XLPE Cable for DC Link

Satoshi NISHIKAWA*, Ken-ichi SASAKI, Koji AKITA, Masatoshi SAKAMAKI, Tatsuya KAZAMA and Kozo SUZUKI

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 250-kV DC transmission project, making it the world's highest voltage DC XLPE cable at that time and the world's first one to be applied to a line commutated converter system. Following the project, we successfully completed a pre-qualification test for a 400-kV DC XLPE cable. Currently, we are working 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 link, XLPE cable, Pre-qualification test, Type test, CIGRE

1. Introduction

In recent years, there has been widespread use of direct current (DC) transmission systems in Europe for interconnection between nations and for power transmission from offshore wind farms.

Conventionally, oil-impregnated paper insulated cables such as fluid-filled (FF) cables*[1] and mass impregnated (MI) cables*[2] have been used for DC transmission systems. However, recently there has been increasing demand for environmentally friendly extruded dielectric cables.

Cross-linked polyethylene (XLPE) cables*[3] are used widely for alternating current (AC) transmission systems, but when a DC voltage is applied, space charge accumulates in the XLPE insulation and DC withstand characteristics are lowered. We have developed a DC-XLPE insulating material with excellent DC characteristics and succeeded in its practical application to a DC-XLPE cable system.

This paper describes the superior characteristics of the DC-XLPE insulating material as well as the results of development tests and actual projects.

2. Characteristics of DC-XLPE Insulating Material

The insulating material for AC XLPE cables, defined as AC-XLPE, exhibits excellent insulating performance for AC voltages, but due to the accumulation of space charge,*[4] it cannot exhibit sufficient performance for DC voltages.

After many years of joint development with Electric Power Development Co., Ltd., we succeeded in the practical application of a DC-XLPE insulating material. This material exhibits superior DC characteristics due to an inorganic filler added to the XLPE. It has the merits outlined below:

· High volume resistivity
· Little accumulation of space charge
· Long DC life span
· High DC breakdown strength
· High allowable conductor temperature of 90°C

2-1 Volume resistivity

Figures 1 and 2 show the results of the measurement of volume resistivity performed using a sheet sample formed by press working. Figure 1 shows the electric field

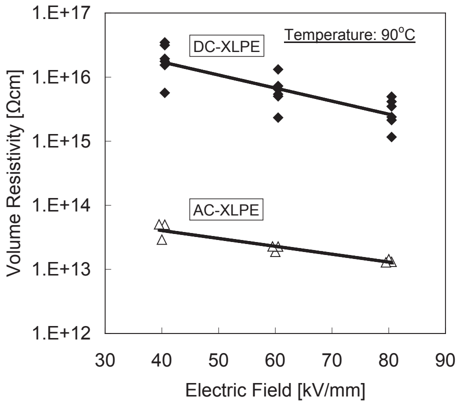


Fig. 1. Electric field dependence of the volume resistivity

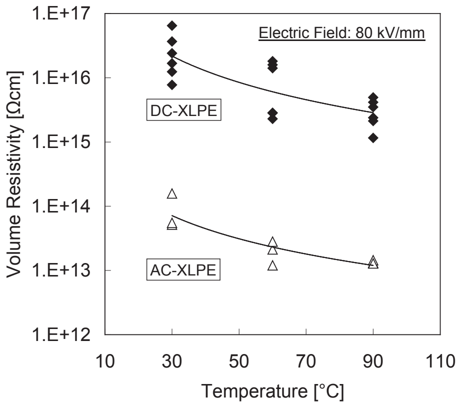


Fig. 2. Temperature dependence of the volume resistivity

dependence of the volume resistivity, and Fig. 2 shows its temperature dependence. DC-XLPE has a volume resistivity roughly 100 times that of AC-XLPE within the scope of the electric fields and temperatures measured.

2-2 Space charge characteristics

In order to specifically quantify the effect of space charge on the electric field, we found the field enhancement factor (FEF) defined by the Eq. (1) and evaluated the stability of the FEF over time.

FEF = Maximum electric field inside sample (kV/mm) / Applied voltage (kV)/ Sample thickness (mm) ···· (1)

Figure 3 shows the changes over time in the FEF for DC-XLPE and AC-XLPE. The figure contains the results for a DC electric field of 20 kV/mm and 50 kV/mm. During the 60 minutes from the start of the measurement, the FEF for DC-XLPE is small at 1.1 or less, and there is hardly any change seen over time. However, for AC-XLPE, the FEF clearly increases over time. Furthermore, the rate of increase in the FEF is greater with 50 kV/mm than it is with 20 kV/mm.

