

Development and Demonstration Testing of Next Generation Ultra-High Voltage DC XLPE Cables with New Insulation Material

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Our Direct Current Cross-Linked Polyethylene (DC XLPE) insulation material is the only compound in the world qualified for use with Line-Commutated Converter (LCC) systems with polarity reversal capability, allowing for a maximum conductor temperature of 90°C, and has already been supplied for multiple commercial projects. However, to further improve the quality and performance of our cables, we developed new DC XLPE cables that incorporate an insulation formulation containing new inorganic fillers. This cable not only passed type tests, including polarity reversal, recommended by Conseil International des Grands Réseaux Électriques (CIGRE), one of the largest international conferences in the power industry, but also additional tests under severe electrical conditions. Moreover, space charge measurements of the cable insulation were conducted using Piezoelectric Effect Acoustic (PEA) methods before and after these long-term tests, revealing that the amount of space charge was low and remained nearly unchanged between the values before and after the tests. These results demonstrate that the new DC XLPE cables have favorable long-term DC characteristics.

Keywords: High-Voltage Direct Current (HVDC), DC cable, space charge, type testing, CIGRE

1. Introduction

With the global expansion of renewable energy adoption, transmission line construction projects connecting regions and nations are spreading worldwide, particularly in Europe. Demand for high voltage direct current (HVDC) cables, suitable for high-capacity, long-distance transmission, is growing globally for these power grids.

Our DC cable uses cross-linked polyethylene (XLPE)*¹ with inorganic fillers as its insulation material. It is the world's only DC XLPE cable with a conductor allowable temperature of 90°C, extremely low space charge*² accumulation that does not adversely affect DC characteristics, and the ability to withstand polarity reversal.*³ Since commencing operation in 2012 as the world's first 250 kV DC XLPE cable in the Hokkaido-Honshu interconnection line, our DC XLPE cables have already been delivered to multiple projects domestically and internationally, including the start of operation of the 400 kV DC XLPE cable for the NEMO Link (UK-Belgium interconnection), which is the world's highest voltage DC XLPE cable, in 2019.^{(1), (2)} Furthermore, our DC 525 kV XLPE cable has passed certification testing in accordance with the test conditions specified in the CIGRE's Technical Brochure 852⁽³⁾ (CIGRE TB 852), the largest international conference in the power industry. We have commenced manufacturing and installing DC 525kV cables for a regional interconnection project in Germany.

However, to meet the anticipated growth in demand for DC XLPE cables, we have developed new DC XLPE materials and cables. The new DC XLPE material achieves further improvements in manufacturability and performance while maintaining the distinctive DC characteristics of a conductor allowable temperature of 90°C and polarity reversal capability.

This report details the manufacturing of a 400

kV-class DC cable using a new DC XLPE material, along with the results of type testing conducted in accordance with CIGRE TB 852 and additional proprietary severe tests. Furthermore, it presents the results of an evaluation using the Pulsed Electro-acoustic (PEA) method⁽⁴⁾ to assess the impact of long-term operational history on the space charge characteristics within the cable insulation.

2. Design and Manufacturing of Cables for Long-Term Electrical Testing

A cable with an insulation thickness of 19.0 mm and a conductor size of 1300 mm² was manufactured for long-term electrical testing and space charge measurements. Additionally, considering potential application to submarine cables, factory joints were also manufactured using this cable. Figure 1 shows the cross-sectional structure of the cable.

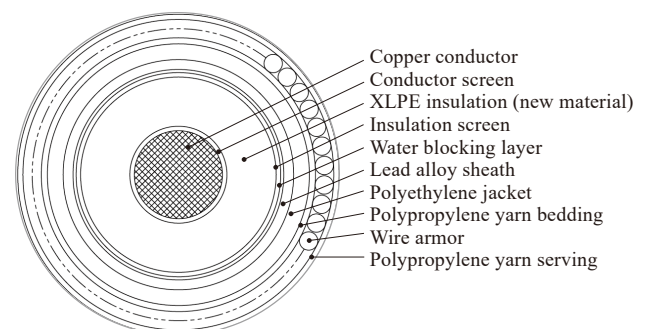


Fig. 1. Cross-sectional structure of the cable

A new DC XLPE material manufactured in-house was used for the insulation of both the cable and the factory joint. The inorganic filler in the new DC XLPE material is finer than that in conventional materials. This enables the use of finer mesh for filtering foreign matter during the DC XLPE material manufacturing process and the cable insulation extrusion process compared to conventional materials, further reducing the risk of foreign matter intrusion into the material and cable insulation.

