Development of High Voltage DC-XLPE Cable System

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We have developed a cross-linked polyethylene (DC-XLPE) insulating material that has excellent properties for DC voltage applications. Our high-voltage (HV) DC XLPE cable and factory joints using this material showed positive results in a polarity reversal test and other long-term tests aiming at high voltage operation up to 500 kV. In addition, this cable passed 250 kV pre-qualification tests and type tests, which also include polarity reversal tests, in accordance with the test conditions specified by the CIGRE TB 219. All the tests were conducted at 90°C and the results showed that our HVDC XLPE cable and accessories are capable of normal operation and polarity reversal operation at 90°C in actual HVDC link lines. J-Power Systems Corporation is now ready to supply this cable and related products to the market.

Keywords: HVDC, XLPE cable, type test, PQ test, CIGRE Technical Brochure

1. Introduction

High voltage direct current (HVDC) power transmission lines in Japan consist of Hokkaido-Honshu DC link and Kii Channel DC link that connects Shikoku with Honshu. As for HVDC power transmission in foreign countries, main applications have been for long-distance power transmission such as intercontinental links. However, in recent years, there has been a growing trend toward its application to offshore wind power generation, which is being actively introduced in Europe as a renewable natural energy source. As its introduction has progressed, the locations of the wind power generation facilities have been shifted from coastal areas to offshore areas due to space constraints. As the power transmission distance has increased, HVDC power transmission technology has drawn more attention.

Previously oil-impregnated insulation cables, such as mass impregnated (MI) cable and oil-filled (OF) cable, have been applied to DC power transmission. In recent years, however, because of the increasing awareness for environmental protection, extruded insulation cables have come to be desired as they have no fear of oil leakage.

On the other hand, cross-linked polyethylene insulation cable, which is currently widely applied to AC power transmission, is known to have a number of problems in insulation when used for DC usage, i.e., prominent accumulation of space charge in cross-linked polyethylene (XLPE) insulation material. Therefore, we have developed a DC-XLPE insulation material that has excellent DC characteristics. We have also developed a DC-XLPE cable using the above mentioned material as insulator. This paper describes the excellent DC characteristics of the DC-XLPE insulation material developed for DC applications, and reports on the implementation status of type tests and pre-qualification (PQ) tests in accordance with the International Council on Large Electric Systems (CIGRE) Technical Brochure on actual cables and accessories.

2. Changes in DC Cable Technology and History of DC-XLPE Cable Development

This chapter introduces the outline of changes in HVDC cable technology and the history of our DC-XLPE cable development.

In 1954, the world's first operation of HVDC power transmission began between the mainland of Sweden and Gotland Island[(1)]. At that time, MI cables using insulating paper impregnated with high viscosity insulating oil were used, and for higher voltage and larger capacity applications, OF cables were adopted, using insulation paper which was impregnated with low viscosity insulating oil and kept in pressurized condition. Since then, MI cables and OF cables, i.e., oil-impregnated paper-insulated cables, have been the mainstream of DC power transmission cables. The oil-impregnated insulation cable technology has developed in response to demand for higher voltage, larger capacity (larger conductors), and longer power transmission[(1)].

On the other hand, extruded insulation cables, in which such material as XLPE is extruded on the conductor, were first applied in Gotland to an 80 kV DC line in 1999[(2)]. Here, a voltage source converter (VSC) was used as an AC-DC converter. As the VSC does not require the inversion of the voltage polarity (polarity reversal) when reversing the direction of a power flow, the problem of a decrease in insulation performance, such as space charge influences, can be reduced. This has made the use of extruded insulation cables easier for DC applications. Since then, for environmental protection, the number of extruded insulation cables, used in combination with VSCs, has increased for HVDC power transmission applications. Recently, in the Trans Bay Cable Project, a 200 kV DC power transmission was realized[(3)]. As of the start of the project in 2010, 200 kV was the world's highest DC operating voltage for extruded insulation cables.

