-C respectively.

As can be seen, Laplace stress is more stringent shape than that of DC stress for cable accessories because due to high volume resistivity of cable insulation than that of joint insulation will take more voltage gradient at high voltage side, if DC resistivity of cable is kept always higher than that of accessories, DC stress design becomes not a bottleneck and impulse stress design, i.e. Laplace stress is a governing factor in the design.

In this hypothesis, it can be also said that if there is no significant space charge accumulation in accessories, this theory can be still valid under polarity reversal conditions. In order to support this hypothesis, authors have demonstrated 250kV and 400kV PQ test at polarity reversal conditions at 90 deg-C, and space charge measurement on the cable sample were made after 400kV PQ test and any significant space change accumulation were observed [3].

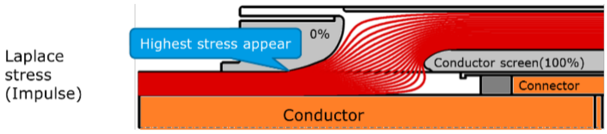

Fig. 9: Laplace stress on joint body

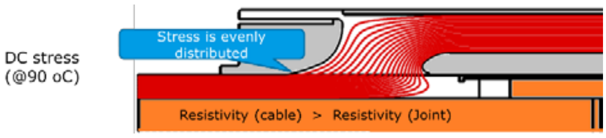

Fig. 10: DC stress in case of high volume resistibty of cable

Material sample tests

Based on this development and design philosophy, monitoring of space charge accumulation characteristics of cable insulation is important and an effective tool for stabilization of cable system performance, because it is not able to demonstrate the long term performance of cable and cable accessories for each production lot. Since successful completion of DC250kV cable project and 400kV PQ test, in each production lots of DC-XLPE cable, not only volume resistivity and breakdown strength, FEF have been monitored. This is an analogy to factory test for AC XLPE cable. For AC XLPE cable, critical change in material and potential defect in production process could be checked by AC high voltage test and PD for each production lot, and every several km of impulse voltage test gives further confidence in the AC insulation performance in accordance with IEC standard, however, different approach to DC XLPE is considered to be necessary.

From our experiences, in addition to AC voltage test, it is also effective to monitor FEF for each production lot as cable insulation performance may vary based on compounding process, cable production process and drying times. In accordance with Chinese standard, GB/ST 31489.1-2015, FEF is specified below 1.2 at 20kV/mm (operational stress) at 70 deg-C but authors monitor it at 50kV/mm as well in order to consider the acceleration factor with higher electrical stress, considering the analogy that type test is always higher stress than the operation stress.

Electrical type test for 400kV cable system

Fig.11 and Fig.12 show the set-up of test circuits. The transition joint was included in the submarine cable circuit.

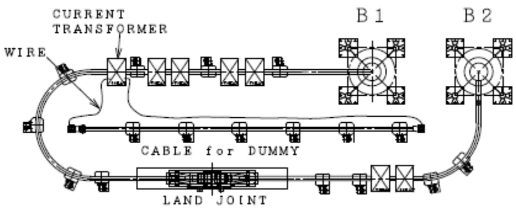

Fig. 11: Test circuit for land cable and accessoris

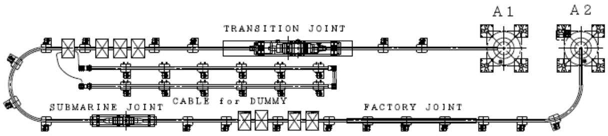

Fig. 12: Test circuit for submarine cable and accessories

The VSC converter system is applied to NEMO project and overhead conductor is not used, however polarity reversal test for LCC system were conducted as well as superimposed lightning impulse voltage test as parts of electrical type test for higher quality demonstration. Also, higher temperature load cycle test at 105 deg-C was demonstrated. The test items of the electrical type test are shown in Table 1.

Table 1: 400kV Electrical type test items

• 24 hours load cycle test at negative polarity o 8 cycles -740kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 24 hours load cycle test at positive polarity o 8 cycles +740kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 24 hours load cycle test with polarity reversal o 8 cycles +/-580kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 48 hours load cycle test at positive polarity o 3 cycles +740kV, 24/24 hours heating/cooling o Conductor temperature of 90 deg-C.
• Superimposed switching impulse test o DC+400kV, SI+840kV, 10 times o DC-400kV, SI-840kV, 10 times o DC+450kV, SI-480kV, 10 times o DC-450kV, Si+480kV, 10 times o Conductor temperature of 90 deg-C.
• Superimposed lightening impulse test o DC+400kV, LI-840kV, 10 times o DC-400kV, LI+840kV, 10 times o Conductor temperature of 90 deg-C.
• Subsequent DC test o DC-740kV, 2 hours, ambient temperature

Additional load cycle and impulse test

The additional load cycle and impulse test were conducted following to the electrical type test at the same circuits. After completion of the additional load cycle and impulse test, the examination was conducted. The test items of the additional load cycle and impulse test are shown in Table 2.

