Expansion of HVDC Cable Application in Response to Growing Demand for Renewable Energy Transmission

Satoshi NISHIKAWA*, Toshio SHIMIZU, Noritsugu NAKAJIMA, Osamu SAITO, Tatsuki SATO, and Satoshi TOMIOKA

The cross-linked polyethylene (XLPE) cable has been used for DC transmission lines. We have been developing the DC XLPE cable for a few decades, and proved its quality and reliability through the research and development process. In 2012, we delivered the cable to Electric Power Development Co., Ltd. for its DC 250 kV transmission project, making it the world's highest voltage DC XLPE cable at that time and the first one to be applied to a line commute converter system. Following the project, we successfully completed two new projects: the 250 kV transmission project of Hokkaido Electric Power Co., Inc. and the 400 kV transmission project of NEMO Link Ltd. Our DC XLPE cable has an allowable continuous conductor temperature of 90 degrees Celsius, which is equivalent to the conventional AC XLPE cable, and withstands polarity reversal of voltage. This cable will meet the various needs of DC transmission that are expected to increase in the future.

Keywords: HVDC interconnector, XLPE cable, PQ test, type test, polarity reversal

1. Introduction

For the application of long-distance power transmission, high voltage direct current (HVDC) cable lines are widely applied around the world such as interconnectors between countries and offshore windfarms.

Mass impregnated (MI) cable and fluid-filled (FF) cable have been applied to HVDC transmission lines for long time, which are widely used for alternating current (AC) power transmission lines, as cross-linked polyethylene*1 (XLPE) cable is more friendly environmentally than MI or FF cable, has been introduced for HVDC application.

However, it is well known that conventional XLPE insulation has a problem when used for DC application, because of prominent accumulation of space charge*2 in insulation.

Research of DC XLPE materials was started in 1980’s, and a DC XLPE insulation material that has excellent DC characteristics even at high temperature was jointly developed with Electric Power Development Co., Ltd.[1]

After development tests, including polarity reversal conditions for DC 250 kV and 500 kV XLPE cables, DC 250 kV cables were adopted for the Hokkaido-Honshu HVDC link owned by Electric Power Development. The operation started in 2012.[2],[3]

This paper introduces new DC-XLPE cable projects for which contracts have been awarded to Sumitomo Electric Industries, Ltd. since the above project and discusses the future developments related to DC-XLPE cables in line with the expansion of renewable energy use.

2. Project to Install a HVDC Interconnector between the U.K. and Belgium

To interconnect electric power using ever-increasing renewable energy, National Grid plc (based in U.K.) and Elia Transmission Belgium SA (based in Belgium) established a joint venture named NEMO Link Limited and decided to construct the first HVDC interconnector between the two countries. We were awarded a contract from NEMO Link Limited to undertake a project to construct a DC 400kV power transmission cable system (NEMO link).[4]

2-1 Route profile

NEMO link is a DC power transmission line for connecting AC-DC converter stations, which were to be constructed in Kent in the southeastern part of the U.K. and Zeebrugge in Belgium. A voltage-source converter*3 (VSC) system, which has been emerging as the mainstream in the HVDC field, was used.

Figure 1 shows the route location of NEMO link. The route length is approximately 141 km, which consists of a submarine section of approximately 130 km and a land section of 2 km on the U.K. side and approximately 9 km on the Belgian side.

The water depth for most of the submarine section is 20 to 40 m, with a maximum water depth of 55 m (see Fig. 2).