Table 1 shows the history of our DC-XLPE cable development. In the 1970s, long-term DC voltage tests were performed in Japan to see if the XLPE cable used for AC

Table 1. History of DC-XLPE cable development

1981-1990	1991-2000	2001-2010	2011-2020

- 1984~1989 Fundamental research on DC insulation material
- 1988~1995 Development of DC 250kV cable and factory joint
- ◆1995, long-term demonstration test of DC250kV cable and FJ
- 1993~2001 Development of DC 500kV cable and factory joint
- ◆2001, long-term demonstration test of DC500kV cable and FJ
- ◎2003, publication of CIGRE TB 219
- 2005~2006 Verification on long-length extruding of DC-XLPE
- ◆2007, DC250kV Type test
- ◆2009, DC250kV PQ test
- 2007~2010 Establishment of manufacturing technology of practical DC-XLPE cable
- ◆2010, DC250kV type test for the Hokkaido-Honsyu DC link project
- ◆2011, DC250kV PQ test for the Hokkaido-Honsyu DC link project
- ◎2012, publication of CIGRE TB 496
- ●2012, installation of DC-XLPE cable for the Hokkaido-Honsyu DC link project, and it was put into operation in December.
- ◆2012-2013, DC400kV PQ test

power transmission can be also used for DC applications. However, due mainly to the effect of space charge accumulation in the insulator, it became clear that there were many problems in terms of DC insulation(1). Based on these results, we started in 1984 a basic development of an XLPE insulation material for DC usage.

We started the research and development of +/−250 kV-class DC-XLPE cable in 1988 and +/−500 kV-class cable in 1993. This series of R&D projects has been done in collaboration with Electric Power Development Co., Ltd.

At the beginning of the development, DC-XLPE cable used a general-purpose inorganic filler material. However, in the process of adapting the cable to higher voltage application, miniaturization, higher purification and higher distribution of the inorganic filler material were pursued. As a result, we achieved a nano-composite insulation material in which inorganic nano particles were distributed uniformly. We will discuss the characteristics of the insulation material in Chapter 3.

In 1995, a long-term verification test was conducted for a +/-250 kV DC-XLPE cable and factory joint (FJ)(4). In 2001, another long-term demonstration test was conducted for a +/-500 kV DC-XLPE cable and FJ to verify their practical performance(5),(6). Furthermore, after receiving the recommendations of CIGRE Technical Brochure 219 (TB 219)(7) published in 2003 regarding the DC test method for extruded insulation cables, a type test and PQ test conforming to the TB 219 have been carried out sequentially.

Meanwhile, for the actual HVDC line, several km of cable core needed to be made as a manufacturing lot. Therefore, in parallel with the above effort, we proceeded to establish a mass production technique for DC-XLPE insulation material such as long extrusion technique. In 2009, we received an order for the Hokkaido-Honshu DC link project from Electric Power Development Co., Ltd. In order to verify the final manufacturing technology, the 250 kV DC-XLPE cable and its accessories were manufactured and subjected to a type test and a PQ test in 2010 and 2011, respectively. The DC-XLPE cable and accessories to be used in the Hokkaido-Honshu DC link project were installed in a test site in the summer of 2012. The cable passed the post-installation test by successfully completing the DC high voltage test at 362.5 kV (= 1.45 PU) for 15 minutes in August 2012 in accordance with CIGRE TB219(8). This cable line was put into operation in December 2012 as the world's highest voltage extruded DC cable in service and the world's first DC extruded cable for line commutated converter (LCC) systems including polarity reversal operation.

Currently, PQ testing for a 400 kV DC-XLPE cable and FJ as well as outdoor termination and joint sections is being carried out for higher voltage applications.

Table 1 shows the history of DC-XLPE cable development and we will describe the details of the long-term verification tests, type tests and PQ tests in Chapter 4.

3. DC Characteristics of DC-XLPE Insulation Material

XLPE cables widely applied in AC power transmission and distribution use cross-linked polyethylene (XLPE) as the insulation material (hereafter denoted as AC-XLPE). AC-XLPE insulation material exhibits excellent insulation performance against AC voltages, but it does not exhibit adequate performance against DC voltages due to such reasons as the accumulation of space charge. By adding nano-size filler materials in the XLPE insulator, an excellent characteristic can be obtained. The XLPE insulation material for DC usage, to which nano particles have been added, (hereafter, DC-XLPE) has the following features in comparison with AC-XLPE:

➢ High volume resistivity (refer to Section 3-1)
➢ Low space charge accumulation (refer to Section 3-2)
➢ Long DC life time (refer to Section 3-3)
➢ High DC breakdown strength (refer to Section 3-4)

We will show these characteristics of DC-XLPE in comparison with AC-XLPE.

