Development of a 500-kV DC XLPE Cable System

by Satoru Maruyama [*], Noboru Ishii [*], Michihiro Shimada [*], Shinji Kojima [*2], Hideo Tanaka [*3], Mitsumasa Asano [*4], Tetsuya Yamanaka [*4], and Shin'ichi Kawakami [*4]

ABSTRACT This paper describes development work on an XLPE cable system for HVDC lines, together with the results of pre-qualification (PQ) tests. XLPE material in which there is no space charge accumulation was applied for the DC extruded cable, and the factory joint was constructed by extrusion molding. In long-term (1-year) tests carried out on the DC XLPE cable system developed here no breakdown occurred, and those samples passed to the impulse test superposed on DC voltage after long-term test.

It was confirmed that the DC XLPE cable system developed here passed PQ tests conforming to CIGRE recommendations and had performance adequate for HVDC transmission lines.

1. INTRODUCTION

DC transmission is more suited to long distance or high power applications than AC transmission. Conventional DC power cables have been oil-filled (OF) or mass impregnated non-drain (MIND) cables, but OF cables are fundamentally unsuited to long-distance transmission, with the limitations imposed by the irksome need for oil refilling, and MIND cables can rarely carry high power due to their rather low operating temperature tolerance.

In AC transmission by contrast, the use of XLPE-insulated cables has been widespread, and 500-kV XLPE-insulated power cables are in actual use in commercial AC lines [1)]. XLPE-insulated cables, being free from oil or grease, are more environment-friendly, and are thus expected to be of service in DC power transmission as well.

Against the background, the authors have developed a 500-kV DC XLPE cable [2), 3)]. This paper describes the development process, together with the results of pre-qualification (PQ) tests.

2. CHARACTERISTICS OF INSULATING MATERIALS FOR DC XLPE CABLE

Previous research or studies on the application of XLPE cables designed for AC use to DC power transmission have indicated that space charges accumulate in their insulation [4)]. As a result, local high electric fields generate, thereby lowering insulation performance, so that these space charges must be suppressed at the design stage, in terms of the performance characteristics for XLPE insulation material under DC voltage.

The following dielectric breakdown characteristics are inherent to DC voltage:

- heat generated due to current in the insulation (Joule heat); and
- local high electric field due to space charge.

Consequently, the properties required for the insulating material for DC XLPE cables are:

(1) high resistivity to reduce leakage current and suppress heat generation; and

(2) absence of local high electric fields due to space charge formation.

The authors identified a polyethylene with a polar group (hereinafter called DC-XLPE) as the insulation with the required properties.

It is known that the polar groups work as trap sites for electric charge [5)]. The existence of trap sites slows down the mobility of electric charges, thereby increasing the resistivity of the polymer insulation. The trap sites also have the effects of preventing the uneven distribution of the space charges thereby stabilizing the behavior of space charge. Furthermore, existing facilities can be used to manufacture the cable, because requirements for the handling of PE material for DC cables are the same as those for ordinary PE material.

Figures 1 and 2 plot the volume-resistivity curve and space charge formation for the subject DC-XLPE. Figure 1 shows that the XLPE satisfies requirement (1) above, i.e., at least 10 times the volume resistivity of the conventional XLPE material for AC cables (hereinafter called AC-XLPE). Figure 2 shows that the XLPE satisfies requirement (2), allowing scarcely any accumulation of space charges, but that the AC-XLPE allows significant

[*] Energy Transmission Research Dept., Ecology & Energy Lab., R&D Div.
[*2] Power Cable Production Dept., Power Cables Div.
[*3] VISCAS Corp.
[*4] Electric Power Development Co., Ltd.

