Investigation on Cable Rejuvenation by Simulating Cable Operation

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ABSTRACT Further research on retired cable rejuvenation via heat treatment was investigated in this paper. Three retired cables with service year of 7, 15 and 30 years were used and annealed at different temperatures following two different heat treatment methods. In the first test, two short cables with a length of 5 m were prepared and cut into five equal segments. Four segments of each cable were annealed at 90, 95, 100, and 105 °C to simulate the cable operation. Then, the cross-linked polyethylene (XLPE) from the cable insulation was peeled, and the peels from the inner, middle and outer positions were selected and subjected to the differential scanning calorimetry (DSC), DC conduction current, and dielectric breakdown strength measurements. The thermal and electrical performance of these samples were analyzed, and the optimum annealing temperature was determined. In the second test, three identical long cables were connected to a transformer, joints, and terminals to build two experimental circuits. The cables were annealed at the optimum temperature determined in the first test. The same measurements were performed on XLPE samples taken from the same positions as those in the first test. The results showed that the short cables exhibited the best thermal and electrical performance when annealed at 95 °C. The three long cables annealed at 95 °C verified that the thermal and electrical properties of the cable insulation were significantly improved. The results of the two different annealing methods, which closely represent the actual cable operations, verified the feasibility that old cables without overheating history could be rejuvenated via heat treatment.

INDEX TERMS Cable, DSC, melting point, crystallinity, electrical conductivity, dielectric breakdown strength.

I. INTRODUCTION

With the development of cities, an increasing number of high-voltage cables have been used in the electric transmission lines of electric networks. As one of the most important units of a electrical power transmission line, high-voltage power cables play an important role in the delivery of electrical power. When a cable in service, a lower insulation failure rate and a longer service year are the two primary goals. During the long-term operation, insulation degradation inevitably occurs, and this phenomenon has aroused much attention from researchers [1]. Research on the assessment of cable insulation aging, including the mechanism and evolution process of degradation under different conditions began in the 1960s, and many effective technologies have since been developed [2], [3]. The goal of such research is to identify the degradation degree of cable insulation and consider the replacement of old cables at the right time [4]. Due to the complexity of the on-site environment and the multiple sources of interference, currently available cable insulation aging assessment applications have insufficient accuracy [5]. Usually, the designed service life for 110 kV AC cables is 30 years, but most cables operate under mild conditions with a relatively low current and temperature in the inner conductor. As a result, many cables have retained excellent insulating properties; some of these cables still meet the standards of cable operation, even those that have reached the designed service year [6]. The question is remains whether the long-
term operation has caused irreversible change in the cable insulation, which would increase the probability of insulation failure accidents if the cables operates for longer years.

As a typical semi-crystalline polymer, the microstructure of cross-linked polyethylene (XLPE) governs its thermal and electrical characteristics in different situations [7]. It is worth noting that multiple studies have reported that the thermal and electrical performances of XLPE were significantly improved after annealing at proper temperatures for a short period [8], [9]. For most commercial cables, the microstructure of XLPE can’t reach thermodynamic equilibrium state during the short manufacturing process [10]. Several studies on retired cables have revealed a phenomenon where, after decades of operation, cables exhibited better electrical properties than new cables because they suffered the annealing process during the cable operation [11], [12]. In our previous research on three retired cables with no overheating history, XLPE sheets near the inner semi-conductive layer were annealed at a series of temperatures near 90 °C. The results showed that the thermal and electrical properties were enhanced when the samples were annealed at elevated temperatures, and the samplers annealed at 95 °C exhibited the best results [13]. Although this study demonstrated that XLPE sheets could be rejuvenated, the test conditions were far from the actual service conditions of a cable; therefore, the results do not sufficiently support the use in a cable line.

In the present study, three retired cables were prepared and annealed by two different methods to explore the feasibility of cable rejuvenation by heat treatment. In the first test, two short cables were annealed at four different temperatures of 90, 95, 100, and 105 °C by simulate the cable operation. Then, the thermal and electric performances of XLPE from different positions of the cable insulation were tested, and the optimum annealing temperature was determined. In the second test, three identical long cables were used to build two actual cable circuits. The high voltage of 64 kV and large current were applied, and the cables were annealed at the optimum temperature determined from the first test. The effects of the two different annealing methods on the thermal and electrical performance of the cable insulation were analyzed, and the feasibility of cable rejuvenation by heat treatment was further accessed.

In the present study, thermal annealing was performed on three retired cables that had operated for 0, 15, and 30 years. The heat treatment was performed by building a small circuit to simulate cable operation. The effects on the cable, including the changes in the thermal and electrical performance at different positions of the insulation layer were analyzed, and the feasibility of cable rejuvenation by heat treatment was discussed.