3-1 Volume resistivity

Volume resistivities of DC-XLPE and AC-XLPE were investigated using sheet specimens formed by press work. The sheet thickness was made to be about 150 µm. The volume resistivity was evaluated with the DC leakage current value measured ten minutes after the measurement was begun. The temperatures were set at 30˚C, 60˚C and 90˚C, and the electric fields were set at 40 kV/mm, 60 kV/mm and 80 kV/mm.

Measured volume resistivities are shown in **Figs. 1 and 2**. **Figure 1** shows the dependence of volume resistivity on the electric field and **Fig. 2** shows the dependence on the temperature. As shown in **Figs. 1 and 2**, within the range of the measurement temperature and electric field, DC-XLPE possesses about 100 times higher volume resistivity than AC-XLPE.

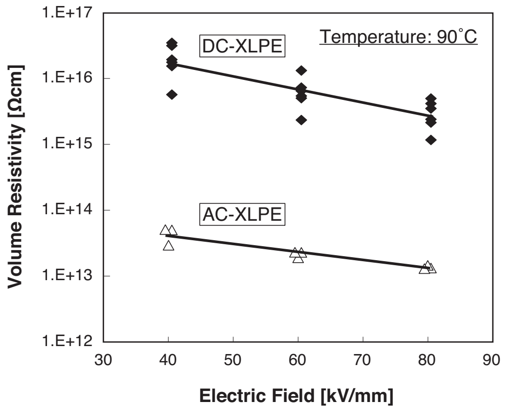

Fig. 1. Electric field dependence of the volume resistivity

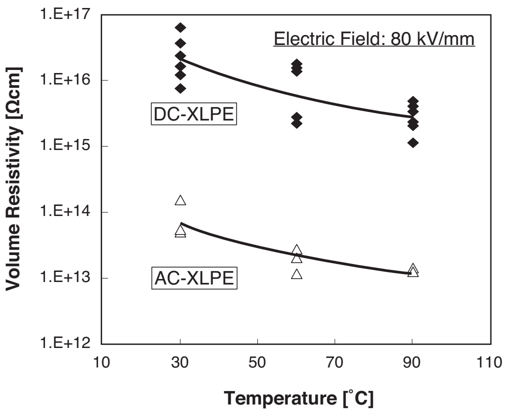

Fig. 2. Temperature dependence of the volume resistivity

3-2 Space charge characteristics

The space charge distribution in DC-XLPE and AC-XLPE was evaluated by using the pulsed electro-acoustic (PEA) method. Pressed sheet specimens with a thickness of about 200-300 µm were used. DC voltages with average electric fields of 20 and 50 kV/mm were applied to the specimens, and the change of space charge distribution was measured at 10-second intervals.

Figure 3 (a) shows the space charge distributions of DC-XLPE and **Fig. 3 (b)** shows the electric field distributions when a DC voltage of 50 kV/mm was applied. In DC-XLPE, space charge was not accumulated inside the specimen, and the result hardly changed over time. It is also seen that the electric field distribution is nearly uniform. On the other hand, space charge distribution and electric field distribution for AC-XLPE when 50 kV/mm was applied are as shown in **Fig. 4**. It is seen that, as time progresses, space charge is accumulated and the electric filed distribution is distorted to a large extent. In particular, in the neighborhood of the anode, negative space charge is accumulated, leading to the occurrence of a large enhancement in the electric field.

