Development of high-stress XLPE cable system

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Summary
The design of newly developed high stress cable, techniques of manufacturing process and test results were described. Super clean cross-linked polyethylene (XLPE) compound produced under the strict quality control in overseas facility and super smooth quality semi-conductive compound produced in-house facility were used to produce model and real cables. The miniature type of model cable was used as a specimen, which represented the real cable’s characteristics. From the test results of model cables, $E_{LAC}$, and $E_{Limp}$ were determined by Weibull distribution. Using these factors, the value of $t_{AC}$ and $t_{Imp}$ for 132kV XLPE cable were calculated to be 5.7mm and 11.6mm, respectively. Based on the thickness obtained, the designed insulation thickness for real cable was determined to be 13mm which was 1.4mm thicker than the value of $t_{Imp}$ calculated. The reliability of this high stress cable was confirmed by both AC and Impulse voltage test. Along with the high stress cable, the pre-molded joints (PMJ) for applying to high stress 132kV XLPE cables were also developed. The type test of cable and accessories were performed in accordance with IEC60840 at the final stage of development. The test demonstrated that high stress cable and accessories met all requirements of test specifications and they were sufficiently reliable. The developed high stress cable has the similar diameter of conventional OF (Oil-filled) cable and so it enables the construction of transmission line easier.

Keywords: High-Stress-Cable-System—Pre-Molded-Joint—Contaminant-Scanning—Semi-Conductive-Tape-Monitoring—Semi-Conductive-Material

1. Introduction

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Cross-linked polyethylene (XLPE) cables are broadly used as extra high voltage transmission lines, presenting attractive features such as superior electrical characteristics, quick installation, easy maintenance and especially environmental affinity compared to OF (Oil-filled) cables. Because the reduction of cable diameter make the transportation, handling and installation easier, the world wide customers’ trend, in view of saving the project cost and increasing environmental concern, is employing the high stress cable of which insulation thickness is reduced. As the insulation thickness of the high stress cable is reduced in comparison with that of normal XLPE cable, higher quality of the insulation material and the corresponding interfaces are required to withstand the higher stress. Therefore, all of the extrusion processes must be kept in super clean environment and the screen interface must be ultra smooth so that insulation is free from contamination and defects.

In order to meet the world wide trend of customers, LG cable has developed high stress cable and accessories on the basis of continuous enhancement in cable manufacturing techniques. This paper describes the design, manufacturing techniques and test results of high stress cable systems.

2. Development of high stress cable systems

2.1. Improvement of cable insulation performance

Recently much efforts into technological progress of increasing design stress for EHV XLPE cable has been reported on CIGRE and Jicable conferences. [1]-[2] In order to enhance the design stress and reliability of EHV XLPE cable, it is essential to minimize the defects, occurring at the conveyance of raw material and the extrusion process as well as in raw material itself. Since the early 1990’s, the demand for XLPE has rapidly increased as an insulation material for transmission cable and currently 500kV XLPE transmission cable is in commercial operation, refer to Figure 1. [2]-[7]

![Fig.1 Transition of voltage grade for XLPE cables](image1)

![Fig.2 Recent evolution of the concentration HV/EHV (relative) of detected contaminants](image2)

Keeping pace with rapid and continuous increase of transmission voltage as well as the higher demand of cable manufacturers on improvement of the electrical performance, the characteristics of XLPE material has improved dramatically. Especially the contaminant level causing the local stress concentration was significantly reduced. As shown in Figure 2, the level was lowered to approximately 50% of the value based on the record of 1997. While conveying the material, the possible stage that the material is exposed to the ambient air is when a bulk box is changed. Thus, in order to minimize the contamination by dust or foreign particles in the ambient air, the material handling room must be maintained as clean as possible. The internal standard of cleanliness level is less than 100 class, which represents the number of particles over 0.5 in 1ft³ for one minute measurement. The actual measurement shows even lower than 10 class. Accompanying with the effort to minimize the contamination, the newly modified in-line contaminant
scanning system was developed. The main idea of the contaminant scanning system is to use the different light transmission characteristics of each contaminant. If any contaminant is present in the material, the image of contaminant is captured by a CCD camera and then is analyzed using the different intensity level of transmitted light through the contaminant. This newly modified contaminant scanning system enables the categorization of the harmful effects of contaminants more precisely based on numerous empirical data. That is, in addition to categorization by the size of contaminant, the categorization by intensity of transmitted light makes it possible to define boundaries between the critical contaminant like metal and less critical contaminant like amber. Figure 3 shows in-line contaminant scanning system.