## II. SAMPLE PREPARATION AND EXPERIMENTAL DETAILS

### A. SAMPLE PREPARATION

Three retired 110 kV AC cables with the service year of 15 and 30 were used for this study, different from the cables used in [13]. No overheated records were reported, it means the temperature in the insulation was always below 90 °C when the cable in service. Some crucial specifications are measured and listed in Table 1. Note that cable 1 and 2 were made by different manufacturers but show the uniform specifications.

The out sheath was kept, and no damage points were found in its outside surface. Firstly, the two cables with a length of 5 m were prepared and cut into five isometric segments. For each segment, the outer sheath and insulation layer in both ends with a length of 10 cm were peeled, and the inner conductor was exposed. Second, the same two cables with a length of 30 m were prepared.

### B. EXPERIMENTAL SETTING

In the first test, the heat treatments were performed on five segments from each cable. One segment was connected to a current generator (AHY-3000, IUXPOWER, China) via copper connectors, as illustrated in Figure 1(a). Figure 1(b) shows the process graph of the changes in the applied current and the resultant temperature in the inner conductor. A large current of $C_1$ was applied to the cable, and the temperature in the inner metal conductor increased to the preset temperature in approximately 12 hours. Then, the current was decreased to a smaller value of $C_2$, balancing the heat production and dissipation, and the temperature was maintained at the preset point for 2 hours. Finally, the current was removed, and the cable was naturally cooled to room temperature. A complete thermal cycle included these three phases: heating, holding, and cooling. Four preset temperatures of 90, 95, 100, and 105 °C were set, which corresponding to the four segments of each cable. The last segment was not annealed and is regarded as a fresh sample. Each segment was annealed at one preset temperature, and the same thermal cycle was repeated 20 times for each segment.

When the heat treatment was finished, a short section (approximately 15 cm) was cut from the middle of each segment and used as test cables, as shown in Figure 1(a). The outer sheath was removed, and the insulation layer was peeled along the surface of the inner conductor and tape-like peels were obtained.

In the second test, the heat treatments were performed on three long cables. Figure 2 shows the experimental settings.

### TABLE 1. Important specifications of selected three cables.

| Sample | $M_I$ | $M_C$ | $d_{IS}$ | $d_I$ | $d_{GC}$ | $S_C$ | $O_F$ |
|--------|-------|-------|----------|-------|----------|-------|-------|
| S1     | XLPE  | Cu    | 2        | 19.8  | 2        | 700   | -     |
| S2     | XLPE  | Cu    | 2        | 19.8  | 2        | 700   | 2000-2015 |
| S3     | XLPE  | Cu    | 2        | 19.8  | 2        | 700   | 1985-2015 |

$M_I$: insulation material, $M_C$: conductor material, $d_{IS}$: inner semiconductor thickness in mm, $d_I$: insulation thickness in mm, $d_{GC}$: outer semiconductor thickness in mm, $S_C$: conductor area in mm², $O_F$: operation period. Other parameters such as cross-linking method are unknown.
of the cable installation. In Figure 2(a), cable 1 and 2 were connected to a transformer, joints, and terminals to form an experimental circuit. The cables and joints were placed on metal stands to ensure a uniform temperature distribution in the insulation layer. In Figure 2(b), cable 3 was connected to the terminals to build a circuit, and the experiment was conducted in another lab. One essential difference between the two circuits is that the outer surface of cable 3 was covered by heat insulation foam with a thickness about 10 mm, to simulate a harsh heat dissipation situation in cable operation. Due to the limited number of long cables, the thermal annealing for the two circuits was performed only at the optimum annealing temperature determined in the first test. Foremost, the temperature evolution in a thermal cycle was similar with the first test, which are coincident with the actual situation of cable operation. The current was applied to the cable through the current transformer, and the rated phase high voltage (64 kV) was applied through voltage resonance. A large current was applied to the cable to ensure that the temperature in the inner conductor could increase to the preset temperature within 8 hours. Then, the current was decreased to a small value, balancing the heat production and dissipation, and the temperature was maintained at the preset temperature for 2 hours. Finally, the current was removed, and the cables naturally cooled to room temperature. Before the experiment, the strength of the applied current in the heating and holding phase was experimentally measured. During the experiment, the voltage was always maintained, and the same thermal cycle was repeated 90 times. After the heat treatment, short sections (20 cm in length) were cut from the three cables. The outer sheath was removed, and the cable insulation was peeled following the approach used in the first test.

C. SAMPLING POSITION
Figure 3(a) shows the obtained tape-like peels. To investigate the annealing effects on the cable insulation, three different positions of the cable insulation were selected to represent the whole cable insulation and evaluate the thermal and electrical performance, as shown in Figure 3(b). They are named inner, mid, and outer position according to their locations in the insulation layer. The samples annealed by the first and second method were named S1 and S2, and named by
the service year: XLPE-7, XLPE-15 and XLPE-30 when the cables annealed by the same method.