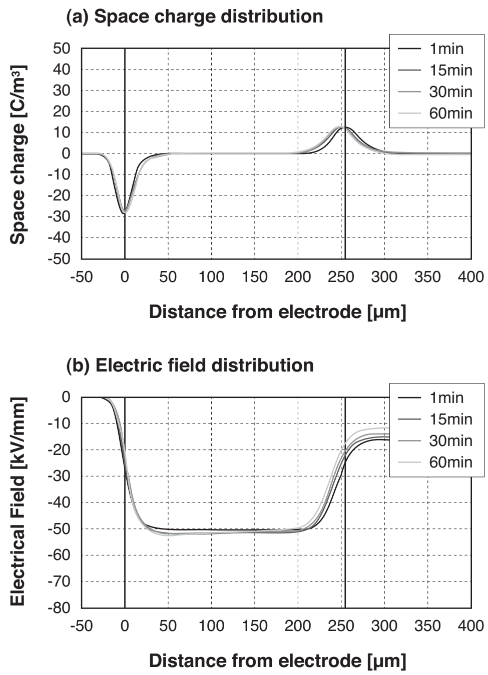

Fig. 3. Space charge and electric field distributions in DC-XLPE at 50 kV/mm, 30˚C

In order to numerically express the effect of space charge on the electric field in a concrete manner, we obtained the field enhancement factor (FEF) as the **Equation (1)** defines below and evaluated its change with time:

$$FEF = \frac{\text{Maximum electric field in specimen [kV/mm]}}{\text{Applied Voltage [kV] / Thickness of specimen [mm]}} \quad \cdots (1)$$

Figure 5 shows the time dependence of the FEF in DC-XLPE and AC-XLPE at 50 and 20 kV/mm. Within the range of 60 minutes from the start of measurement, the FEFs of DC-XLPE are small, being 1.1 or below, and hardly change with time. On the other hand, the FEFs of AC-

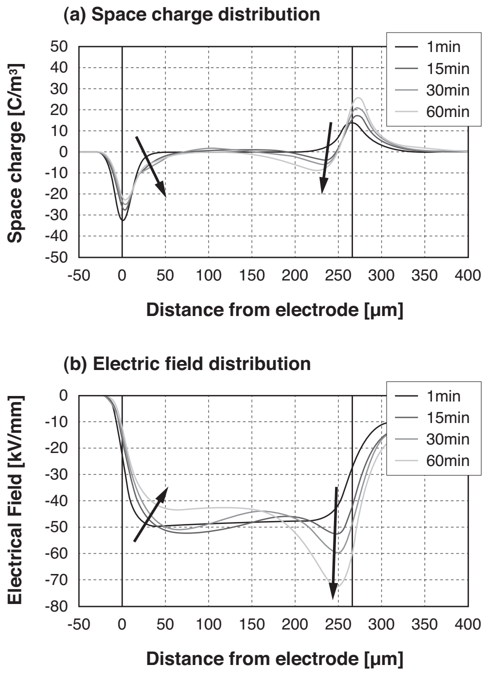

Fig. 4. Space charge and electric field distributions in AC-XLPE at 50 kV/mm, 30˚C

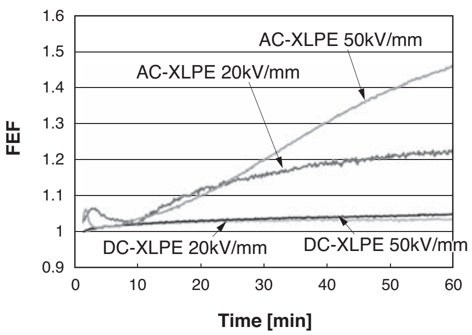

Fig. 5. Time dependence of field enhancement factor in DC-XLPE and AC-XLPE at 50 kV/mm, 20 kV/mm, 30˚C

XLPE show a clear trend of increase with time. Moreover, the increase rate of the FEF is greater in the case of 50 kV/mm than that in the case of 20 kV/mm.

To investigate the time-dependent change of the space charge characteristics of DC-XLPE, the FEF was evaluated for a longer time. **Figure 6** shows the evaluation results on the time dependence of the FEF in DC-XLPE. The evaluation was conducted for several days. From **Fig. 6**, the FEF in DC-XLPE is found to be stable and remain less than 1.1 for several days from the beginning.

These results indicate that, by adding nano-sized particles to DC-XLPE, the amount of space charge accumulation is kept low in the electric field of several ten kV/mm as compared with that in AC-XLPE. The results also revealed that the electric field enhancement within the specimen is suppressed to a very low level.

