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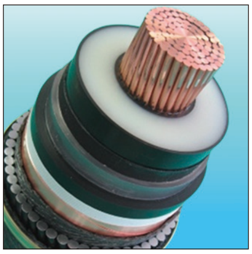

Research on Environmentally Friendly Non-Crosslinked Materials for Direct Current Applications

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In response to growing environmental concern, the demand for direct current (DC) cables has increased, particularly in Europe, due to the rise of renewable energy sources. Our company has focused on developing eco-friendly non-crosslinked materials for DC applications by skipping the crosslinking process, achieving energy efficiency and reducing lead time by removing the drying process. Our research shows that we have successfully developed the non-crosslinked material for DC applications. The mechanical and electrical properties are equivalent to those of filled type DC-XLPE, and the material has sufficient DC lifespan. We produced model cables, confirming stable fundamental characteristics. The absence of crosslinking byproducts ensures stable volume resistivity, enhancing quality compared to filled type DC-XLPE. We aim to continue prototyping and evaluating cables for high reliability similar to filled type DC-XLPE.

Keywords: direct current cable, non-crosslinked material, volume resistivity, space charge

1. Introduction

Increasingly active efforts are being made worldwide for greenhouse gas emissions reduction. The European Commission, for example, has set a goal of reducing greenhouse gas emissions by at least 55% compared to 1990 levels by 2030. Similarly, in its Green Growth Strategy Through Achieving Carbon Neutrality in 2050, the Japanese government declared that Japan will reduce its greenhouse gas emissions to zero by 2050.(1) Amid these circumstances, along with the increasingly wide use of renewable energy sources, including offshore wind power generation and photovoltaic power generation, development of transmission networks that send generated electricity is under way. With long-distance, high-voltage power transmission, in particular, demand for direct current (DC) cables has been growing because, in such power transmission, DC is more advantageous than alternating current (AC).

Under these circumstances, current power cables predominantly use insulation made of crosslinked polyethylene*1 (XLPE). XLPE is superb in terms of insulation performance and heat resistance; however, it is incompatible with material recycling because it is crosslinked. Additionally, it has the issues of increased power consumption during manufacturing and a longer amount of lead time because it requires crosslinking and drying processes.*2 In contrast, without the need for crosslinking, non-crosslinked materials serve as a solution to these issues and enable the manufacturer to manufacture more environmentally friendly cables.(2)

Against this backdrop, Sumitomo Electric Industries, Ltd. has worked on developing a non-crosslinked material for DC applications that has excellent DC characteristics and is environmentally friendly, as reported in this paper.

2. Fundamental Properties of Non-Crosslinked Material for DC Applications

The volume resistivity of cable insulation is a critically important factor for reducing power loss in ultra-high-voltage DC transmission. Take as an example three horizontally arranged 500 kV DC, 2,500 mm^2 cables installed in air, in duct; Figure 1 shows volume resistivity (ρ)-dependent changes in transmitted power for a bipolar metallic return configuration at a conductor temperature of 90°C and a transmission current of 2,000 A (transmitted power: approximately 2,000 MW).

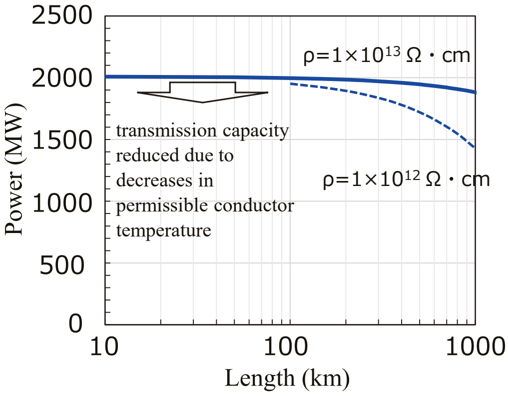

Fig. 1. Transmitted power versus DC cable transmission distance

When the insulation has a volume resistivity of 1 × 10^{14} Ωcm, power transmission will have no significant loss even at a distance of 1,000 km. Higher volume resistivity is more advantageous with DC cables. Therefore, Sumitomo Electric has made its filled type XLPE for DC applications (DC-XLPE)(3) with high volume resistivity even at 90°C, thereby ensuring the high reliability of its ultra-high-voltage DC cables. For this reason, the development goal for the non-crosslinked material for DC applications was set to achieve comparable volume resistivity to that of filled type DC-XLPE.