Furthermore, the finer inorganic filler also causes the material to become transparent at high temperatures. This enables insulation transparency testing of DC XLPE cables, increasing the probability of detecting defects in the internal and external semiconductive layers and foreign matter contamination within the insulation.

3. Long-Term Electrical Testing

3-1 Type testing

Type tests equivalent to a 525 kV DC electric field stress were conducted at our Ibaraki Works. As shown in Fig. 2, the electrical test loop for the type test was divided into two loops: Loop 1 incorporating a Gas Insulated Switchgear (GIS) termination and Loop 2 incorporating an outdoor termination. This enabled long-term performance verification of the new DC XLPE cable in combination with each type of termination.

Additionally, a repair joint and factory joint were incorporated into Loop 1.

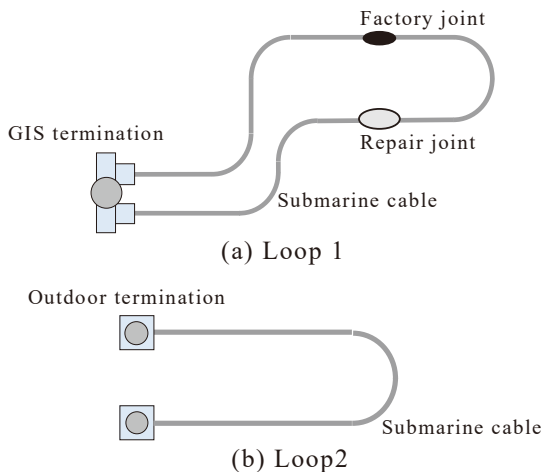


Fig. 2. Schematic diagram for the test loops of the long-term electrical test

Cables submitted for the electrical test loop were subjected to the coiling test and tensile bending test shown in Table 1 prior to installation on the loop. These tests were performed to provide mechanical history expected during actual cable manufacturing and laying operations.

After mechanical testing, the wire armor and serving were removed in order to prevent heat generation in the wire armor when AC current is applied to the cable during electrical testing.

Electrical testing was conducted in accordance with

Table 1. Mechanical testing conditions

Test item	Test conditions
Coiling test	Min. coiling diameter: 12 m Number of coiling times: 3 times
Tensile bending test	Bending radius: 3 m Tensile force: 21 ton

the type test conditions specified in CIGRE TB 852. The test conditions are shown in Table 2.

Table 2. Test conditions of the electrical type test according to CIGRE TB 852

Test item	Test condition
24-hour load cycle test (1)	Applied voltage: DC -750 kV (1.85 U_0) Number of cycles: 12 cycles Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
24-hour load cycle test (2)	Applied voltage: DC +750 kV (1.85 U_0) Number of cycles: 12 cycles Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
Load cycle test with polarity reversals	Applied voltage: DC +/-588 kV (1.45 U_0) Polarity reversal: every 8 hours Number of cycles: 8 cycles Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
48-hour load cycle test	Applied voltage: DC +750 kV (1.85 U_0) Number of cycles: 3cycles (6 days) Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
Superimposed switching impulse voltage test	DC: +405 kV (U_0), SI: -486 kV (1.2 U_0), 10 times DC: +405 kV (U_0), SI: +851 kV (2.1 U_0), 10 times DC: -405 kV (U_0), SI: +486 kV (1.2 U_0), 10 times DC: -405 kV (U_0), SI: -851 kV (2.1 U_0), 10 times Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
Superimposed lightning impulse voltage test	DC: +405 kV (U_0), LI: -851 kV (2.1 U_0), 10 times DC: -405 kV (U_0), LI: +851 kV (2.1 U_0), 10 times Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
Subsequent DC test	Applied voltage: DC -750 kV Test duration: 2 hours Conductor temperature: No heating

The test conditions were based on those for the Voltage Source Converter (VSC) system, which is common in recent DC transmission systems. However, to verify the actual performance of DC XLPE insulation, the polarity reversal test for the LCC system, which imposes more severe conditions on the insulation, was added. Furthermore, to evaluate lightning resistance, a DC superimposed lightning impulse test was also added.