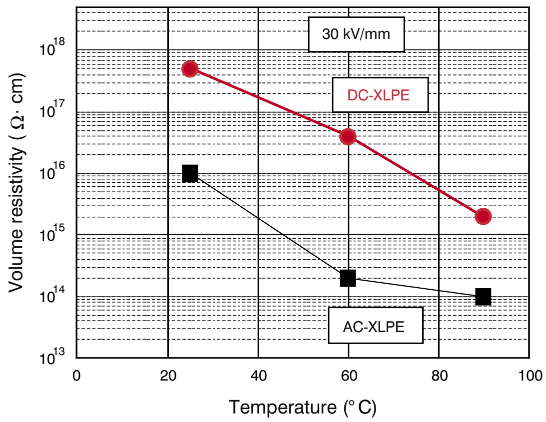

Figure 1 Volume resistivity of XLPE materials.

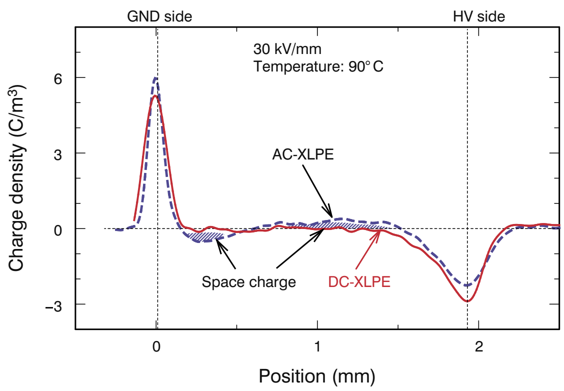

Figure 2 Space charge characteristics of XLPE materials.

accumulation of space charges in specific regions close to the inner semiconductive layer. On analysis we have found that the subject XLPE satisfies the electric insulation requirements for DC XLPE cable.

3. ELECTRICAL CHARACTERISTICS OF MODEL CABLES

We examined the dielectric breakdown characteristics of model cables to investigate the subject DC-XLPE material.

3.1 Breakdown Characteristics

Dielectric breakdown test in the model cables was carried out under the following conditions.

Test sample:
conductor size: 200 mm²
insulation thickness: 9 mm
Test temperature: 90°C at conductor (ΔT=20°C)
Here, ΔT means the temperature difference between the conductor and the shielding layer.

Figure 3 plots dielectric breakdown strength for DC-XLPE vs. AC-XLPE, showing that DC-XLPE clearly surpasses AC-XLPE in DC breakdown strength. Thus the DC-XLPE has better characteristics than the AC-XLPE from the standpoint of short-term operation in DC breakdown strength.

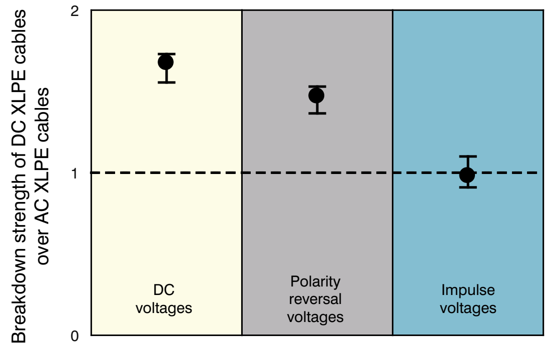

Figure 3 Short term breakdown characteristics of model cables.

3.2 Long-term Electrical Properties

Long-term tests were carried out on a model cable using DC-XLPE to confirm that the “n” value of the inverse power law for the model cable under DC voltage was 15 or higher, and that the model cable had an “n” value equal to that of an ultra high voltage XLPE cable [1].

We were able to obtain satisfactory results from the model cables in terms of both the short-term breakdown characteristics and long-term characteristic stability of the DC-XLPE developed here.

3.3 Space Charges

3.3.1 Under low electric field

We investigated the space charge characteristics of the model cable in a low electric field equivalent to an operating field.

A pulsed electroacoustic method [6] was applied to measure the space charges, where the electric field distribution was calculated based on the measured space charge distribution. The test conditions were as follows:

Test sample:
conductor size: 100 mm²
insulation thickness: 3 mm
Test temperature: 90°C at conductor
Applied electric field: 30 kV/mm
Application time: 2,160 h

Figure 4 plots the electric field distribution for a DC XLPE cable, while Figure 5 plots the electric field distribution for an AC XLPE cable.