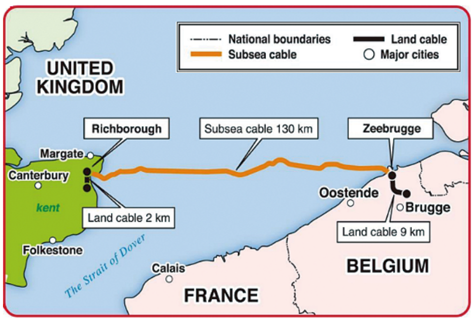

Fig. 1. Route location of NEMO link

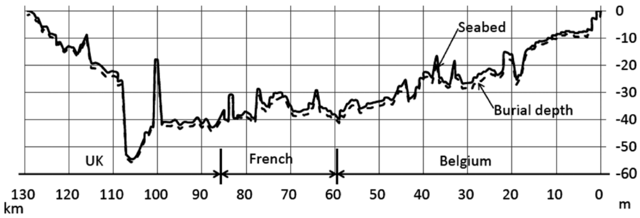

Fig. 2. Water depth profile of NEMO link

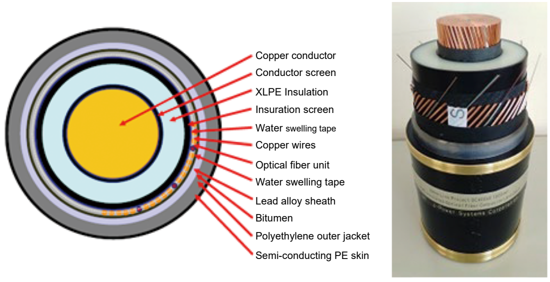

Fig. 4. Construction of the land cable for NEMO link

2-2 Overview of the line configuration and delivered products

NEMO link consists of positive electrode and negative electrode cables. Outdoor terminations were used at an AC-DC converter station on each end. They were connected with the submarine cables at the shore section via land cables. Submarine cables were connected by offshore joints. Table 1 shows the main products and quantity delivered.

Table 1. Main products and quantity delivered for NEMO link

Item	Quantity
Submarine cable	Approx. 59 km/approx. 71 km × 2 cables each
Land cable	Approx. 22 km (38 drums)
Outdoor sealing end	4 sets
Land joint	34 sets
Transition joint	4 sets
Offshore joint	2 sets

(1) Submarine cables

Figure 3 shows the construction of the submarine cable. The conductor size is 1,100 mm^2 with a function to prevent water penetration in the longitudinal direction. The insulation thickness is 19 mm. The composite optical fibers were integrated for data communication and Distributed Temperature Measurement System (DTS).

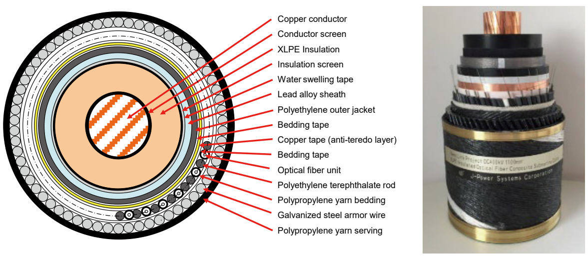

Fig. 3. Construction of the submarine cable for NEMO link

(2) Land cables

The land cable construction is shown in Fig. 4. The conductor size is 1,600 mm^2, and the insulation thickness is 19 mm, which is the same as that of the submarine cables. The composite optical fibers were also integrated in the copper wire layer.

(3) Joints

A pre-molded one-piece type joint, which is used up to AC 400 kV, was applied to both land and offshore sections. A pre-fabricated composite type joint was applied to transition joints which connected the submarine cable with the land cable.

Outdoor terminations, which consisted of a polymer bushing and incorporated a rubber insulator inside, were employed for termination.

The construction of each joint and termination is shown in Figs. 5, 6, and 7.

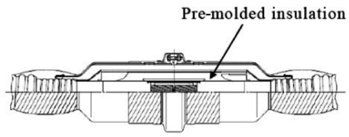

Fig. 5. Construction of land and offshore joint

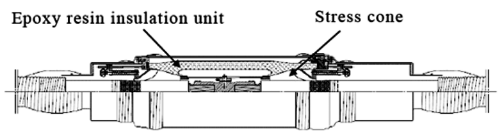

Fig. 6. Construction of transition joint

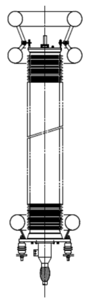

Fig. 7. Construction of outdoor termination

2-3 Type test

Prior to delivery of the products, a type test was conducted to verify the performance. All the delivered products shown in Table 1 were tested.

A tensile bending test was applied to submarine cable and pulling test was applied to an offshore joint prior to electrical test. The condition was equivalent to installation into a water depth of 100 m, which includes a margin for the actual water depth.

Basically, the electrical test conditions were in accordance with CIGRE TB 496. To perform more rigorous verification, line-commutated convertor*4 (LCC) conditions using a polarity reversal test were used. Ninety 24 h load cycles were also added. Six out of the 90 load cycles used the conditions to increase the conductor temperature up to 105°C. DC superimposed impulse tests after the load cycles were repeated twice. The test was completed without any problem. The delivered products were confirmed to be sufficiently reliable. Figure 8 shows a type test circuit diagram, and Table 2 shows the electrical test conditions for the type test.

