Effects of Type Tests on Cross-linking By-product Migration and Conductivity Characteristics in HVDC Cables (Postprint)

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Abstract

To ensure that high-voltage direct current (HVDC) cables meet anticipated service conditions and long-term operational stability, type testing is required. An analysis was conducted on changes in cross-linking by-product content from the inner layer to the outer layer in the cable' s main insulation before and after type testing, as well as on curves of current density versus electric field strength at different temperatures. Experimental results indicate that type testing suppresses carrier migration at low field strengths, promotes the migration of cross-linking by-products from the inner layer toward the middle and outer layers, and that the greater the content of cross-linking by-products and the higher the temperature, the lower the threshold electric field for current density.

Full Text

Preamble

Effect of Type Test on Migration Process of Cross-Linked By-Products and Conduction Characteristics of HVDC Cables

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Abstract

To ensure that high-voltage direct current (HVDC) cables meet expected service conditions and long-term operational stability, type testing is required. This study analyzes changes in cross-linking by-product content from the inner to outer layers of cable main insulation before and after type testing, along with current density versus electric field strength curves at various temperatures. Experimental results demonstrate that type testing suppresses charge carrier migration under low electric fields while promoting the migration of cross-linking by-products from the inner layer toward the middle and outer layers. Furthermore, higher by-product content and elevated temperatures both correlate with lower threshold electric fields for current density.

Keywords: Type test, cross-linking by-product, temperature, current density, threshold electric field

1 Introduction

With the development of flexible DC transmission and marine industries, the advantages of ultra-high-voltage DC transmission have become increasingly apparent. HVDC cables offer large current carrying capacity, high electric field strength tolerance, low dielectric losses, and absence of AC magnetic field issues [1]. Polymeric insulation is predominantly used for HVDC cable main insulation, offering lower density, higher operating temperatures, and superior mechanical properties compared to self-contained oil-filled and impregnated paper insulation [2-3]. Cross-linked polyethylene (XLPE) is currently the most widely employed main insulation material, with China deploying XLPE DC cables at various voltage levels in three flexible DC transmission projects in Nan'ao, Zhoushan, and Xiamen since 2012.

Since XLPE-insulated cables have relatively short operational histories both domestically and internationally, comprehensive systematic studies on field-operated samples are impractical. To guarantee expected performance and operational stability, type tests and pre-qualification tests must be conducted before actual service. Comparative analysis of cable electrical properties before and after these tests enables evaluation and prediction of long-term operational performance.

XLPE is produced through chemical or physical methods that transform polyethylene (PE) molecules from linear to three-dimensional network structures, thereby enhancing thermal and mechanical properties [4]. The most prevalent cross-linking method involves peroxide chemical cross-linking using electrical heating [5]. The peroxide cross-linking agent employed is dicumyl peroxide (DCP), which decomposes upon heating to produce cross-linking by-products. The decomposition process is illustrated in [Figure 1: see original paper]. Numerous by-product species are generated, with -methylstyrene, acetophenone, and cumyl alcohol being the primary focus of current research [6]. These by-products exist as impurities in cable main insulation. At high electric fields, they dissociate into positive and negative ion pairs that migrate under electrical stress, forming local traps and accumulating heterocharge.

This intensifies local electric fields, causes field distortion, and can potentially trigger cable breakdown under severe conditions [7-8]. Therefore, analyzing by-product content and migration processes in cross-linked polymer insulated cables is crucial for operational assessment.

Research indicates that type tests may promote secondary cross-linking of XLPE materials, with thermal cross-linking reactions dominating [5]. However, the migration process of cross-linking by-products during type tests remains unclear, and their distribution significantly influences charge migration during actual cable operation [6], representing an important consideration for improving HVDC cable insulation field distribution.

Trap distribution in HVDC cable materials substantially affects conduction characteristics under high DC stress. Unlike AC systems where dielectric constant remains essentially constant during operation, steady-state field distribution in DC cable insulation is determined by conductivity and internal space charge, with conductivity being highly dependent on field strength and temperature [8-12]. Simulation results show that temperatures near the conductor can be 10–20°C higher than in outer regions. Excessive temperature gradients can cause field reversal and reduced field uniformity compared to normal operation [13], exacerbating internal temperature differences. Additionally, positive and negative ions from by-product dissociation form space charge. The influence of space charge on polymer conduction mechanisms can be explained through space charge limited current (SCLC) theory, which A. Rose described in detail [14]. As electric field increases, current transitions from the ohmic regime to the SCLC regime [14]. Increased conductivity raises dielectric losses, causing local overheating that adversely affects normal operation.