Table 2: Additinal load cycle and impulse test

• 24 hours load cycle test at negative polarity o 42 cycles -740kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 24 hours load cycle test at positive polarity o 42 cycles +740kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 24 hours load cycle test at negative polarity o 3 cycles -740kV, 8/16 hours heating/cooling o Conductor temperature of 105 deg-C.
• 24 hours load cycle test at positive polarity o 3 cycles +740kV, 8/16 hours heating/cooling o Conductor temperature of 105 deg-C.
• Superimposed switching impulse test o DC+400kV, SI+840kV, 10 times o DC-400kV, SI-840kV, 10 times o DC+450kV, SI-480kV, 10 times o DC-450kV, Si+480kV, 10 times
• Superimposed lightening impulse test o DC+400kV, LI-840kV, 10 times o DC-400kV, LI+840kV, 10 times
• Subsequent DC test o DC-740kV, 2 hours

These electrical tests have been completed successfully including additional load cycle test.

Development of 525kV DC XLPE cable system

For future potential projects, DC 525kV type test have been conducted on DC XLPE cable with various accessories. Followings are main characteristics of cable system:

- o DC 525kV cupper conductor 2500mm2 cable to carry 2.5GW with bipole
- o DC 525kV streight through joint (pre-mold one piece)
- o DC 525kV outdoor type sealing end (polymer bushing)

Type test were conducted in accordance with CIGRE TB496 with VSC with additional sequence for porality reversal (LCC) and superimposed lightning impulse test at elevated voltage (2.21Uo) as shown in Table 3, considering safety margin as a development test.

It is remarkably noted that based on the successful development experience in 400kV cable system, and material control scheam for cable insulation, our proposed DC 525kV joint consists of pre-mold one-piece type EPDM mold. The joint body can be minimized as shown in Fig 13 below.

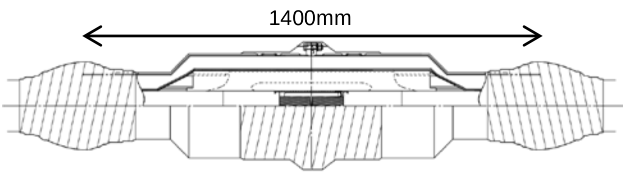

Fig.13: DC525kV Pre-molded one-piece joint

Table 3: DC 525kV type test

• 24 hours load cycle test at negative polarity o 8 cycles -972kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 24 hours load cycle test at positive polarity o 8 cycles +972kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 24 hours load cycle test at polarity reversal o 3 cycles -761kV, 8/16 hours heating/cooling o Conductor temperature of 90 deg-C.
• 48 hours load cycle test at positive polarity o 3 cycles +972kV, 24/24 hours heating/cooling o Conductor temperature of 90 deg-C.
• Superimposed switching impulse test o DC+525kV, SI+1161kV, 10 times o DC+525kV, SI-657kV, 10 times o DC-525kV, SI-1161kV, 10 times o DC-450kV, Si+657kV, 10 times
• Superimposed lightening impulse test o DC+525kV, LI-1161kV, 10 times o DC-525kV, LI+1161kV, 10 times
• Subsequent DC test o DC-972kV, 2 hours
• Volume resistivity measurement

In conclusion, type test for 400kV project, and development results for 525kV cable system based on our design philosophy, material control and accessory design have brought us further confidence on the robustness of DC-XLPE cable system. After 400kV type test completion for Nemo link, cable installation has begun in 2017 and the system will be commissioned in 2019, which will be breaking record of operational experience of HVDC extruded cable system.

REFERENCES

[1] C.Watanabe Y.Itou H.Sakai S.Katakai M.Watanabe Y.Murata “Practical Application of +/-250 kV DC-XLPE Cable for Hokkaido-Honshu HVDC Link” CIGRE 2014 B1-110

[2] Y.Murata M. Sakamaki S. Mashio, O.Matsunaga, S.Kashiyama, S.Asai and S.Katakai “HVDC and Power Electronic Systems for Overhead Line and Insulated Cable Applications” CIGRE SanFransisco Colloqium 2012 B1-3

[3] T.Katayama T.Yamazaki Y.Murata S.Mashio T.Igi N.Hozumi M.Hori, “Space Charge Characteristics in DC-XLPE Cable after 400 kV PQ test” Jicable 15 A7-2