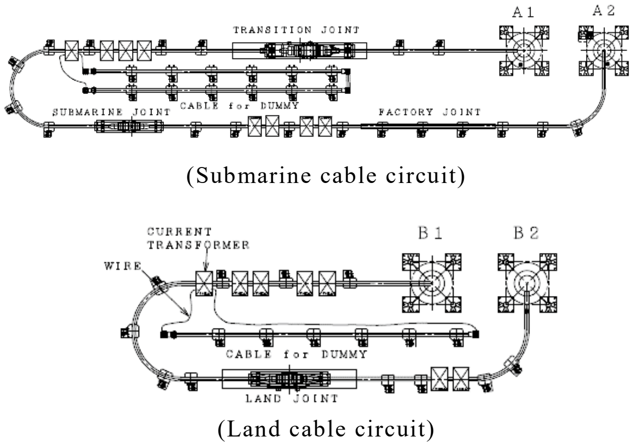

Fig. 8. Type test circuit diagram

Table 2. Electrical test conditions for the type test

Test item	Test conditions
24 h load cycle test	Applied voltage: ±740 kV (1.85U_0) × 8 days each (16 days in total) Max. conductor temperature: 90°C Load cycle: 8/16 hours heating/cooling
Load cycle test with polarity reversals	Applied voltage: ±580 kV (1.45U_0) × 8 days Max. conductor temperature: 90°C Load cycle: 8/16 hours heating/cooling
48 h load cycle test	Applied voltage: +740 kV (1.85U_0) × 3 times (6 days) Max. conductor temperature: 90°C Load cycle: 24/24 hours heating/cooling
DC superimposed switching impulse voltage test	DC+400 kV/Imp+840 kV(2.1U_0) 10 times DC-400 kV/Imp-840 kV(2.1U_0) 10 times DC+450 kV/Imp-480 kV(1.2U_0) 10 times DC-450 kV/Imp+480 kV(1.2U_0) 10 times Conductor temperature: 90°C
DC superimposed lightning impulse voltage test	DC+400 kV/Imp-840 kV(2.1U_0) 10 times DC-400 kV/Imp+840 kV(2.1U_0) 10 times Conductor temperature: 90°C
DC withstand voltage test	−740 kV × 2 hours (ambient temperature)

2-4 Manufacturing and delivery of cables

The cables were manufactured based on a quality control plan, which was formulated in advance. AC withstand voltage tests were conducted on all the lots.

In the manufacture of the submarine cables, the cables were connected by factory joints (FJs) because there was limitation of length in the insulation extrusion process per lot.

The FJs were also fabricated based on a quality control plan, as in the case of the cables. Quality was ensured by conducting an X-ray inspection to check for metal particles in insulation, an AC withstand voltage test, and a partial discharge test.

The completed cables were subjected to a DC withstand voltage test (−740 kV for 1 h), which is specified in CIGRE TB 496, as a factory acceptance test.

The submarine cables were shipped in two batches: two 59 km cables and two 71 km cables. For shipment, a 33,000-ton cargo vessel docked at a wharf of the factory, and each cable was transpooled into the cargo compartment of the vessel. The cables were transported to Europe. Photo 1 shows a submarine cable coiled in the cargo vessel.

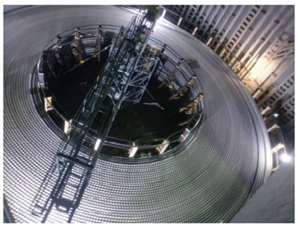

Photo 1. Submarine cable coiled in a cargo vessel

2-5 Cable installation and commissioning test

The submarine cables, which were transported in the cargo vessel, were re-wound on a turntable on a cable laying vessel, which was operated by a construction company, in the U.K.

In Europe, positive and negative electrodes of DC submarine cables are usually bundled and installed together. The turntable of the cable laying vessel was also designed to wind and unwind two cables at the same time.

The submarine cables consisted of two sections. First, two 59 km cables were laid and buried, and their ends were sunk under the sea. Then, the ends were salvaged with the arrival of the two 71 km cables. The cables were connected by offshore joint on the vessel and sunk under the sea again. They were protected using a concrete mat because they could not be buried.

Photo 2. Cables laid in the shore section and a cable laying vessel

After the cable laying work, including the land sections, was completed, a DC withstand voltage test of 740 kV for 2 h was conducted as a completion test in accordance with CIGRE TB 496. Commercial operation started on January 31, 2019, one day earlier than schedule. The HVDC cables have been operated without any problem at the highest voltage in the world. Photo 2 shows the cable laying status.