Figure 4 indicates that the DC XLPE cable incurred scarcely any accumulation of space charges at the outset of voltage application, and the consequent electric field distribution was determined by the electrostatic capacitance. Yet, over time, we see a trend toward a wide-spread accumulation of negative charges in the insulation due to the injection of charges from the inner semiconductive layer. Consequently, the electric field distribution increases on the outer semiconductive layer side and decreases on the inner side. This pattern of electric field distribution is almost the same as that determined by resistivity, for instance in an OF cable.

Figure 5 clearly indicates that even a cable using AC-XLPE induces an electric field distribution not

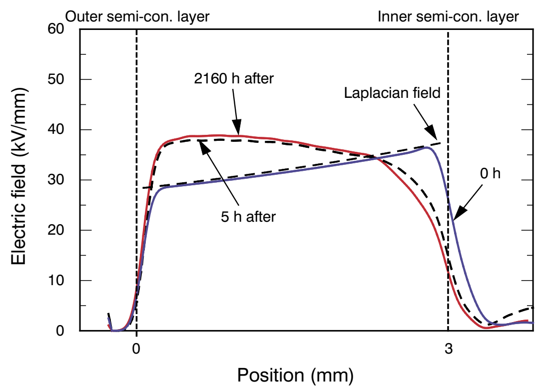

Figure 4 Electric field distribution in DC XLPE cables under DC voltage.

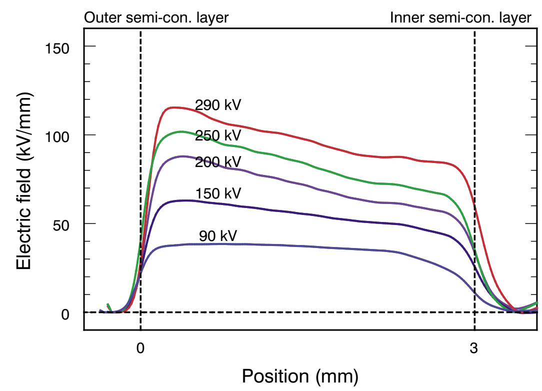

Figure 6 Electric field distribution in DC XLPE cables as a function of applied voltage.

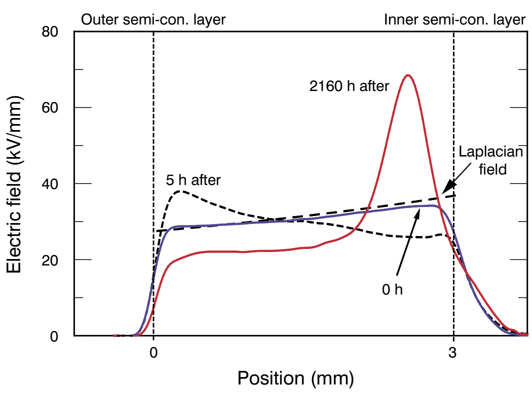

Figure 5 Electric field distribution in AC XLPE cables under DC voltage.

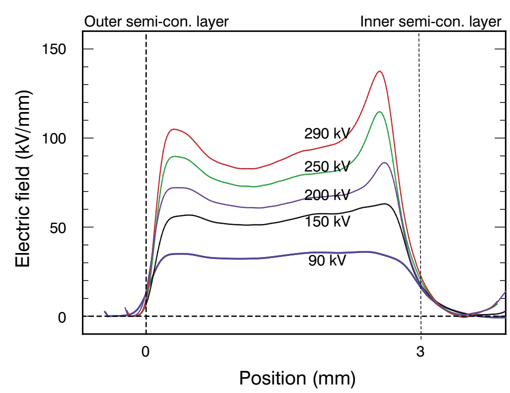

Figure 7 Electric field distribution in AC XLPE cables as a function of applied voltage.

significantly different from that in a cable using DC-XLPE, up to the elapse of several hours of voltage application. But after that the electric field near the inner semiconductive layer with positive charges (hetero-charges) accumulated is locally emphasized.