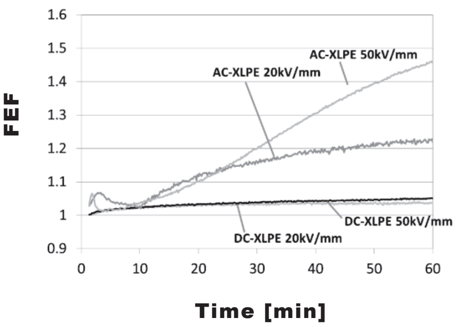


Fig. 3. Time dependence of FEF in DC-XLPE and AC-XLPE at 50 kV/mm, 20 kV/mm, 30°C

We performed further evaluations of the DC-XLPE to determine the changes in the space charge characteristics over a longer period of time. Figure 4 shows the results of an evaluation over several days of the changes in the FEF on DC-XLPE with a DC field of 50 kV/mm. It can be seen from Fig. 4 that the FEF for DC-XLPE is stable at 1.1 or below over a period in the order of a few days.

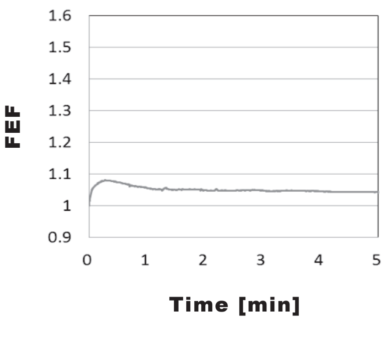


Fig. 4. Time dependence of FEF in DC-XLPE

The electric fields applied to the actual cables are around 20 kV/mm and it was confirmed that, under this level of electric field, the amount of space charge accumulation is less than that with AC-XLPE and the field enhancement inside the sample is minimized.

2-3 DC V-t characteristics

We have evaluated the DC V-t characteristics with the sheet samples. Figure 5 shows the DC V-t characteristics for both DC-XLPE and AC-XLPE. The vertical axis on this figure is the average electric field (E_{mean}) calculated from the voltage applied to the sample divided by the sample thickness. The horizontal axis is the time (t) from when the voltage was applied to the sample until dielectric breakdown occurred.

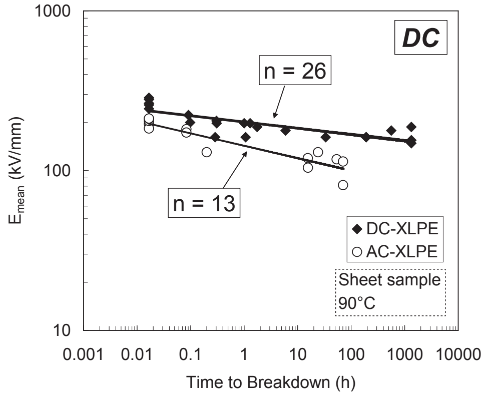


Fig. 5. DC V-t characteristics of DC-XLPE and AC-XLPE at 90°C

These results indicate that the DC breakdown strength decreases over time for both materials. However, when DC-XLPE and AC-XLPE are compared, the values of the breakdown stress are higher for DC-XLPE and also the decline rate of breakdown stress over time is lower for DC-XLPE.

We therefore evaluated the life span for DC. For AC-XLPE, we assume that the relationship in Eq. (2) applies between the electric field E and the time to breakdown t to determine the life exponent n, and use it in insulation design. We therefore tried to perform the same approach to determine the design life based on these results.

$E^n \times t = const.$ ·· (2)

As a result, we obtained n = 26 for DC-XLPE and n = 13 for AC-XLPE. These results show that the expected life under a DC voltage has been improved due to the effects of the addition of the inorganic filler in DC-XLPE.

2-4 DC breakdown characteristics on model cable

The model cable with a conductor size of 200 mm^2 and DC-XLPE insulation thickness of 9 mm was prepared. Then the DC breakdown tests with a conductor temperature of 90°C were performed.