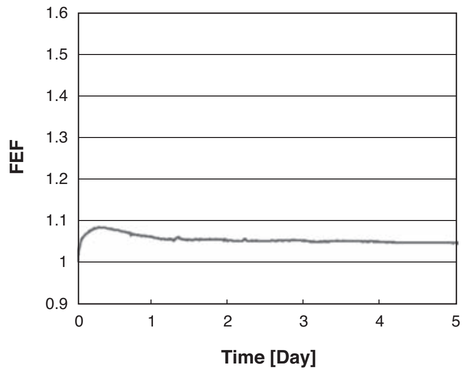

Fig. 6. Time dependence of field enhancement factor in DC-XLPE

3-3 DC V-t characteristics

The DC Voltage-time (V-t) characteristics of DC-XLPE and AC-XLPE were investigated on the pressed sheet specimens with a thickness of about 200 μm. A vacuum drying treatment was applied to the AC-XLPE sheet samples to reduce the by-products of cross-linking since they were known to affect the space charge characteristics as described in Section 3-2. On the other hand, no such treatment was given to the DC-XLPE specimens.

The effective portion of the electrode diameter was 25 mm. The sheet specimens were placed between the high voltage electrode and the ground electrode, and a DC voltage was applied in the silicone oil. Then evaluation was made for the time required for the breakdown. The test was conducted at 90˚C.

Figure 7 shows the DC V-t characteristics of DC-XLPE and AC-XLPE. In this figure, the vertical axis shows the average electric field, E_{mean}, which was calculated by dividing the applied voltage by the thickness of the specimen. As shown in **Fig. 7**, both cases show long breakdown time and low stress, and DC-XLPE has higher DC breakdown strength and longer life time than AC-XLPE.

Assuming that the relationship of **Equation (2)** is satisfied between the time to breakdown "t" and the electric field "Emean," the life exponent "n" can be evaluated.

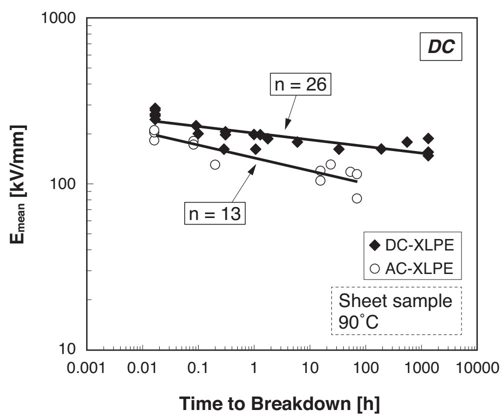

Fig. 7. DC V-t characteristics of DC-XLPE and AC-XLPE at 90˚C

$E^n \times t = const.$ ....(2)

As a result, the life exponent "n" is calculated to be 26 for DC-XLPE and 13 for AC-XLPE, showing that the life characteristics of DC-XLPE under DC voltage are improved as nano-sized particles are added.

3-4 DC breakdown strength of model cables

We made model cables that have a 9 mm insulator made of the DC-XLPE insulating material. The conductor size of the model cables was 200 mm^2. The model cables were subjected to DC breakdown tests at 90˚C.

Figure 8 shows breakdown strengths of the DC-XLPE cables[5] and our previous data for AC-XLPE cables[9]. The DC breakdown strength of DC-XLPE cable is more than twice that of AC-XLPE cable.

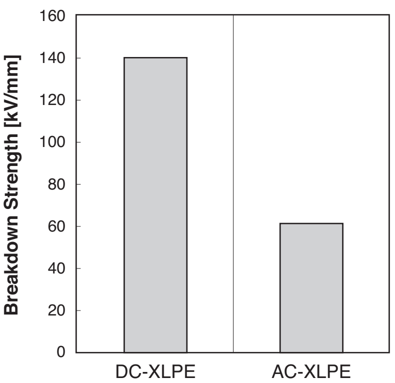

Fig. 8. DC breakdown strength of the model cable at 90˚C

3-5 Mechanism for the appearance of excellent DC properties

As described above, DC-XLPE has a higher initial DC breakdown strength and longer DC life time to insulation breakdown than AC-XLPE. The mechanism of appearance of these excellent properties is considered to be as follows:

① In a DC-XLPE insulator, the amount of accumulated space charge and the enhancement of the electric field are small.