The maximum temperature of the cable conductor during load cycle and superimposed tests was set to 90°C or higher, and the maximum temperature gradient of the insulation (ΔT_{max}) was set to 16°C or higher.

Furthermore, the test voltages shown in Table 2 were set to be equivalent to the electric field stress applied to the insulation during the type test of a 525 kV DC cable. As shown in Table 3, setting $U_0 = 405$ kV and the load cycle test voltage to $1.85U_0 = 750$ kV ensures that the maximum electric field stress is equivalent to or greater than that during the DC 525 kV type test.

Table 3. Comparison of maximum electrical field between the test cable and a 525 kV DC cable

	Test cable	525 kV DC cable
Cable structure	Insulation thickness: 19.0 mm Conductor size: 1300 mm ²	Insulation thickness: 25.0 mm Conductor size: 2500 mm ²
Max. electrical field under rated voltage (U_0)	$U_0 = 405$ kV Max. electrical field: 29.2 kV/mm	$U_0 = 525$ kV Max. electrical field: 28.4 kV/mm
Max. electrical field under type test voltage ($1.85 U_0$)	$1.85 U_0 = 750$ kV Max. electrical field: 54.1 kV/mm	$1.85 U_0 = 972$ kV Max. electrical field: 52.6 kV/mm

3-2 Additional heating cycle testing

After completing the type tests listed in Table 2, additional heating cycle tests shown in Table 4 were conducted. For the additional tests, the DC voltage was increased to 800 kV to verify the dielectric strength under higher electric field conditions. A load cycle test for the VSC system specified in CIGRE TB 852 was performed at a conductor temperature of 90°C. At this time, the maximum electric field was 57.7 kV/mm, approximately 10% higher than the electric field stress during the 525 kV type test shown in Table 3.

Table 4. Test conditions of additional heating cycle test

Test item	Test condition
24-hour load cycle test with higher voltage (1)	Applied voltage: DC -800 kV Number of cycles: 12 cycles Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
24-hour load cycle test with higher voltage (2)	Applied voltage: DC +800 kV Number of cycles: 12 cycles Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
48-hour load cycle test with higher voltage	Applied voltage: DC +800 kV Number of cycles: 3 cycles (6 days) Max. conductor temperature: 90°C ΔT_{MAX} : 16°C
24-hour load cycle test with higher voltage and higher temperature (1)	Applied voltage: DC -800 kV Number of cycles: 3 cycles Max. conductor temperature: 100°C ΔT_{MAX} : 16°C
24-hour load cycle test with higher voltage and higher temperature (2)	Applied voltage: DC +800 kV Number of cycles: 3 cycles Max. conductor temperature: 100°C ΔT_{MAX} : 16°C

Furthermore, to verify performance under conditions where space charge accumulation within the cable insulation and the corresponding electric field distortion increase even more, load cycle tests were conducted with 800 kV DC at conductor temperature of 100°C on Loop 1.

The new DC XLPE cable passed the type tests recommended by CIGRE TB 852 and additional heating cycle tests without failure, demonstrating an insulation withstand voltage equivalent to or exceeding DC 525 kV electric field stress.

4. Space Charge Measurement

To evaluate the effects of voltage application history and heating history on the space charge characteristics of

the new DC XLPE cable insulation, space charge measurements were performed and compared on Cable Sample A (without charging and energizing history) and Cable Sample B (after long-term electrical testing). Both cable samples were taken from the same lot manufactured as a continuous length.

The space charge measurement was performed using the PEA method. Figure 3 shows the space charge measurement circuit for the PEA method. For Cable Sample A with no electrical test history, the measurement was performed using the test loop shown in Fig. 3 (a).

For Cable Sample B, which had undergone long-term electrical testing, space charge measurements were performed by integrating the PEA measurement device into the long-term electrical test loop, as shown in Fig. 3 (b).