Figure 6 shows the results of the breakdown test[1] of DC XLPE in comparison with an AC-XLPE cable.[2] It can be seen from Fig. 6 that the DC breakdown strength on the model cable using DC-XLPE is at least two times greater than that on the model cable using AC-XLPE.

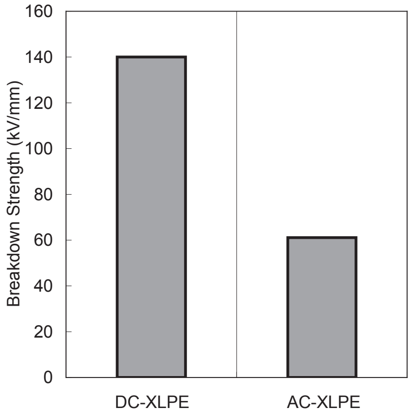


Fig. 6. DC breakdown strength of the model cable at 90°C

2-5 Temperature characteristics

As is seen from the volume resistivity temperature characteristics shown in Figs. 1 and 2 and from the breakdown strength shown in Fig. 6, even at 90°C, DC-XLPE has sufficiently high DC performance compared with AC-XLPE. It is therefore possible to set the allowable conductor temperature to 90°C, in the same way as for AC-XLPE.

3. Development Tests and Actual Projects

Multiple long-term development tests were performed for the DC-XLPE cables during the time from the basic development work to their practical application. As a result, there has already been sufficient verification of the performance for cables up to a maximum voltage of 500 kV and for factory molded joints (FJs) that allow the connection of submarine cable in the factory.(1),(3),(4) However, in the actual project, it was necessary to perform type tests in accordance with the customers' specifications. It was also necessary to perform pre-qualification (PQ) tests to demonstrate the long-term performance of the cable system including land joints.

This section describes the evaluation test performed to support an actual project from 2010 onwards.

3-1 Electric Power Development Co., Ltd. Hokkaido-Honshu (Kitahon) HVDC Link

The Kitahon HVDC Link owned by the Electric Power Development Co., Ltd., is a power transmission line that crosses the Tsugaru Channel with submarine cables and connects Hokkaido with Honshu (the main island of Japan). It is a bipolar, DC ±250-kV line with a transmission capacity of 600 MW. Two FF cables had already been laid and put into operation, but it was decided to add one more cable and DC-XLPE cable was selected(5) in order to replace the old FF cable installed in the 1970s. The features of this line include that the line commutated converter (LCC)*5 is used and the voltage polarity reversal is required in operation and also that there is a direct connection to overhead transmission lines from underground cable. Before the delivery of the product, PQ and type tests were implemented for DC 250-kV XLPE cables (submarine cables and underground cable) and their accessories. The submarine cables were tested with FJs in the test loop. For the reinforced insulation of the FJ, the tape mold method was selected. For the intermediate connections, the transition joints for the connection of the submarine cable and underground cable were used and also the oil-impregnated paper insulation type terminations were tested. The constructions of the specimens are shown in Figs. 7 to 10.