The above bottleneck (formation of a local high electric field) is one of the causal factors in identifying AC XLPE cables as not suitable for the operation under DC voltage.

Along the way, we found that DC-XLPE exhibits stable behavior in its electric fields, which will not be localized, even in long-term operation.

3.3.2 Under High Electric Field

We measured the space charge up to the threshold of the breakdown electric field (the high-electric field region) and investigated the relationship between the breakdown characteristics and the electric field due to space charge. The space charge was measured under the following conditions.

Test sample:
- conductor: 100 mm^2
- insulation thickness: 3 mm

Temperature: 90°C at conductor
Applied voltage: 90~290 kV
Application time: 30 min at each voltage

Figure 6 shows the electric field distribution in a cable using DC-XLPE, and Figure 7 shows the distribution in one using AC-XLPE.

From Figure 6, it is clear that in every region from low to high electric field, the electric field distribution is similar and is high on the outer semiconductive layer side and low on the inner semiconductive layer side. No local high electric field was formed in any region.

From Figure 7, it is clear that in a cable using AC-XLPE, the same tendency is exhibited in the low electric field region as in DC XLPE cable. However, as the electric field is increased, hetero-charges accumulate in the neighborhood of the inner semiconductive layer and a local high electric field is formed even in a short time. That is to say, it was found that in an AC XLPE cable the electric field distribution was different inside a low electric field versus a high electric field. It can also be said that the formation of a local high electric field at high electric field is related to the reduction of DC breakdown strength discussed below.

Commercial power lines would undergo a polarity reversal and a loading cycle, and the space charge characteristics ought to remain stable. Using the same sample and temperature, we checked on the following characteristics.

3.3.3 Under Polarity Reversal

Figure 8 plots the electric field distribution in polarity reversal, with curve A showing electric field distribution resulting from a voltage of +75 kV applied for 5 hours, and curve B showing the results just at a reverse shift to