**D. TEMPERATURE DISTRIBUTION**

Before the experiment, all the required factors at different preset temperatures, including the strength of the applied current in the heating and holding phase and the time duration

![Diagram of small simulation circuit](image)

**TABLE 2.** Experimentally measured parameters.

| $T_a$(°C) | $t_h$(h) | $I_1$(A) | $I_2$(A) |
|-----------|----------|----------|----------|
| 90        | 12       | 14.3     | 1200     |
| 95        | 12       | 15.9     | 1240     |
| 100       | 12       | 17.1     | 1280     |
| 105       | 12       | 17.6     | 1310     |

$T_a$: annealing temperature, $t_h$: time in heating phase, $I_1$: time in cooling phase, $I_2$: applied current in heating phase, $I_3$: applied current in cooling phase.

in the three phases, were measured experimentally by using a small simulation circuit as shown in Figure 4, three holes were drilled through the insulation layer, and three thermocouples were inserted in the holes, as shown in Figure 4(a). In this case, the temperature in the three sampling positions also be measured.

The values of current amplitude and duration in heating and holding phase were summarized in Table 2, and the temperature distribution in the three layers at different preset temperature were summarized in Table 3.
E. MEASUREMENT

The thermal properties were tested by differential scanning calorimetry on a DSC 214 (NETZCH, Germany). In each measurement, a sample with a weight of 5 mg was used. The temperature was increased from 25 to 140 °C at a rate of 10 °C/min and kept for 5 min; then cooled to 25 °C at the rate of −10 °C/min; the same scanning was repeated twice.

The electrical performance was tested by the measurement of DC conduction current and dielectric breakdown strength. The DC conduction current was measured at 90 °C by using a conventional three-electrode conduction measurement system. A DC electric field of 20 kV/mm was applied, and the current was recorded for 3600 s at 90 °C. The dielectric breakdown strength $E_B$ was measured by using a pair of the plate electrode system. The sample was inserted between the two electrodes and totally immersed in the silicone oil. The voltage was applied to the two electrodes and linearly increased at a rate of 1 kV/s until the sample breakdown. Fifteen repeated measurements were done, and the average was calculated as the valid data.

III. RESULTS AND DISCUSSION

A. ANNEALING EFFECT ON S1 SAMPLES

An amount of important data was separately and shown in this part, because the results its vital for the following experiment.

Figure 5 shows the melting point, melting range, electrical conductivity, and dielectric breakdown strength as a function of annealing temperature. In the left three graphs, the results show that $\Delta T_m$ of the three positions identically decreases as the annealing temperature increases and reach the smallest values at the inner, mid, and outer positions when the cables were annealed at 100, 105, and 105 °C, respectively. Conversely, the crystallinity of the three positions firstly increases, reaching the highest values at the same annealing temperatures. The changes in melting curves in Figure 4 show the emergence and growth of thinner lamellae, which led to an enlargement in the crystalline region. The thickness of the thinner lamellae increases, approaching that of the original lamellae, which facilitate a denser crystal distribution, namely, results in a narrower melting range. For each position of the cables shown in the right three graphs, $\sigma_{DC}$ decreases and $E_B$ increases as the annealing temperature increases, although some exceptions to these trends exist. The inner and mid positions of XLPE-15 exhibit the smallest $\sigma_{DC}$ values at annealing temperatures of 95 and 100 °C, respectively, whereas the highest $E_B$ values of both positions are observed at an annealing temperature of 95 °C. Similarly, the inner and mid positions of XLPE-30 exhibit the highest $E_B$ values at an annealing temperature of 95 °C, the smallest $\sigma_{DC}$ values at these positions are observed at annealing temperatures of 100 and 95 °C, respectively. The out position of the two cables exhibits the smallest $\sigma_{DC}$ value and the highest $E_B$ value at the same annealing temperature of 105 °C. It is well known that charge transport is harder in the crystalline region, whereas the highest $\sigma_{DC}$ values of both positions are observed at 100, 105, and 105 °C. However, the actual temperature in the out position is 94.3 °C at the annealing temperature of 105 °C, which is obviously lower than the optimum point. The relationship between the annealing temperature and the changes in the four values can be interpreted by the master curve derived by Gandica and Magill [15]. When the annealing temperature is below the optimum annealing point, the temperature increase will result in higher thermal energy and increase the rate of molecular chain arrangement, allowing for long molecular chain movement. This increase favors the thickening of the lamellae and the emergence of new crystals, which dominate this process rather than the crystal melt. When the temperature is above the optimum annealing point, the higher thermal energy accelerates the molecular chain movement, especially for the long chains. However, the free chains hardly arrange into an ordered state, and the ordered chains start to diffuse from the original lamellae. As a result, the original thicker lamellae melt, and new thin lamellae emerge.