② In a DC-XLPE insulator, volume resistivity is higher and thermal breakdown resulting from localized Joule heating is less likely to occur than in an AC-XLPE insulator.

We believe that these two effects actually interact with each other and DC breakdown strength becomes higher and DC life time becomes longer. The positive effects of adding nano-sized particles, such as the increase of volume resistivity and the decrease of accumulation of space charge, are also observed in low-density polyethylene. Such effects have been reported by many others[10],[11].

Various studies are being conducted on the mechanism that these positive effects, i.e., low accumulation of space charge and high volume resistivity, are created. For example, Ishimoto et al. measured a thermally stimulated current in a nano-composite material and suggested that nano-sized filler makes a deep trap site and captures the charge[12]. Maezawa et al. proposed that the induced potential well is formed around the nano-sized particles, and the nano-sized particles in a high electric field work as a deep trap to capture the charge and prevent the movement of carriers[13].

When the trap site is formed in the insulation material, the internal carriers which play a leading role in electrical conductivity are captured and the hopping conduction is suppressed. As a result, the internal carrier mobility is reduced, and thus, the volume resistivity is thought to be raised.

Next, we consider space charge formation by the inner carriers. It is likely that the inner carriers gradually move toward the counter electrode due to the applied electric field, and are unevenly distributed in the insulator, which causes the formation of space charge in the insulation material. When nano-sized particles are added, carriers moving with electrical charge are trapped by the nano-sized particles that are uniformly dispersed in the insulator. This prevents the localization of inner carriers, and thus, prominent differences in the density of space charge are reduced. Therefore, it is thought that space charge accumulation is suppressed.

Finally, we consider the injected charge from the electrode. The injected charge is captured by the trap formed by the nano-sized particles near the electrode and remains there. This trapped charge tends to cause the relaxation of the electric field near the electrode, which suppresses the further injection of charge and limits space charge formation. In fact, homo space charge is often formed in front of the electrode in nano-composite material. As shown in **Fig. 3**, in a DC-XLPE insulator, homo space charge is seen to accumulate in front of the electrode, although the amount is small.

As described above, in the DC-XLPE insulation material, uniformly dispersed nano-sized particles, which work as traps, increase volume resistivity and suppresses space charge accumulation. Due to the synergistic effects of these two, good DC cable characteristics, such as improved DC breakdown strength and long DC life time, are exhibited.

4. Long-Term Demonstration of Actual-Scale DC-XLPE Cable and Accessories

As noted in Chapter 2, prior to the practical use in the HVDC project, our DC-XLPE cable and accessories have been subjected to several long-term demonstration tests from the early stage of development. **Table 2** summarizes the results of the long-term demonstration tests. This chapter details some of these tests.

4-1 Long-term demonstration tests of 500 kV-class cable and FJ

As shown in **Table 1**, the basic development of the DC-XLPE cable was started in 1984. Some step-up efforts were made for +/-250 kV-class and +/-500 kV-class DC-XLPE cables sequentially. A 500 kV-class cable and a factory joint (FJ) were manufactured using the DC-XLPE insulation material to demonstrate the basic long-term performance as a DC cable in these tests[5],[6]. The thickness of the insulator was 23 mm. The conductor size was 3,000 mm^2, assuming a

Table 2. Long-term tests for DC-XLPE cables and accessories

Year	Rated Voltage	TB 219	PQ / Type	Tested Item
2001	500 kV	– *1	Long-term tests*1	Cable, FJ
2007	250 kV	Applied	Type	Cable, FJ, Outdoor terminations
2009	250 kV	Applied	PQ	Cable, FJ, Outdoor terminations
2010	250 kV	Applied	Type	Cable, FJ, Transition joint*4, Outdoor terminations
2011	250 kV	Applied	PQ	Cable, FJ, Transition joint*4, Outdoor terminations
2011	320 kV	Applied*2	Load Cycling tests*2	Cable, FJ, Transition joint*4, Land joints, Outdoor terminations
2013*3 (in progress)	400 kV	Applied	PQ	Cable, FJ, Transition joint*4, Land joints, Outdoor terminations

All the long-term tests included a polarity reversal test at the maximum temperature of 90˚C
*1: The equivalent life time is 40 years, based on inverse power law (V^n x t = const.)
*2: Load cycling tests of the type test for LCC systems were conducted.
*3: Tests will be completed in 2013.
*4: A joint connecting a marine cable with a land cable on shore.

power transmission capacity in bi-pole mode of 3,000 MW.