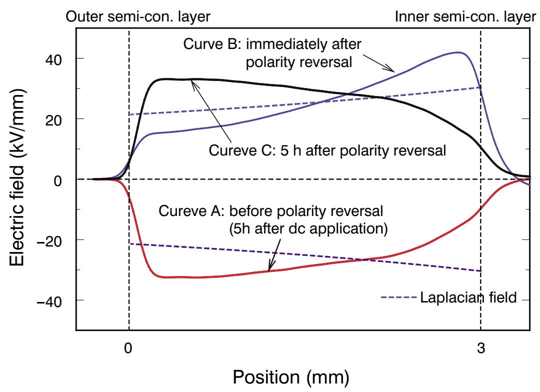

Figure 8 **Variation of electric field distribution in polarity reversal.**

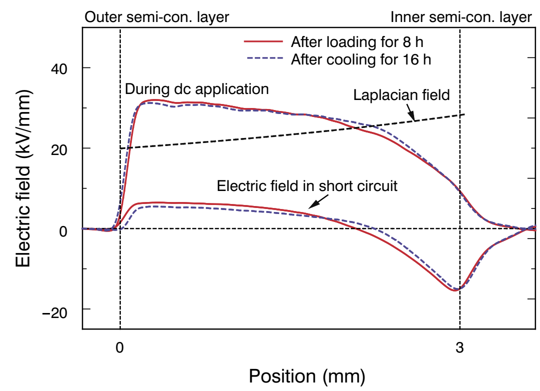

Figure 9 **Variation of field distribution under loading cycle.**

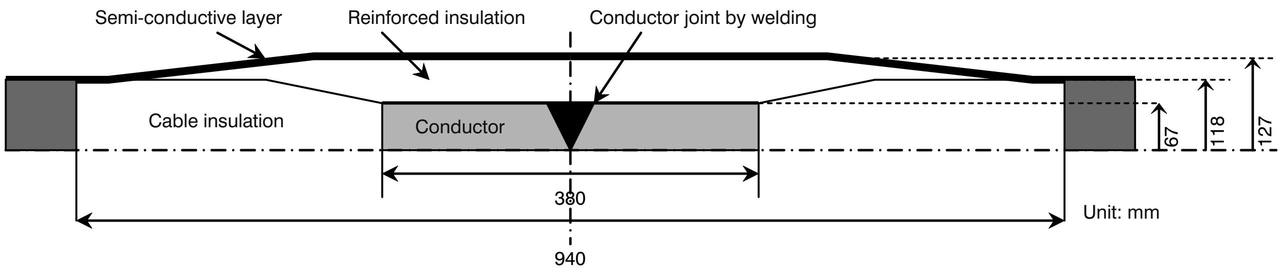

Figure 10 Structure of factory joint for 500-kV DC XLPE cable.

−75 kV. At the same time, the electric field distribution was disturbed by the space charges generated under a voltage of +75 kV. At the elapse of about 5 hours under −75 kV, the electric field distribution resumed the pattern shown by curve C before the reversal of the polarity of voltage application. As a result, we have made sure that the behavior of space charges remains stable.

3.3.4 Under Loading Cycle

Figure 9 plots the electric field distribution with a loading cycle under -75 kV DC. We found that even 30 loading cycles had hardly any effect on characteristics, let alone one or two cycles. In other words, we suppose that loading cycles will not affect the accumulation of space charges.

From the above perspective, DC-XLPE will act with more advantage on the space charge characteristics in a DC XLPE cable. In these respects it is inferred that DC-XLPE has the more advantageous space charge characteristics for a DC XLPE cable.

4. 500-KV DC XLPE CABLE AND FACTORY JOINTS

4.1 Cable Design

Assumed operating conditions of 500-kV DC-XLPE are:

DC voltage U_0: 500 kV
Impulse voltage: 850 kV
(arrester protection level: 1.7 U_0)

The insulation needs to be designed to work under the above conditions, but the methodology for DC-XLPE insulation cable design has not yet matured. This is because the accumulation of space charges in a solid insulating material disturbs or deranges the electric field, which in turn cannot easily be evaluated. A method has therefore been proposed for designing the insulation thickness for a DC XLPE cable based on evaluation of the electric field in the insulation under DC voltage[7]. This design technique was applied to determine the insulation thickness for a 500-kV DC XLPE cable, which turned out to be 23 mm.

4.2 Development and Evaluation of Factory Joints

Intermediate joints (factory joints) are needed to allow the use of longer cable length. A factory joint needs to be almost of the same diameter as the cable diameter, where an extrusion molded joint (EMJ) technique[8] has been applied to work on reinforced insulation. Figure 10 shows the structure of a factory joint for a 500-kV DC XLPE cable.

A welding technique was adopted for the conductor joints, because the connected parts of the conductor, for which a sleeve was used, have no flexibility and differ in diameter from the cable conductor.

Table 1 shows the results of electrical and mechanical tests of 500-kV DC XLPE cables and factory joints. The electrical tests were preceded by mechanical tests (bending, twisting, etc.). Those tests verified that the 500-kV DC XLPE cables and factory joints fulfilled the requirements in terms of short-term electrical characteristics.

Table 1 Electrical and mechanical properties of 500-kV DC XLPE cable and factory joints.

	Cable & factory joint (land cable type)	Cable & factory joint (submarine cable type)	Requirement
Mechanical preconditioning	Bending: 4 m Twisting: 7.2°/m	Tensile bending [9] Tension: 245 kN Bending: 8 m ϕ	
DC withstand	Good	—	1200 kV / 3 h
Polarity reversal withstand	Good	Good	±750 kV / 3 cycles
Lightning impulse withstand	Good	—	±1250 kV / 3 times
Opposite polarity impulse withstand test superposed on DC voltage	Good	Good	DC 500 kV + Imp 850 kV

Table 2 Dimensions of cable for PQ tests.