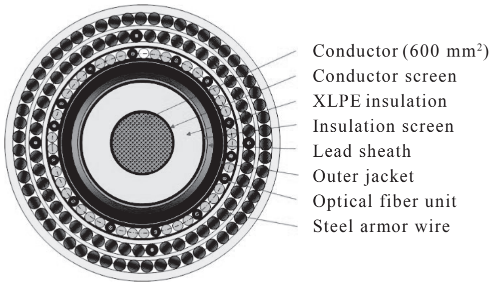


Fig. 7. Submarine cable for Kitahon HVDC Link

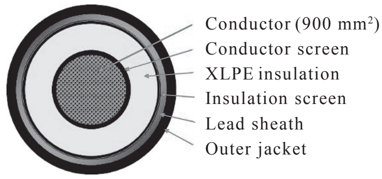


Fig. 8. Land cable for Kitahon HVDC Link

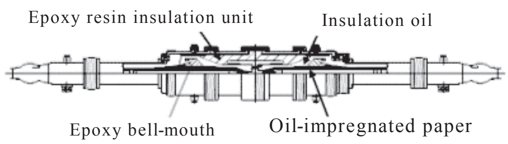


Fig. 9. Transition joint for Kitahon HVDC Link

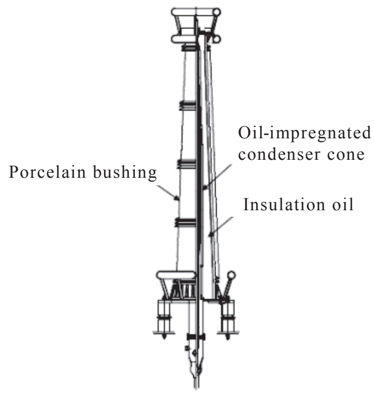


Fig. 10. Outdoor termination for Kitahon HVDC Link

The conditions used for these tests were in accordance with the LCC test protocol specified in International Council on Large Electric Systems Technical Brochure (CIGRE TB) 219[6] recommendation for testing extruded insulation cables for HVDC up to 250 kV. The tests included the polarity reversal test. Furthermore, with consideration of the allowable temperature during actual use, we set the test temperature to be 90°C. The type tests were completed in 2010 and the PQ tests were completed in 2011. This project involved the laying and jointing work and the completion test of approximately 42 km of submarine cables, approximately 1.3 km of underground cables, and their accessories. After the successful installation, operations started in December 2012 and have continued to today without accident. This line was the first example in the world of the application of XLPE cables to an LCC system, and at the time the operations started, it was the highest voltage DC-XLPE in the world.

3-2 PQ tests for 400-kV DC-XLPE cables

After the completion of the project described above, we decided to implement evaluations for even higher voltages. We implemented a PQ test for submarine and underground cables (both with a conductor size of 1,000 mm^2) and the various cable accessories foreseeing 400-kV HVDC systems with a bipolar transmission capacity of 1,000 MW.[7]

For the submarine cables including the FJ, to apply a mechanical history before the electrical test, we first implemented the coiling test and tensile bending test before laying the test lines. Also, we tested pre-molded one piece joint for the intermediate connections of the land section, prefabricated composite joint for the transition joint, and pre-molded type termination (polymer insulating bushing and porcelain insulating bushing). The specifications for these accessories followed those for AC, for which there are already proven results. The test conditions include the polarity reversal test for the LCC system in accordance with CIGRE TB 496,[8] which is the revision of CIGRE TB 219 and covers the voltage class up to 500 kV. Table 1 shows the test conditions and Fig. 11 shows the layout of the PQ test circuit. This test was completed in 2013 successfully.

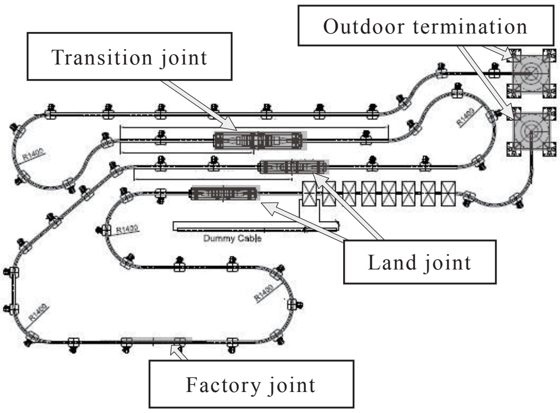


Fig. 11. Layout of the PQ test circuit

Table 1. Condition of the PQ test

Test item	Test condition	Requirement
Mechanical pre-conditioning	Coiling test (for submarine cable with FJ) Coiling diameter: 6m Number of coiling turns: 8 turns Number of testing times: 3 times Tensile bending test (for submarine cable with FJ) Tension: 134kN Number of testing times: 3 times	No outer damage
Load cycle test (1)	Applied voltage: +580 kV (1.45U_0) Temperature: 90°C (max.) Load cycle: 8/16 hours heating/cooling	30 days
Load cycle test (2)	Applied voltage: -580 kV (1.45U_0) Temperature: 90°C (max.) Load cycle: 8/16 hours heating/cooling	30 days
Load cycle test with polarity reversals (1)	Applied voltage: +/-500 kV (1.25U_0) Polarity reversal: every 8 hours Temperature: 90°C (max.) Load cycle: 8/16 hours heating/cooling	20 days
High load test (1)	Applied voltage: +580 kV(1.45U_0) Temperature: 90°C (max.) (without load cycle)	40 days
High load test (2)	Applied voltage: -580 kV(1.45Uv) Temperature: 90°C (max.) (without load cycle)	40 days
Zero load test	Applied voltage: -580 kV(1.45U_0) Temperature: ambient temperature	120 days
Load cycle test (3)	Applied voltage: +580 kV(1.45U_0) Temperature: 90°C (max.) Load cycle: 8/16 hours heating/cooling	30 days
Load cycle test (4)	Applied voltage: -580 kV(1.45U_0) Temperature: 90°C (max.) Load cycle: 8/16 hours heating/cooling	30 days
Load cycle test with polarity reversals (2)	Applied voltage: +/-500 kV(1.25U0) Polarity reversal: every 8 hours Temperature: 90°C (max.) Load cycle: 8/16 hours heating/cooling	20 days
Superimposed switching impulse voltage test	DC: +400 kV, SS: -480 kV, 10 times DC: -400 kV, SS: +480 kV, 10 times Temperature: 90°C (max.)	No Breakdown
Superimposed lightning impulse voltage test	DC: +400 kV, LI: -840 kV, 10 times DC: -400 kV, LI: +840 kV, 10 times Temperature: 90°C (max.)	No Breakdown
Subsequent DC test	Applied voltage: DC -580 kV (2 hours) Temperature: ambient temperature	No Breakdown