3. Project to Install DC 250 kV XLPE Cable in a Submarine Tunnel between Hokkaido and Mainland Japan

An existing interconnector between Hokkaido and Mainland Japan (Honshu) using DC 250 kV submarine cable was constructed by Sumitomo Electric and has been operated by Electric Power Development Co., Ltd since 2012.

To further enhance stable supply in the Hokkaido area, Hokkaido Electric Power Co., Inc. decided to construct a DC 250 kV Hokuto-Imabetsu interconnector with transmission capacity of 300 MW on a new route (hereinafter referred to as the "New Hokkaido-Honshu HVDC link"). Sumitomo was awarded a contract from Hokkaido Electric Power Co., Inc. to undertake a project to construct a DC 250 kV transmission cable system.

3-1 Overview of the project

A Voltage source converter*4 (VSC) was used for this power transmission system for the first time in Japan. This is one of a few HVDC lines in the world for VSC systems which consists of both overhead sections (98 km) and underground section (24 km).

The existing submarine railway tunnel (Seikan Tunnel) across the Tsugaru Strait was used for the route of the underground power transmission line. One DC cable and one return line (dedicated metallic return) were laid. When the HVDC link started operation, it was the longest extra-high-voltage cable laid in a submarine tunnel across a strait in the world. An overview of the route is shown in Fig. 9.

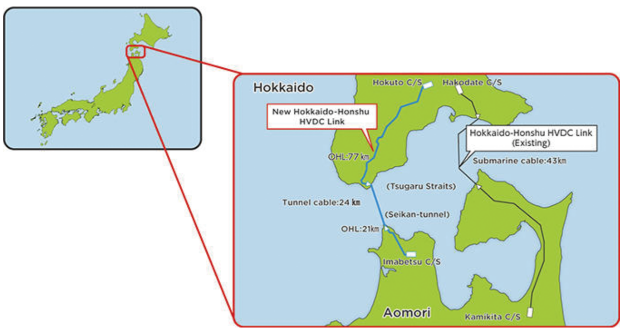

Fig. 9. Route location of the New Hokkaido-Honshu HVDC link

3-2 Overview of the delivered products

Regarding the cable conductor size, 800 mm², 1,000 mm², and 1,500 mm² were selected depending on the environment of the section to lay the cable. The continuous permissible conductor temperature was designed at 90°C. Photo 3 shows the cable construction.

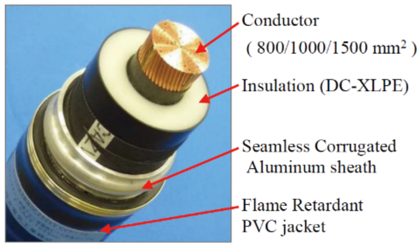

Photo 3. Construction of the New Hokkaido-Honshu HVDC link

Pre-molded one-piece type joint was used for connection of the cables with the same conductor size, prefabricated composite type joint was used only for connection of cables with different conductor sizes. The basic structure of each joint is the same as that of Figs. 5 and 6.

3-3 Type test

A type test was conducted to verify the performance of the products prior to delivery of the cables and joints to the project site.

Figure 10 shows an overview of the type test circuit, and Table 3 shows the test conditions. The test conditions for VSC systems, as recommended in CIGRE TB 496, were used. The withstand voltage against a DC superim-

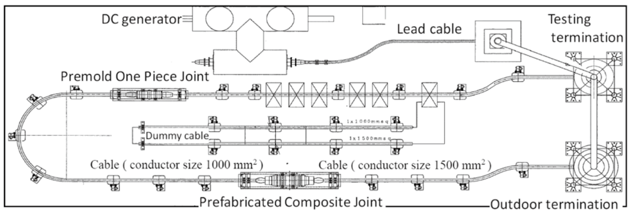

Fig. 10. Type test circuit diagram

Table 3. Electrical test conditions for the type test

Test item	Test conditions
24 h load cycle test	±481 kV (1.85 U_0 × 1.04*) × 12 days each (24 days in total) Max. conductor temperature: 90°C Load cycle: 8/16 hours heating/cooling
48 h load cycle test	+481 kV (1.85 U_0 × 1.04*) × 3 times (6 days) Max. conductor temperature: 90°C Load cycle: 24/24 hours heating/cooling
DC superimposed switching impulse voltage test	DC+250 kV/Imp-345 kV(1.4U_0) 10 times DC-250 kV/Imp-550 kV(2.2U_0) 10 times DC-250 kV/Imp+345 kV(1.4U_0) 10 times DC+250 kV/Imp+550 kV(2.2U_0) 10 times Conductor temperature: 90°C
DC superimposed lightning impulse voltage test	DC+250 kV/Imp-720 kV(2.9U_0) 10 times DC-250 kV/Imp+720 kV(2.9U_0) 10 times Conductor temperature: 90°C
DC withstand voltage test	−481 kV × 2 hours (ambient temperature) −600 kV × 3 hours (90°C)