In addition to volume resistivity, DC cables need to meet several characteristic requirements, including mechanical properties. As a recommended approach for the characterization of non-crosslinked materials, items such as tensile strength at break, elongation, heat aging characteristics, and deformation due to heat, as specified in Technical Brochure (TB) 852 of the International Council on Large Electric Systems (CIGRE), are included. This report evaluates a non-crosslinked material for DC applications that fulfills all these requirements. In addition, this paper also evaluates space charge accumulations because DC cables are inevitably subject to the accumulation of space charge.*3 This paper reports on the fundamental DC electrical characteristics of the non-crosslinked material for DC applications developed by the authors.

2-1 Volume resistivity

We have developed a non-crosslinked material for DC applications, which is comparable in volume resistivity to filled type DC-XLPE, through repeated improvements in order to achieve the volume resistivity target set in the preceding section. Figure 2 illustrates the results of a volume resistivity comparison between the non-crosslinked material, conventional XLPE for AC applications (AC-XLPE), and filled type DC-XLPE at 90°C.

The comparison with different conventional XLPE materials, as depicted in Fig. 2, has proven that the non-crosslinked material has definitely higher volume resistivity than that of conventional AC-XLPE and is comparable in performance to filled type DC-XLPE, thus achieving the set volume resistivity target.

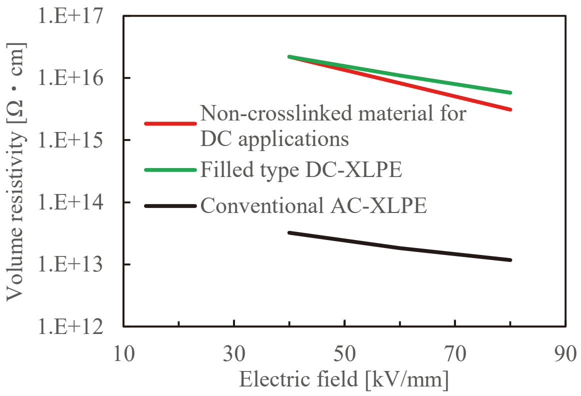

Fig. 2. Volume resistivity of non-crosslinked material for DC applications and conventional XLPE (90°C)

2-2 Space charge characteristics

To examine space charge accumulation trends, the pulsed electro-acoustic (PEA) method*4 was used, and press-molded sheets of this material were evaluated. The evaluation results are illustrated in Fig. 3. The accumulation with time of space charge was not observed. Because, with materials that are apt to accumulate space charge, space charge accumulation begins in 60 min, this material is highly unlikely to accumulate space charge.

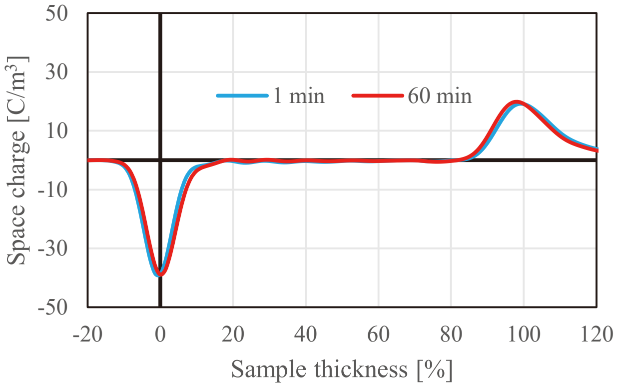

Fig. 3. PEA measurement results of non-crosslinked material (30°C)

2-3 DC voltage-time characteristics

Sheet samples of this material were prepared and evaluated as to their DC voltage-time characteristics. Figure 4 presents their DC voltage-time characteristics. The mean electric field applied to the sample is plotted on the y-axis, and time to breakdown, on the x-axis. To evaluate the lifespan of this material in DC applications, it was assumed that the relationship expressed by Eq. (1) would hold between the electric field E and the time to breakdown t, and the lifespan index n was determined.

$$E^n \times t = const. \quad \cdots\cdots (1)$$

The results showed that $n = 24$ for this material. Consequently, this material is comparable in lifespan index n to filled type DC-XLPE and is highly probable to have a sufficient lifespan in DC applications. Meanwhile, it characteristically has a high absolute value of initial breakdown electric field at approximately 300 kV/mm.