3-3 Hokkaido Electric Power Co., Inc., Hokuto-Imabetsu HVDC Link

In order to further stabilize the supply of electric power in Hokkaido, the Hokkaido Electric Power Co., Inc. decided to construct a 250-kV HVDC power transmission line connecting Hokkaido and Honshu via a new route and Sumitomo Electric was awarded for the underground power transmission line section (approx. 24 km). The features of this line include that the voltage sourced converter (VSC)*6 system was selected, that the line is connected directly to overhead transmission lines, and that the cable is to be laid inside the Seikan Tunnel which is an existing undersea railway tunnel. It will be the world's longest high-voltage cable to be laid inside a submarine tunnel.

In this project, we also produced 250-kV DC-XLPE underground cable and its accessories and implemented type tests before the delivery. As the conditions for the type tests, we selected the conditions for VSC systems in accordance with CIGRE TB 496. We performed the tests using aluminum sheathed PVC over-sheathed cables with conductor sizes of 1,000 and 1,500 mm^2. We used pre-molded one piece joint (for the connection of the same diameters) and prefabricated composite joint (for the connection of different size conductors) that had already had performance verified in 400-kV level PQ tests and outdoor termination (oil-impregnated paper insulated type with porcelain bushing) that we had already delivered in the past. Figures 12 and 13 show the structures of these joints.

The type tests have already been completed successfully and we have begun the manufacturing of the product.

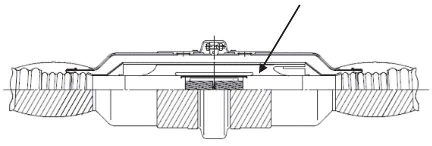


Fig. 12. Pre-molded one piece joint

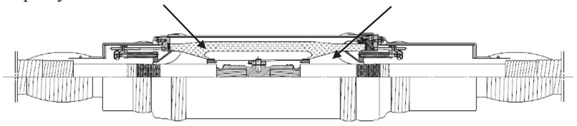


Fig. 13. Prefabricated composite joint

3-4 NEMO Link Limited, UK / Belgium HVDC Interconnector

J-Power Systems Corporation (JPS), a subsidiary of Sumitomo Electric, was awarded a contract for an HVDC interconnector cable system between UK and Belgium. The contract was awarded by NEMO Link Limited, a joint venture between National Grid Interconnector Holdings Limited, a subsidiary company of the UK's National Grid Plc, and the Belgian Elia System Operator SA. The cable system consists of a 130-km subsea cable route and an 11.5-km land cable route, and 400-kV DC-XLPE cable is applied to this project. The cable will be connected to HVDC converter stations in both Kent and Herdersbrug (Brugge).

In this project, the type test was conducted in accordance with the CIGRE TB 496. Although the VSC system was applied to this HVDC system, the test condition of the LCC system was also included as severer side. The type test was completed and manufacturing is ongoing.

Table 2 shows the supply items. Those accessories are all based on the design tested in the 400-kV PQ tests.