*Multiplied by 1.04 to include an electric field of 1,500 mm² based on the test (1,000 mm²) posed lightning impulse, as required in the test, was set to 720 kV (2.9 U0) by taking into consideration the arrester protection level of the actual line. This value was more rigorous than the recommended value in CIGRE TB 496 (2.1 U0).

3-4 Cable laying work and completion test

As the submarine tunnel does not have any delivery entrance in the submarine section, it was decided to install and carry cables from the inclined cable shaft from the Hokkaido and Aomori sides.

The cable laying work was completed in the summer of 2018. The operation started in March 2019. The HVDC link has been operated without any problem. The status of cables laid in the tunnel is shown in Photo 4.

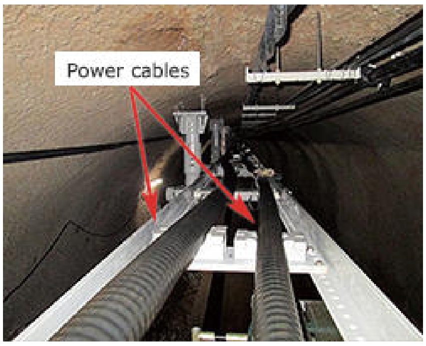

Photo 4. Status of cables laid

4. Other DC Cable Projects

Sumitomo Electric has undertaken DC cable projects other than the above. An overview is described below.

4-1 Land DC cable project in India

To eliminate the shortage in electric power supply in the southern part of India and stabilize the power transmission grid, a power transmission system of DC 320 kV and 2,000 MW, which consisted of an underground cable section of approximately 27 km and an overhead line section of approximately 187 km, was planned. The cross-section of the project is shown in Fig. 11.

In a hybrid line of XLPE cables and overhead power transmission lines, XLPE cables must meet high performance requirements because an overvoltage accompanied by polarity reversal is likely to occur due to a lightning stroke in the overhead line sections.

It was also necessary to meet the steady allowable temperature of 90°C because a high current close to 1,600 A per cable was designed to flow through the line.

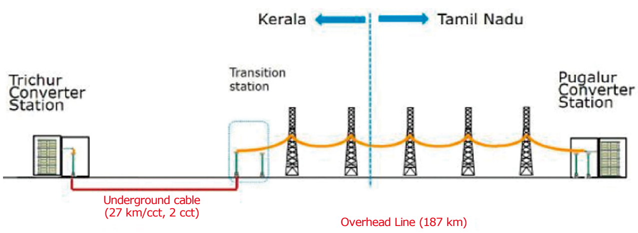

Fig. 11. Cross-section diagram of the HVDC project in India

Sumitomo Electric was awarded the contract because its DC-XLPE met these conditions. It delivered DC cables of approximately 108 km. Commercial operation started in March 2021.

4-2 Project to partially renew the interconnector between Germany and Denmark

A DC 400 kV LCC power transmission system was in place between Germany and Denmark. The fluid filled cables of the land section in Germany had severely deteriorated, so it was decided to replace the cables. Sumitomo Electric was awarded the contract because it owned DC-XLPE technology for LCCs involving polarity reversal operation. This is the first project in the world to use DC-XLPE cables for 400 kV LCC power transmission. Manufacture of cables is underway toward completion in 2023.

4-3 DC interconnector project between the U.K. and Ireland

This project was also planned for electric power interchange focused primarily on renewable energy. Sumitomo Electric was awarded the contract in September 2021.

A line with a route length of 190 km (submarine: 160 km, land: 30 km) will be constructed from 2022 to 2024 to achieve power transmission of 500 MW at DC 320 kV using a VSC system. An overview of the route of this project is shown in Fig. 12.