These tests were carried out before the publication of CIGRE TB 219, so the test conditions did not match those of TB 219. But the concept of the test conditions was the same as TB 219; especially the test voltage and period, which were based on the V-t Law (Inverse power law, V^n x t = const.). In this test, the voltage and time were based on the V-t law, the life exponent was defined as n = 15, and the test period was set to be equivalent to the actual operation of 40 years. The test temperature was 90˚C and the polarity reversal test was included.

The long term test was completed in 2001. After that, the cable and FJ were placed under an impulse breakdown test. The remaining Imp breakdown voltage was 1950 kV and it was equivalent to the initial breakdown voltage. These results confirmed that the manufactured cables and FJs had sufficient performance to be used for actual operation at the operating temperature of 90˚C with polarity reversal.

4-2 Type test and PQ test of +/-250 kV DC-XLPE cable and accessories for Hokkaido-Honshu DC link

As shown in **Table 2**, 250 kV type and PQ tests have been carried out multiple times. This section describes the results of the most recent 250 kV tests that were conducted in 2010 and 2011

The 250 kV DC-XLPE cables and accessories were manufactured and subjected to a type test and PQ test for the use in the Hokkaido-Honshu DC link facility owned by the Electric Power Development Co., Ltd. This DC link consists of a bi-pole transmission line with a capacity of 600 MW. For the submarine cable usage, factory joints (FJs) were also manufactured. Reinforced insulation layer of FJ was formed by tape-wrapped molding method. A transition joint (TJ), which connects the marine cable with a land cable, was also subjected to a type test and PQ test. An outdoor termination, which consists of oil-impregnated paper and a condenser cone, was also subjected to the PQ and type tests.

These tests were done under the conditions that include a polarity reversal test for LCC systems as recommended in CIGRE TB 219. The test temperature was set at 90˚C.

The type test was successfully completed in 2010. The 250 kV-class PQ test conducted in accordance with TB 219 was completed in 2011. **Photo 1** shows the view of the entire PQ test site. From these results, it was verified that the HVDC XLPE cable and accessories can be applied to actual DC link lines at 90˚C in both the ordinary operation and polarity reversal operation.

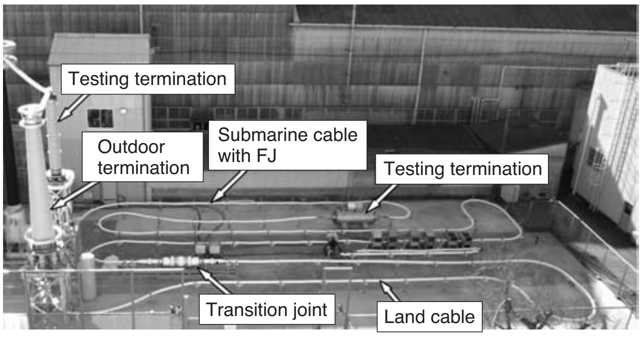

Photo 1. View of 250 kV PQ test

The external view of the submarine cable used for the Hokkaido-Honshu HVDC link is shown in **Photo 2**. The DC-XLPE cable and accessories were installed in summer 2012. After the installation of the cable system, a DC high voltage test at 362.5 kV (= 1.45 PU) for 15 minutes was successfully completed in August 2012[(8)]. This cable line was put into operation in December 2012 as the world's highest voltage extruded DC cable in service and the world's first DC extruded cable for an LCC system including polarity reversal operation.