For the better quality of EHV XLPE cable, so far all the research works have been focused on insulation materials and its manufacturing process such as reduction of voids, contaminants, and defects in the insulation. However, with the current abilities to control the insulation material and process, it is time to take a step forward and put efforts to increase the electrical performance at the highest stressed region which is the interface between insulation and semi-conductive layer. Especially the protrusion in the semi-conductive layer increases the local electrical stresses in proportion to the size and sharpness so that the tree is initiated and finally leads to electrical failure. The main causes of the protrusion are contaminants and moisture in the raw material, degree of dispersion of carbon black, and mixing ratio. Since the raw semi-conductive material contains a great deal of carbon black, it is needed to use the screen mesh less dense than that of insulation extrusion process. Unless used, the extrusion pressure will rise up dramatically and lead the distortion of semi-conductive layer. However, using less dense screen mesh could increase the possibility of protrusion because of bad filtering and mixing. Therefore, newly designed semi-conductive material was developed to lower the extrusion pressure by adding low density polyethylene type process agent (PA) so that smoothness between interfaces is enhanced and the possibility of distortion is lowered.

Distortion of semi-conductive layer is caused by termed scorch during the extrusion as well as the tearing and protrusion of semi-conductive tape. It increases the local stress drastically and leads the electrical failure of the cable. In order to prevent scorch, most of cable manufacturers try to compensate the variation of manufacturing conditions using real time temperature and pressure monitoring system and also examine the raw material thoroughly before using it and manage extrusion tools properly. Also for preventing the interface distortion due to the semi-conductive tape, the monitoring device is definitely required to check the status of semi-conductive tape before the conductor enters the cross head. For that reason, the surface scanning device using a three directional CCD camera was invented to monitor the surface of semi-conductive tape so that the distortion can be
detected previously. Figure 4 illustrates the real time monitoring device of semi-conductive tape.

![Real time monitoring device of semi-conductive tape](image)

**Fig.4 Real time monitoring device of semi-conductive tape**

### 2.2. Design of XLPE cable insulation

Insulation thickness is generally determined by thickness for AC voltage ($t_{AC}$) or thickness for impulse voltage ($t_{Imp}$), and the larger one is selected as the designed thickness. Each thickness is given by following equations respectively.

$$t_{AC} = \frac{U_m}{\sqrt{3} \times E_{L,AC} \times k_1 \times k_2 \times k_3} \quad ------- (1)$$

$$t_{Imp} = \frac{B \times k_4 \times k_5 \times k_6 \times E_{L,Imp}}{E_{L,Imp}} \quad ------- (2)$$

where, $U_m$: maximum line voltage (= 145kV)

$k_1$: temperature factor (= 1.2),

$k_2$: aging factor (= 2.3),

$k_3$: safety factor (= 1.1),

$k_4$: temperature factor (= 1.25)

$k_5$: aging factor (= 1.1),

$k_6$: safety factor (= 1.1)

$E_{L,AC}$: Min. AC breakdown stress (= 45kV/mm)

$E_{L,Imp}$: Min. Impulse breakdown stress (= 85kV/mm)

BIL: Basic Impulse Insulation Level (=650kV)

In the above equations, $E_{L,AC}$ and $E_{L,Imp}$ were determined by Weibull distribution plot of model cable and the thickness dependence of breakdown stress given in equation (3).

$$E_{L(t)} = \alpha \times t^{-0.18} \quad ------- (3)$$

Where, $\alpha$ is 175 for Imp and 77 for AC.

From the above equations, $t_{AC}$ and $t_{Imp}$ were calculated to be 5.7mm and 11.6mm, respectively. Considering safety margins, the insulation thickness was chosen to be 13 mm for 132kV XLPE cable.
2.3. Design of cable joint

The pre-molded type joint was also developed for the 132kV high stress cable. Considering electrical and mechanical performances, silicone rubber was selected as main insulation material. The construction of the pre-molded joint is represented in Figure 5.

**Table 1. Structure of 132kV XLPE Insulated Cable**

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (Um/U/Uo)</td>
<td>kV</td>
<td>145/132/76</td>
</tr>
<tr>
<td>Conductor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal cross-sectional area</td>
<td>mm²</td>
<td>630 (Compacted)</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>mm</td>
<td>30.2</td>
</tr>
<tr>
<td>Conductor screen thickness</td>
<td>mm</td>
<td>Approx. 1.0</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>mm</td>
<td>Nom. 13.0</td>
</tr>
<tr>
<td>Insulation screen thickness</td>
<td>mm</td>
<td>Approx. 1.0</td>
</tr>
<tr>
<td>Lead alloy sheath thickness</td>
<td>mm</td>
<td>2.5</td>
</tr>
<tr>
<td>PE jacket thickness</td>
<td>mm</td>
<td>4.0</td>
</tr>
<tr>
<td>Overall diameter</td>
<td>mm</td>
<td>Approx. 76.0</td>
</tr>
<tr>
<td>Weight of cable</td>
<td>kg/m</td>
<td>Approx. 14.6</td>
</tr>
</tbody>
</table>

**Table 2. Design values of parameters**

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Design value at working condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>4.0 (kV/mm)</td>
</tr>
<tr>
<td>τ</td>
<td>1.0</td>
</tr>
</tbody>
</table>

For the electrical design of pre-molded joint, it is essential to control radial and longitudinal electrical stresses $E$, $\tau$ respectively. Radial stress depends on the shape of semi-conductive electrode and dielectric strength of insulation material. Longitudinal stress is dependent on the length between the two semi-conductive electrodes and interface pressure. Radial and longitudinal stress determines insulation thickness and joint length, respectively. With aids of computer simulation, the optimized shape of semi-conductive electrode and stress relief cones are determined. Figure 6 and Table 2 show the design parameters and their corresponding design value.