Item		Unit	Cable	FJ
Conductor	Cross-sectional area	mm^2	3000	3000
	Diameter	mm	67	67
Inner semi-conductive layer		mm	2.5	3
Insulation thickness		mm	23	26
Insulation diameter		mm	118	125
Outer semi-conductive layer		mm	1.0	1.5
Lead sheath		mm	4.5	4.7
Anticorrosion sheath (PE)		mm	6.0	7.0
Nominal diameter		mm	145	154

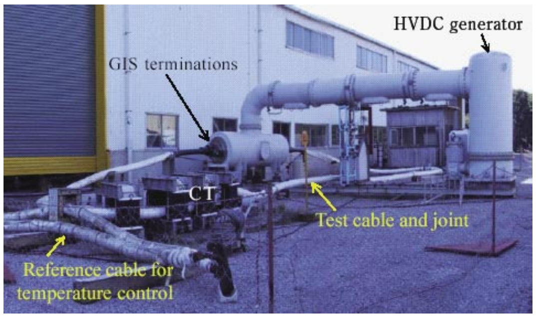

Figure 11 Set-up for long-term test.

Table 3 Long term test conditions for 500-kV DC XLPE cable system.

Test item	Temperature	DC withstand		Polarity reversal withstand	
		Voltage	Term	Voltage	Term (times)
Loading cycle	8 h loading / 16 h Cooling	±750 kV	60 days		
Constant high load	90°C at conductor	±750 kV	40 days	±700 kV	20 days (60)
No load	Room temperature	+750 kV	120 days		
Loading cycle	8 h Loading / 16 h Cooling	±750 kV	64 days	±700 kV	61 days (183)

4.3 Pre-qualification Tests on 500-kV DC XLPE Cable System

Pre-qualification (PQ) tests were carried out to demonstrate the performance of 500-kV DC XLPE cable system developed here, in anticipation of commercial use.

4.3.1 Long-term Test Conditions

A long-term test was carried out on the 500-kV DC XLPE cable system developed here. The sample was as follows:

500-kV DC XLPE cable: 50 m in length
Factory joint: 1
GIS terminations: 2

Table 2 shows dimensions of the cable for PQ tests.

Figure 10 shows the structure of a factory joint extrusion molded using the same material as the cable insulation. A stress-relief cone was adopted for the GIS terminations.

Table 3 shows long-term test conditions of PQ tests and Figure 11 shows the setup for the long-term test.

4.3.2 Remaining Test Conditions

If no breakdown occurs during testing, the remaining characteristics ought to be examined. Consequently, an opposite polarity impulse withstand test superposed on DC voltage was applied. That is, a DC voltage was loaded for 3 hours at a conductor temperature of 90°C. Subsequently, an opposite polarity impulse voltage of 1000 kV was superposed 10 times repeatedly on the DC voltage of 500 kV.

Finally, we covered all the test requirements in Section 4.3, but found no breakdown throughout the long-term test and the remaining characteristic test. This demonstrated that the 500-kV DC XLPE cable system developed here fulfills the characteristic requirements for an HVDC transmission cable.

The conditions for the above test were approximately the same as those under CIGRE recommendations for “Testing DC extruded cable systems for power transmission up to 250 kV”[10].

Namely, these pre-qualification tests are the first examination result based on the CIGRE recommendations on extruded HVDC cables, although the rated voltage of 500-kV was higher than that.

5. CONCLUSION

This R&D program identified a polyethylene with a polar group as the insulation material for a DC XLPE cable. Its electrical characteristics were discussed mainly in terms of the behavior of space charge accumulation. The XLPE selected has turned out to be highly suitable for DC cable.

Subsequently, the subject DC-XLPE was applied to develop, design and fabricate 500-kV DC XLPE cables and factory joints, which were in turn evaluated. A pre-qualification test was then carried out to assess the 500-kV DC XLPE cable system, which was found successful in all tests.

In conclusion, the DC XLPE cable system developed here was verified as having the highest suitability for HVDC transmission lines.

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