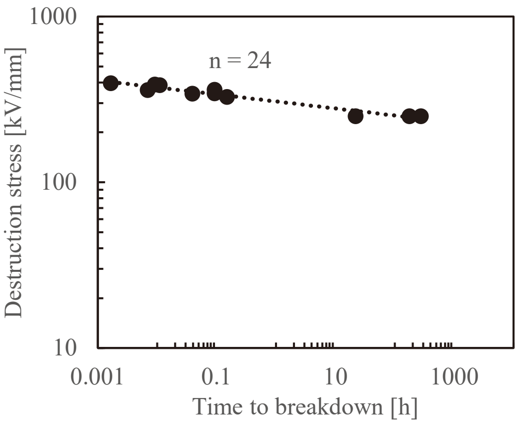

Fig. 4. DC voltage-time characteristics of non-crosslinked material (90˚C)

3. Evaluation of Model Cable

3-1 Moldability

The evaluation that used sheet samples of this material showed that, in DC cable applications, the material was comparable in performance to filled type DC-XLPE. As a next step, a prototype model cable with 9-mm thick insulation, made of this material, was constructed and evaluated.

Regarding the moldability of the prototype model cable, it could be molded without any issues although it was non-crosslinked. The cable could be routed without any problems and be handled similarly to filled type DC-XLPE. Electrical testing was conducted, as shown in Table 1, and the results were favorable in every aspect.

Table 1. Electrical Test Results of Model Cable

Test	Test condition	Result
DC withstand voltage	±400 kV for 1 h (90°C)	Good
Impulse withstand voltage	+900 kV for three times (90°C)	Good
DC-superimposed impulse withstand voltage	–200 kV applied for 10 h --> +800 kV impulse for three times (90°C)	Good

3-2 Volume resistivity (distribution in the direction of thickness)

Using a model cable immediately after extrusion, the insulation was turned into a sheet and evaluated as to volume resistivity in the direction of thickness. The results are given in Fig. 5.

A volume resistivity comparison across the inner and outer regions of the model cable insulation revealed no difference. With filled type DC-XLPE, which requires a drying process due to the need to remove crosslinking byproducts, the inner and outer regions of cable insulation have varying amounts of crosslinking byproducts depending on drying time and temperature, resulting in volume resistivity variation. However, without using a crosslinking agent, this material exhibits stable volume resistivity in the direction of thickness immediately after extrusion and thereafter. It is highly probable that this characteristic will be additionally advantageous with increasing thickness of the cable insulation layer in higher-voltage applications.

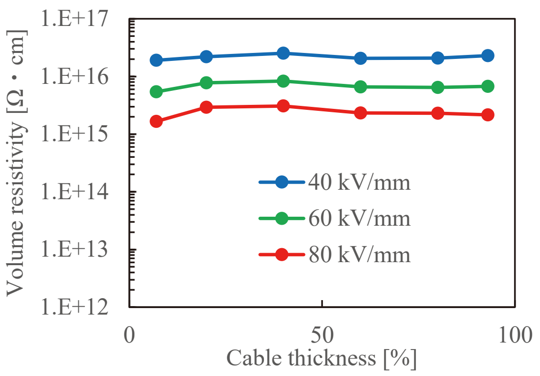

Fig. 5. Volume resistivity of model cable in the direction of thickness (90˚C)

3-3 Space charge (model cable at 30˚C and 90˚C)

As a next step, space charge accumulation was investigated. The PEA measurement results are shown in Fig. 6 and Fig. 7 for the model cable. Note that regarding the sample thickness, the outer surface of the model cable insulation is set to 0%.

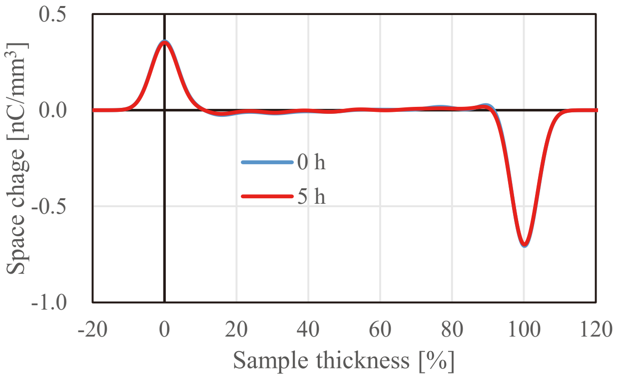

Fig. 6. PEA measurement results of model cable (30°C)