**Fig.5 The construction of pre-molded Joint**

For the electrical stability at the interface, adequate interface pressure should be maintained. In the case of the pre-molded joint, the interface pressure is maintained by elastic retention of material itself.
Thus, considering the compatibility with the cable accommodated and pressure relaxation for long-term use, the appropriate expansion ratio of joint sleeve and the proper value of interface pressure must be decided. For the safe operation more than 30 years, expansion ratio is determined to be about 10 ~ 40%. Figure 7 shows the profile of interface pressure along the interface between XLPE cable insulation and silicone rubber sleeve.

3. Development tests

3.1. Weibull test results

To verify the compatibility of design and manufacturing process of high stress cable and its accessories, the development tests were performed at high voltage laboratory of LG Cable. The miniature type of model cable was used as a specimen. The model cable must represent a real cable’s characteristics. So the model cables used in this test were manufactured with same material and machine for real high stress XLPE cable. The insulation thickness of model cable was 4mm. And the specimen length for breakdown tests was more than 10m excluding test terminations. A total of 40 samples were tested for both A.C. and impulse breakdown test, and this number is twice as the number which is recommended in CIGRE WG 21-09. Figure 8 shows the Weibull plot of AC breakdown test, which gives the minimum insulation breakdown stress for designing XLPE cables; \( E_{\text{L,AC}} = 59.9 \text{kV/mm} \) is obtained.

Figure 9 shows the Weibull plot of impulse breakdown test; \( E_{\text{L,Imp}} = 136.9 \text{kV/mm} \). These results are the mean stress, which were calculated from dividing the breakdown voltage by insulation thickness of the
breakdown part of a model cable.

### 3.2. Performance test results of high stress cable

The reliability of high stress cable was confirmed by both AC and Impulse test. The test results are summarized in Table 3.

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Condition</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC voltage</td>
<td>585kV/1hour and then 50kV/10min. step-up</td>
<td>More than 935kV</td>
</tr>
<tr>
<td>Lightening Impulse</td>
<td>-1100kVp/3shots and then -100kVp/3shots step-up</td>
<td>More than -2300kVp</td>
</tr>
</tbody>
</table>

### 3.3. Performance test results of PMJ

Before preceding the evaluation of the joint sleeve, the optimized manufacturing conditions were chosen by the numerous tests for the specimens. All specimens were specially designed to have imbedded semi-conductive silicone rubber electrodes in order to simulate the real joint sleeve. The results of A.C. and impulse tests were represented in Figure 10 and 11, respectively.

The target performance of the joint sleeve was set as below, considering various factors such as temperature, aging and safety factors.

- **Impulse** = \( BIL \times \text{temperature factor} \times \text{safety factor} \approx 895kV \\
- **AC** = \( \frac{U_m}{\sqrt{3}} \times \text{temperature factor} \times \text{aging factor} \times \text{safety factor} \approx 270kV/6hrs \\
  \text{Aging factor} = \sqrt{(30\text{years} \times 365\text{days} \times 24\text{hours})/6\text{hours}} \) (assuming \( n = 12 \))

The target performance of the joint sleeve was set as below, considering various factors such as temperature, aging and safety factors.

In order to evaluate the performance of the joint sleeve, more than 40 joint sleeves were tested for AC and impulse voltage tests. From these tests, it was found that all joints had sufficient performance exceeding the target performances.

### 4. Type tests

The type test of 132kV high stress XLPE cable and accessories has been performed as the final stage of development. The circuit for the type test is shown in Figure 12. The type test including outer protection test has been carried out in accordance with IEC 60840 and test results are represented in Table 4. All tests were successfully completed and fully verified the reliability of the high stress cable and accessories system.
5. Conclusion

High stress XLPE cable and accessories for 132kV were developed based on our technical enhancement of design, manufacturing and verification on extra high voltage cable system. New semi-conductive material to lower the extrusion pressure was developed and surface scanning device which monitors the surface defects of semi-conductive tape was newly invented. As with the in-line monitoring system, the function of analyzing different light intensity level was added for more accurate categorization of various contaminants.

This high stress XLPE cable with a reduced diameter and weight has many advantages such as easy transportation and low project cost. Additionally, this newly developed high stress cable system enables the replacement of existing OF (Oil Filled) cable system because its diameter was reduced to as similar as that of OF (Oil Filled) cable.

6. References