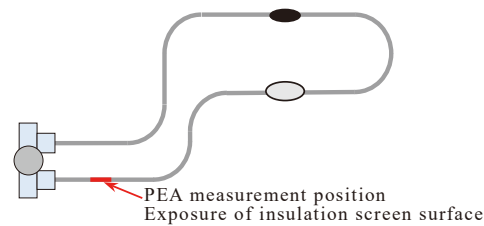
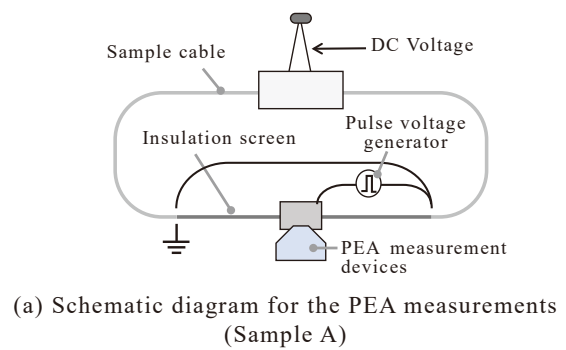


Fig. 3. The experimental setup for the space charge measurements using the PEA method

Table 5 shows the measurement conditions for space charge in each sample. For the DC voltage, sample A was tested at -400 kV, while sample B was tested at ±405 kV corresponding to $U_0 = 405$ kV from the long-term electrical test. This voltage difference arose because U_0 had not been determined during sample A testing. The measurement duration is 10 hours. For Cable Sample A, the temporal evolution of the space charge distribution was measured from 0 to 10 hours.

Table 5. Electrical and thermal conditions for the space charge measurements using the PEA method

	Sample A	Sample B
DC voltage	-400 kV	+405 kV / -405 kV
Conductor temperature	90–95°C	90–95°C
ΔT	> 16°C	> 16°C
Time to keep voltage and temperature	10 h	10 h

Figure 4 shows the space charge measurement results for Cable Sample A without voltage application and heating history. In Fig. 4 (a), a slight accumulation of negative homo charge is observed at the inner side insulation. This space charge accumulation relaxes the electric field at inner side insulation compared to the Laplacian field distribution, as shown in Fig. 4 (b).

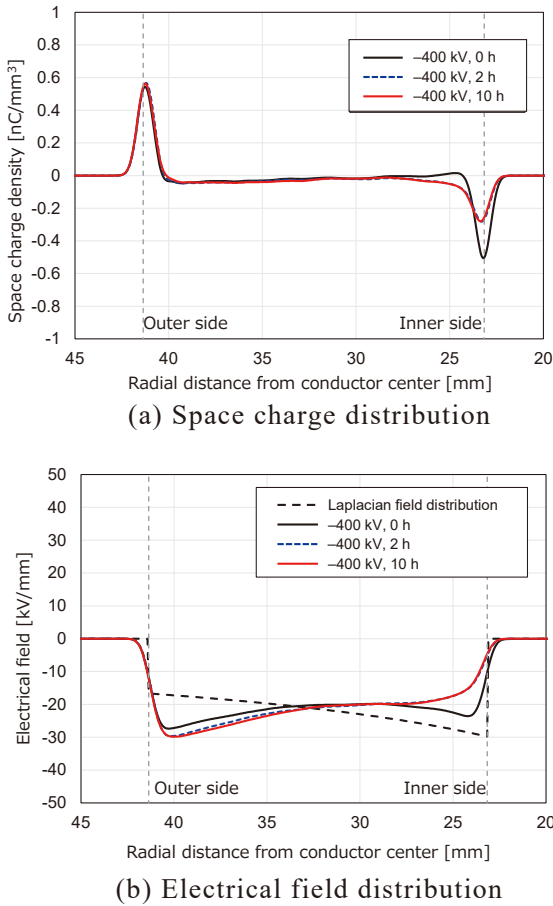


Fig. 4. The result of space charge measurement for Cable Sample A

Furthermore, no significant difference in space charge accumulation or electric field distribution was observed between the 2-hour and 10-hour points after measurement initiation. This indicates that space charge accumulation and electric field distortion can be considered to have reached near saturation approximately 10 hours after the DC voltage application.