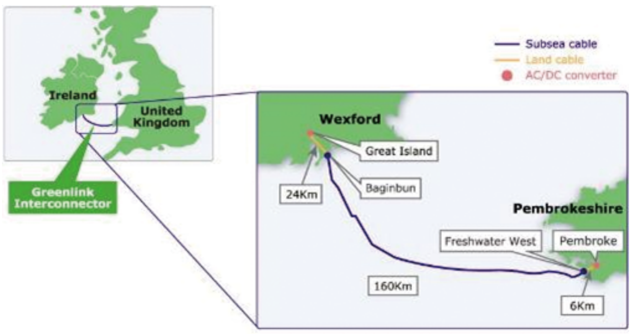

Fig.12. Route location of the U.K.-Ireland interconnector

4-4 DC 525 kV long-haul underground power transmission project in Germany

In Germany, offshore windfarms have been rapidly developed in its exclusive economic zone in the North Sea as part of its policy to spread the use of renewable energy. Meanwhile, it is imperative to strengthen the power transmission network to the demand area in the southern part. Multiple underground (land) power transmission lines, each spanning more than several hundred kilometers in route length, have been planned.

Sumitomo Electric participated in the PQ test of DC 525 kV XLPE cables, which was organized by four transmission system operators in Germany, as the only Asian manufacturer. The company passed the performance verification test, which lasted for more than one year. The capability of Sumitomo Electric's DC-XLPE cables to withstand polarity reversal were highly evaluated. The company was awarded a contract to construct the underground section (approx. 320 km) of a HVDC transmission line, consisting of an overhead section and an underground section, which was planned by Amprion GmbH. Preparation work for manufacturing and installation has been undertaken.

5. Conclusion

Offshore windfarms and interconnectors between countries have been actively constructed and planned mainly in Europe. Accordingly, the application of DC-XLPE cables has been expanding.

These developments are expected to spread globally, leading to further expansion of the use of DC-XLPE cables and application of higher voltage.

In terms of DC-XLPE cables currently in operation, NEMO link, for which Sumitomo Electric delivered its products, has the highest voltage in the world (400 kV). In Germany, it has been decided to use DC 525 kV XLPE land cables. In submarine cable projects, 525 kV is expected to become the norm in line with construction of long-distance and large-capacity lines.

Sumitomo Electric's high technology for DC-XLPE is expected to help meet the abovementioned needs. We will continue to further improve performance and reduce costs.

Technical Terms

＊1 Cross-linked polyethylene: Cross-linked polyethylene is an insulating material whose mechanical characteristics at high temperature has been improved by enhancing the intermolecular bonding of polyethylene through a cross-linking reaction. Previously, the mechanical characteristics of polyethylene were poor at high temperature. Cross-linked polyethylene has been used for AC since the 1960s.

＊2 Space charge: Space charge refers to the charge that accumulates in insulation when a DC voltage is applied to a solid insulation. Presence of the space charge distorts an electric field.

＊3 Voltage source converter (VSC): VSC refers to a DC power transmission system which uses a voltage-source converter (VSC). It is not necessary to reverse the voltage polarity to change the direction of power transmission (current).

＊4 Line-commutated converter (LCC): LCC refers to a DC power transmission system which uses an AC-DC converter incorporating a thyristor. The voltage polarity is reversed to change the power transmission direction.

References

(1) Y. Maekawa, C. Watanabe, M. Asano, Y. Murata, S. Katakai, and M. Shimada, 2001, "Development of 500 kV XLPE Insulated DC Cable," Trans. IEE of Japan, Vol.121-B, No.3, pp.390-398 (2001) [in Japanese]

(2) C. Watanabe, Y. Itou, H. Sasaki, S. Katakai, M. Watanabe, Y. Murata, "Practical Application of +/-250 kV DC-XLPE Cable for Hokkaido-Honshu HVDC Link," CIGRE 2014, B1_110_2014 (2014)

(3) S. Nshikawa, K. Sasaki, K. Akita, M. Sakamaki, T. Kazama, K. Suzuki, "XLPE Cable for DC Link," SEI TECHNICAL REVIEW No. 84, pp. 59-64 (April 2017)

(4) T. Igi, S. Asai, S. Mashio, S. Nishikawa, S. Tomioka, T. Miyazaki, T. Kazama, "Qualification, installation and commissioning of world's first DC 400 kV XLPE cable system," Jicable 2019 A6-1

Contributors The lead author is indicated by an asterisk (＊).

S. NISHIKAWA＊
• Assistant General Manager, Power Cable Projects Division

T. SHIMIZU
• Assistant General Manager, Power Cable Projects Division

N. NAKAJIMA
• Group Manager, Power Cable Accessories Division

O. SAITO
• Assistant Group Manager, Power Cable Projects Division

T. SATO
• Assistant Group Manager, Power Cable Division

S. TOMIOKA
• Assistant Group Manager, Power Cable Projects Division