This study analyzes cross-linking by-product content, migration processes, and conduction characteristics in a 320 kV extruded insulation DC submarine cable from the Zhoushan flexible DC transmission project before and after type testing. The cable' s main insulation is divided into inner, middle, and outer layers based on distance from the central conductor. By measuring by-product content variations from inner to outer layers and corresponding conduction characteristics at different temperatures and field strengths, we investigate how by-product migration affects cable insulation conduction properties, providing a reference basis for future insulation condition assessment of extruded insulation DC submarine cables.

2.1 Type Test and Sample Preparation

Type tests were conducted according to the national standard GB/T 31489.1—2015 "Power Cable Systems with Extruded Insulation for DC Voltages up to and Including 500 kV—Part 1: Test Methods and Requirements." The electrical test procedure is shown in [Figure 2: see original paper], with specific electrical test methods detailed in . To investigate insulation layer properties from inner to outer regions, cables were sliced as illustrated in [Figure 3: see original paper]. Sample thickness ranged from 300 to 400 m, with the central region of each slice selected for gas chromatography-mass spectrometry analysis and conduction characteristic studies.

2.2 Gas Chromatography-Mass Spectrometry

For detailed analysis of by-product diffusion, the cable insulation layer was divided into six equidistant layers from inner to outer surfaces. Gas chromatography-mass spectrometry was used to identify and quantify cross-linking by-products in each layer. Before analysis, samples were prepared by cutting 1 g of material from the center of each layer into thin strips, placing them in a vial with 15 ml chloroform and 15 ml n-hexane, sonicating for 20 minutes, settling for 10 minutes, and repeating this cycle three times. After settling for one hour, 3 g of anhydrous sodium sulfate was added, mixed uniformly, and left to stand for another hour before the supernatant was analyzed. The equipment used was an Agilent 7890-5975 GC-MS system.

Gas chromatography separates organic compounds based on their different partition coefficients between gas and stationary phases through repeated distribution. Mass spectrometry measures the mass-to-charge ratio of ions by bombarding gaseous molecules with an electron beam, accelerating the resulting ions into a mass analyzer, and recording them according to their mass-to-charge ratio to obtain mass spectra. This combined approach enables identification and quantification of cross-linking by-products in cable composite insulation.

2.3 Conduction Characteristics Measurement

Conduction measurements on cable slices were performed using a laboratory-built three-electrode current measurement system consisting of a high-voltage DC source, temperature control system, ammeter, and electrode assembly. The DC source provided 0–10 kV output with ripple coefficient less than 1%. Temperature was controlled using a Chino CP350 digital controller with ±0.25% (±1 digit) precision. Current was measured with a Keithley 6517A electrometer with minimum theoretical resolution of 0.75×10^{1} A. The electrode system employed a guarded three-electrode configuration to eliminate surface leakage current effects, with a measuring electrode diameter of 20 mm. The high-field conduction system structure is shown in [Figure 4: see original paper], and the complete measurement system is shown in [Figure 5: see original paper].

The cable main insulation was divided into inner, middle, and outer layers as shown in [Figure 3: see original paper]. The central region of each layer was selected for testing. Polarization current curves were measured at temperatures of 30°C, 50°C, 70°C, and 90°C. Due to XLPE’ s low thermal conductivity, measurements commenced 10 minutes after the temperature controller reached the setpoint to ensure thermal equilibrium. At each temperature, voltage was increased stepwise according to electric field strengths of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 15, 17, 19, and 20 kV/mm. Each voltage step was applied for 10 minutes, followed by a 2-minute short-circuit period to eliminate effects from previous measurements.

3.1 Effect of Type Test on Cross-Linked By-Products Migration

Based on GC-MS principles, the three cross-linking by-products exhibit different binding affinities with the stationary phase, resulting in distinct retention times following the order: cumyl alcohol > acetophenone > -methylstyrene, as shown in [Figure 6: see original paper]. In cable main insulation, the content ranking is cumyl alcohol > acetophenone > -methylstyrene. To clearly visualize -methylstyrene content variations across the six layers before and after type testing, a logarithmic vertical axis is used in [Figure 7: see original paper].

Before type testing, -methylstyrene content was lowest in the first (innermost) layer and higher in the fourth and sixth layers. Acetophenone content gradually increased from inner to outer layers. Cumyl alcohol content was lowest in the first layer, increased progressively through the fourth layer, and remained relatively constant from the fourth to sixth layers. After type testing, -methylstyrene remained lowest in the first layer but peaked in the third layer, showing high middle-layer concentration with reduced inner and outer layer content. Acetophenone content continued increasing through the first three layers but decreased in the fourth layer, with the fifth and sixth layers reaching similar maximum values. Cumyl alcohol content increased through the first three layers, with relatively uniform distribution in the outer three layers. Overall, all three by-products showed lower inner-layer content and highest outer-layer content.