Figure 5 shows the space charge measurement results for Cable Sample B after the long-term electrical test. The space charge distribution at -405 kV after 10 hours, shown in Fig. 5 (a), is similar to the space charge distribution at -400 kV after 10 hours for Cable Sample A shown in Fig. 4 (a). Furthermore, as shown in Fig. 5, the polarity of the DC voltage merely reverses the polarity of the space charge distribution and electric field distribution; it does not affect the distribution trend.

Based on these measurement results and the fact that Sample B passed the long-term electrical test, it can be

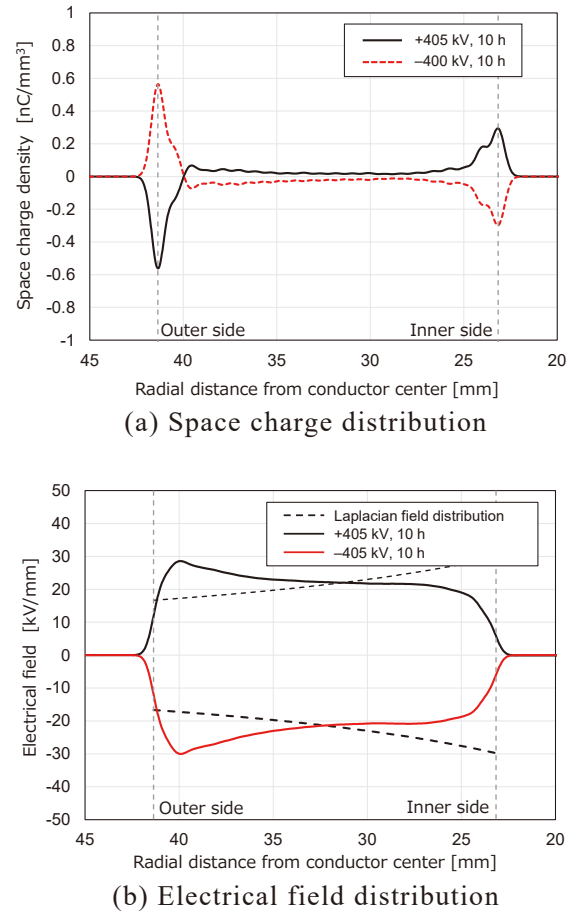


Fig. 5. The result of space charge measurement for Cable Sample B

considered that space charge accumulation in new DC XLPE insulation is harmless for its DC characteristics. Furthermore, it is evident that long-term voltage application history and heating history do not affect the space charge characteristics of the insulation.

5. Conclusion

To evaluate the performance of new DC XLPE cable materials, we conducted type tests in accordance with CIGRE TB 852 and our proprietary additional heating cycle tests. They confirmed that the insulation material is suitable for operation under a voltage equivalent to a 525 kV DC electric field, with a conductor allowable temperature of 90°C, and is also applicable for polarity reversal operation. Furthermore, space charge measurements were performed before and after long-term electrical tests, confirming that voltage application history and heating history had little effect on the space charge characteristics of the insulation, maintaining excellent electrical properties.

Currently, our company is planning to conduct DC 525 kV Pre-Qualification tests (PQ Test) and type tests according to CIGRE TB 852 on cables using the new DC XLPE material. This new DC XLPE material excels not only in DC performance but also in manufacturability and

quality. After passing the tests, we aim to apply it to expanding DC transmission line construction projects both domestically and internationally.

Technical Terms

- *1 Cross-linked Polyethylene (XLPE): The most widely used resin material for insulated cables is cross-linked polyethylene. Cross-linking reactions bond the polyethylene molecules together, which increases the heat resistance and allows the insulation to withstand the temperature rises during cable operation.
- *2 Space Charge: A charge accumulation of positive or negative polarity within an insulation. This space charge causes localized electric field distortions within the insulation.
- *3 Polarity Reversal: The reversal of the voltage applied to a DC cable from positive to negative, or from negative to positive. In LCC DC transmission systems, the polarity of the DC voltage is reversed when changing the direction of the power flow.

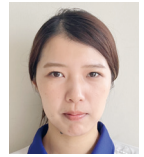
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