4-3 PQ test of 400 kV cable and accessories

Assuming that the cable is used for a bi-polar transmission line with a capacity of 1000 MW, a 400 kV DC-XLPE submarine cable having the size of 1000 mm^2 and its accessories were tested. **Photo 3** shows the external view of the cable.

The cable and FJ were subjected to a coiling test with a minimum coiling diameter of 6 m, and the test was conducted three times. The cable, combined with the FJ, was

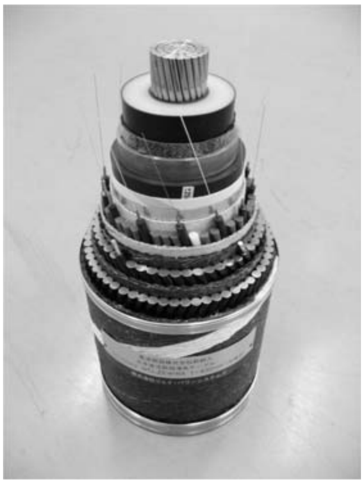

Photo 2. +/-250 kV DC-XLPE submarine cable for the Hokkaido-Honshu DC link line

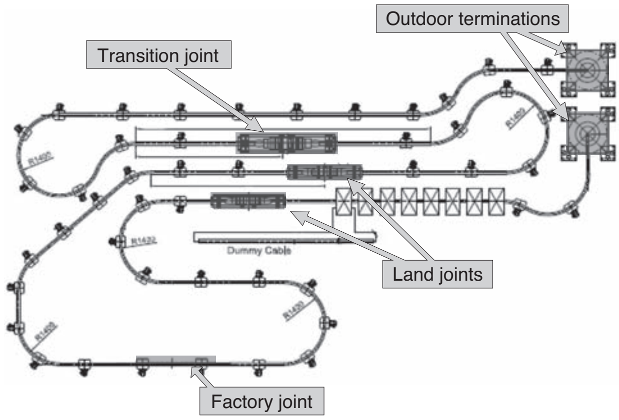

Fig. 9. Layout of 400 kV PQ test

Photo 3. 400 kV DC-XLPE cable

Photo 4. View of 400 kV PQ test

then subjected to tensile bending tests for three times. The tensile bending tests were conducted using a sieve with a diameter of 8 m at 134 kN. After these mechanical tests, the cable and FJ were installed in the PQ test circuit.

For land joints, a pre-molded joint (RBJ) that consists of a one-piece rubber unit and a pre-fabricated joint (PJ) that can fix the cable conductor in the position were developed. These joints were also subjected to the PQ test after the initial test.

Two sets of outer terminations were subjected to the PQ test: one is a porcelain insulator, and the other is a polymer insulator.

Figure 9 shows the layout of the PQ test, and **Photo 4** shows the site where the test is being conducted. Prior to the 400 kV PQ test, we performed a load cycling test under the 320 KV-class type test conditions for the LCC system. The load cycling test has been already completed, and the 400 kV PQ test is currently being performed under the test conditions that include a polarity reversal test for the LCC system in accordance with the recommendation of CIGRE TB 496[14]. The test temperature is 90˚C. The PQ test is scheduled to complete in 2013.

5. Conclusion

We have developed DC-XLPE insulating materials that have excellent properties for DC voltage applications. The DC-XLPE cables using these materials have already completed long-term demonstration tests for high voltage transmission up to 500 kV. A 250 kV-class type test and PQ test were also completed under the test conditions that conform to CIGRE TB 219. Following this success, we have been conducting a 400 kV-class PQ test under the conditions that conform to CIGRE TB 496.

All the long-term demonstration tests included a polarity reversal test. They were conducted at the conductor temperature of 90˚C. From these results, we verified that our DC-XLPE cable and accessories can be applied in the 90˚C normal operation and polarity reversal operation in actual HVDC links.

DC power transmission technology is not only applied to the conventional long-distance and large-capacity power transmission, but also expected to find wide applications as an environment-friendly technology that enables high-efficiency power transmission in conjunction with renewable energy technologies such as off-shore wind power generation and mega-solar power generation as well as smart grid technology. As described in this paper, our DC-XLPE cable system provides a practical solution to the demand of the times. We will continue to contribute to the establishment of HVDC infrastructure around the world.

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