Table 2. Supply items for NEMO Link

Items	Description
Submarine cable	Copper conductor; 1,100 mm^2, Optical fibers incorporated, Single wire armored
Land cable	Copper conductor; 1,600 mm^2, Optical fibers incorporated
Land joint	Pre-molded one piece joint
Transition joint	Prefabricated composite joint
Offshore joint	Pre-molded one piece joint
Outdoor termination	Pre-molded type with polymeric bushing

4. Conclusion

Our DC-XLPE insulation materials have superior characteristics such as an allowable conductor temperature of 90°C under normal operation and the possibility of polarity reversal operation. As a result of these innovations, our DC-XLPE cable started operation in 2012 on the Kitahon DC trunk line of the Electric Power Development Co., Ltd. as the world's highest-voltage cable at that time and the world's first DC extruded cable applied to an LCC HVDC system.

We also have two further projects in progress following the successful completion of the 400-kV PQ tests.

In addition to the application of HVDC transmission technology to large-capacity and long-distance power transmission lines such as those between nations, there are expectations for its applications to the transmission of renewable energy, such as offshore wind power and Megawatt-class photovoltaic power, to distant locations.

As described above, our DC-XLPE cable system has sufficient performance and practicability to respond to the demands of the era such as these. We believe that it will make a contribution to the construction of power infrastructure around the world.

Technical Terms

*1 Fluid-filled (FF) cable: Main insulation is composed of oil impregnated paper and low viscosity oil is pressurized from remote end(s) for the entire cable route.

*2 Mass impregnated (MI) cable: Main insulation is composed of oil impregnated paper without oil pressure. High viscosity non-drain oil is used during the production to minimize oil migration.

*3 Cross-linked polyethylene (XLPE) cable: Main insulation is a solid dielectric without oil and it is dominantly used for AC cable from Low voltage to EHV voltage.

*4 Space charge: Space charge is a concept in which excess electric charge is treated as a continuum of charge distributed over a region of space, rather than distinct point-like charges and it is typically formed by dipole molecules in solid insulation.

*5 Line commutated converter: A classic topology of HVDC converter, which generally consists of thyristor valves and harmonic filter. The term of line-commutated indicates that the conversion process relies on the line voltage of the AC system to which the converter is connected for the commutation from one switching device, such as thyristors.

*6 Voltage sourced converter: Other topology of HVDC converter, which generally consists of an IGBT switch and capacitor bank to control voltage without influence from AC grid. In contrast to LCC HVDC converters, voltage-source converters maintain a constant polarity of DC voltage, and power reversal is achieved by changing the voltage slightly instead by reversing the direction of current.

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) Y. Maekawa, A. Yamaguchi, Y. Sekii, M. Hara and M. Marumo: "Development of DC XLPE Cable for Extra-High Voltage Use," Trans. IEE of Japan, Vol.114-B, No.6, pp.633-641 (1994)

(3) K. Terashima, H. Suzuki, M. Hara, K. Watanabe: "Research and Development of +/-250 kV DC XLPE Cables," IEEE Transactions on Power Delivery, Vol.13, No.1, pp.7-16 (1998)

(4) Y. Maekawa, T. Yamanaka, T. Kimura, Y. Murata, S. Katakai and O. Matsunaga, 2002, "500kV XLPE Insulated DC Submarine Cable," The Hitachi Densen, No.21, pp.65-72 (2002) [in Japanese]

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

(6) Working Group WG21-01 CIGRE, "Recommendation for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV," CIGRE Technical Brochure 219 (2003)

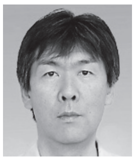
(7) Y. Murata, M. Sakamaki, Y. Tanji, T. Katayama, T. Igi, O. Matsunaga, "400kV DC-XLPE Cable and Accessories," CIGRE AORC Technical Meeting 2014, B1-1095 (2014)

(8) Working Group B1.32 CIGRE, "Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV," CIGRE Technical Brochure 496 (2012)

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

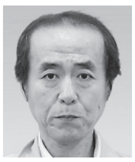
S. NISHIKAWA*
- General Manager, Global Power Cable Project Engineering Division

K. SASAKI
- Group Manager, Quality Assurance Department



K. AKITA
- Group Manager, J-Power Systems Corporation

M. SAKAMAKI
- Assistant General Manager, Technology Development Department



T. KAZAMA
- Assistant Manager, Power Cable Accessories Division

K. SUZUKI
- Assistant Manager, Power Cable Division