To further investigate diffusion processes, each layer’ s by-product content was normalized to the total content for that species using Equation (1), with results presented in [Figure 8: see original paper]. After type testing, -methylstyrene migrated from both inner and outer layers toward the middle layer. Acetophenone migrated outward from inner layers, with reduced content in the first and second layers and significant increase in the third layer. Cumyl alcohol showed noticeable decreases in the first and second layers and increases in the third, fifth, and sixth layers, indicating outward diffusion from inner to outer layers. In summary, type testing produced a clear diffusion trend of cross-linking by-products from inner to outer layers in the cable main insulation.

3.2 Effect of Type Test on Conduction Characteristics

Analysis of current density versus temperature and electric field strength for inner, middle, and outer insulation layers before and after type testing is presented in [Figure 9: see original paper]. As temperature increased from 30°C to 90°C, current density increased dramatically by 2–4 orders of magnitude. For pre-test samples, current density rose from 10 A/m^2 at 1 kV/mm (30°C) to 10 A/m^2 at 90°C, and from 10 A/m^2 to 10 A/m^2 at 20 kV/mm. For post-test samples, current density increased by 2–3 orders of magnitude, from 10 ^{1} A/m^2 at 1 kV/mm (30°C) to 10 A/m^2 at 90°C, and from 10 A/m^2 to 10 A/m^2 at 20 kV/mm.

Under isothermal conditions, current density showed minimal variation at low electric fields but increased sharply above a distinct transition point. Comparing the three insulation layers at different temperatures, pre-test current density was approximately one order of magnitude higher than post-test values at low fields, while high-field current densities were similar before and after type testing. This indicates that type testing affects charge carrier migration at low field strengths while having minimal impact at high fields.

The phenomenon of current density transitioning from gradual to steep increase with electric field can be described by space charge limited current theory. At low electric fields, conduction is dominated by thermal equilibrium charge carriers that are minimally affected by the field. As field strength increases, the potential barrier for charge injection from electrodes decreases, significantly increasing injected carrier concentration. At this stage, trap distribution in the dielectric influences carrier transport. With further field increase, traps become essentially filled, and carrier transport depends primarily on injection efficiency and mobility, with trap effects becoming negligible.

To further characterize temperature and type test effects on conduction properties, lgJ-lgE double logarithmic plots are employed as shown in [Figure 10: see original paper]. The electric field at which current density shows a clear transition is defined as the threshold electric field, below which current density follows Ohm' s law:

$$J = e\mu n_0 \frac{V}{d}$$

where is charge carrier mobility, e is elementary charge, d is sample thickness, and n is thermal equilibrium charge carrier density. At high applied voltages, conduction in polymer dielectrics is generally considered to follow space charge limited current mechanisms, with steady-state current density obeying Child' s law [15].

Segmented linear fitting was performed on lgJ-lgE plots for inner, middle, and outer layers before and after type testing. As shown in [Figure 9: see original paper], the threshold electric field for pre-test inner layer exceeded 20 kV/mm at

30°C, decreasing progressively with temperature. At 30°C, 50°C, and 70°C, pre-test threshold fields for all three layers were significantly higher than post-test values. At 90°C, threshold fields were similar before and after testing.

Table 2 presents threshold electric fields extracted from J-E curves. At 30°C, 50°C, and 70°C, type testing caused significant threshold field reductions, with decreasing magnitude. This correlates with by-product content distribution and migration. Higher by-product content creates more space charge traps, increasing trap influence on carrier mobility and requiring lower field strength for the transition from ohmic to space charge limited current regime. Before type testing, higher by-product content in middle and outer layers resulted in substantially lower threshold fields compared to the inner layer. After type testing, further by-product migration toward middle and outer layers caused additional threshold field reduction. At lower temperatures, threshold fields are strongly influenced by by-product content and distribution. At 90°C, threshold fields reached minimum values with no significant difference before and after type testing, indicating dominant temperature effects.

5 Conclusions

Based on the analysis of cross-linking by-product content variations from inner to outer layers and current density versus electric field strength curves at different temperatures before and after HVDC cable type testing, the following conclusions are drawn:

1. Type testing causes -methylstyrene to migrate from inner and outer layers toward the middle layer, while acetophenone and cumyl alcohol migrate from inner to outer layers.
2. Type testing suppresses charge carrier migration at low field strengths while having minimal effect on high-field carrier migration.
3. As temperature increases, the threshold electric field for current density gradually decreases. At lower temperatures, migration of the three cross-linking by-products alters space charge trap distribution, reducing threshold fields in inner, middle, and outer layers after type testing compared to before. At higher temperatures, threshold fields show little difference before and after type testing, as temperature effects become dominant.

Cross-linking by-products exist as impurities in cable main insulation. At high applied electric fields, they dissociate into positive and negative ion pairs that migrate under electrical stress, acting as local traps that form heterocharge and enhance local field strength, causing field distortion. By-product migration alters local trap distribution and density within the insulation layer, affecting space charge limited current. This influence was further investigated through analysis of threshold electric field variations.

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