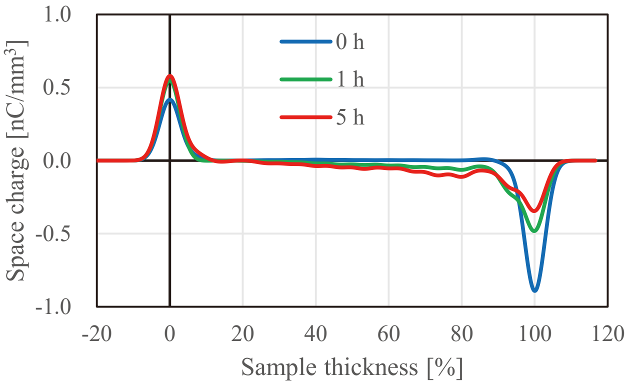

Fig. 7. PEA measurement results of model cable (90°C)

Under the application of –180 kV DC voltage at 30°C, as illustrated in Fig. 6, the charge accumulation condition did not change even after 5 h, presumably accumulating almost no charge. In comparison, under the application of –180 kV DC voltage at 90°C, as shown in Fig. 7, a change was observed between the initial stage and after 5 h of voltage application. The change was manifest as early as after 1 h of voltage application; therefore, it is highly probable that charge accumulation advanced relatively early. Meanwhile, the accumulated charge was negative—being the same as the polarity of the voltage applied to the conductor—making it reasonable to infer that the charge injected by voltage application accumulated in the proximity. Figure 8 depicts the electric field present during voltage application at 90°C.

The graph reveals changes in electric field taking place with increasing accumulation of space charge, starting from the initial stage of voltage application. After 5 h of voltage application, electric field relaxation occurred because of accumulation, within the inner region, of charge

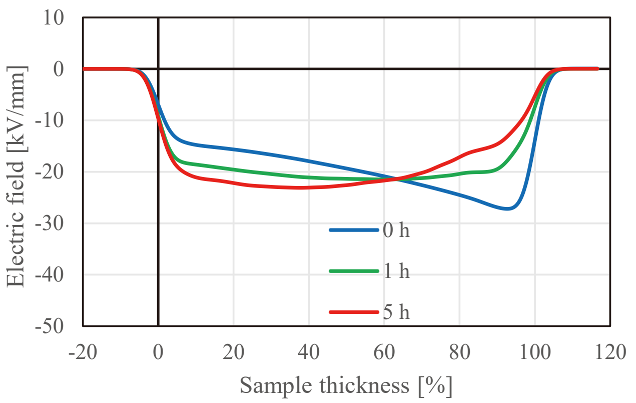

Fig. 8. Electric field distribution of model cable during PEA measurement (90˚C)

with the same polarity as that of the voltage applied to the conductor. Because of the absence of extreme electric field enhancement as compared with the initial stage of voltage application, the insulation presumably has no problem in terms of the cable's DC characteristics.

4. Conclusion

Sumitomo Electric has delivered high-reliability DC cables effective for reducing power loss, using filled type DC-XLPE with high volume resistivity. In the meantime, the company has newly developed a non-crosslinked material for DC applications, reducing greenhouse gas emissions during manufacturing and making it suitable for material recycling, in line with the recent growing trend towards environmental soundness. This material is comparable in volume resistivity to filled type DC-XLPE and will surely allow Sumitomo Electric to continue delivering highly reliable DC cables, meeting the ever-growing market demand for DC cables. Going forward, we will work on making prototype cables and evaluating them with the aim of promptly making them available on the market and, at the same time, will verify the material's recyclability.

Technical Terms

＊1 Crosslinked polyethylene: An insulating material made by creating chemical bonds between molecular chains of polyethylene through crosslinking reaction for improved heat resistance.

＊2 Crosslinking and drying processes: For a crosslinking reaction to take place, it is necessary to heat organic peroxides up to their decomposition temperature. This heating process is the crosslinking process. The crosslinking reaction leaves cracked residues of organic peroxides, which degrade the characteristics of insulating materials. The process intended to remove the crosslinking byproducts is the drying process.

＊3 Space charge: Electric charge accumulated in solid insulation. Under the application of a DC voltage, space charge distorts the electric field.

＊4 Pulsed electro-acoustic (PEA) method: A method of measuring the distribution of electric charges accumulated in insulation. Charge distribution data can be obtained by applying pulses to a sample and using the resultant space charge oscillation.

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