\[ E_B \text{ increases and } \sigma_{DC} \text{ decreases; correspondingly, charge transport is easier in the amorphous region, whereas } E_B \text{ usually decreases and } \sigma_{DC} \text{ increases [14].} \]

For the present two cables, the inner and mid positions exhibit the optimum values of the measured factors at annealing temperatures of 100 and 105 °C, respectively. It indicates that an optimum annealing point exists around 99 °C. However, the actual temperature in the out position is 94.3 °C at the annealing temperature of 105 °C, which is obviously lower than the optimum point. The relationship between the annealing temperature and the changes in the four values can be interpreted by the master curve derived by Gandica and Magill [15]. When the annealing temperature is below the optimum annealing point, the temperature increase will result in higher thermal energy and increase the rate of molecular chain arrangement, allowing for long molecular chain movement. This increase favors the thickening of the lamellae and the emergence of new crystals, which dominate this process rather than the crystal melt. When the temperature is above the optimum annealing point, the higher thermal energy accelerates the molecular chain movement, especially for the long chains. However, the free chains hardly arrange into an ordered state, and the ordered chains start to diffuse from the original lamellae. As a result, the original thicker lamellae melt, and new thin lamellae emerge.
No heat treatments are performed at higher temperatures, and the optimum annealing temperatures for the mid and outer position cannot be confirmed unless the annealing is performed at higher temperatures. However, more attention should be paid to the inner position than the middle and outer positions since the former is subjected to the most substantial thermal and electrical pressures and is more likely to result in serious aging in cable insulation. Importantly, the cables annealed at 100 °C contributed to the best thermal performance for the inner position and remarkably enhanced the thermal performance of the middle and outer positions. The annealing temperature at 105 °C caused negative changes in the inner positions, wherein the crystallinity and melting point decreased and the melting range increased. In terms of the thermal performance, 100 °C was the optimum annealing temperature.

The highest $E_B$ values and smallest $\sigma_{DC}$ values in the inner and mid positions are observed when the cables were annealed at 95 or 100 °C, whereas for the outer position, these values are always observed at an annealing temperature of 105 °C. In terms of the electrical performance, 95 °C is regarded as the optimum annealing temperature for the two cables. A combination of the thermal and electrical performance results shows that a discrete point of 95 °C is the optimum annealing temperature.

### B. ANNEALING EFFECT ON S2 SAMPLES

The results of the above tests on the S1 samples show that 95 °C is the optimum annealing temperature. In this test, this point is selected as the annealing temperature for the S2 samples. Before the experiment, the strength of the applied current in the heating and holding phase, and the time in the heating and cooling phase were measured experimentally, the results are summarized in Table 4.

| Table 4. Experimentally measured parameters. |
|---------------------------------------------|
| $T_0$(°C) | $t_h$(h) | $t_c$(h) | $C_1$(A) | $C_2$(A) |
|----------|----------|----------|----------|----------|
| 95       | 8        | 16       | 1490     | 1180     |
| 95       | 8        | 16       | 890      | 810      |

$T_0$: annealing temperature, $t_h$: time in heating phase, $t_c$: time in cooling phase, $C_1$: applied current in heating phase, $C_2$: applied current in holding phase.

During the heat treatment process, a phase voltage of 64 kV was applied and maintained until the end of the heat treatment process. A large current of 1490 A was applied to the circuit 1, the temperature in the inner conductor increases to the preset temperature of 95 °C in approximately 8 hours. Then, the current decreased to 1180 A, balancing the heat production and dissipation, and the temperature was maintained at the preset temperature for 2 hours. Finally, the current was removed, and the cables naturally cooled to room temperature in 16 hours. For circuit 2, a current of 890A applied to the cable in the heating phase, and the current of 810A applied in the holding phase. The maximum temperature in the metal conductor in the holding phase was 92±2 °C due to the fluctuations in the room temperature in the high-voltage laboratory. For simplicity, the samples from this annealing process were called treated samples, to distinguish from the S1 samples annealed at the same temperature.

Figure 6 shows the melting endotherm spectra measured in the first and second heating phases for the samples. In the left three graphs, a low-temperature melting peak appears in each position of XLPE-15 and XLPE-7, that means thin lamellae with lower melting point emerged during the cable in operation [16], [17]. When the cables were annealed at the maximum temperature of 95 °C, the existing low-temperature melting peak in each sample was shifted to a higher temperature, it indicates the thin lamellae was grew to thicker lamellae. In XLPE-30, a low-temperature melting peak appears in the three positions, it also indicated that thin lamellae emerged in the annealing process. A distinct distance exists between the two melting peaks in the three positions of each cable, it is larger in the out position and smaller in the mid position, while the two melting peaks are partly overlapped in the inner position. This phenomenon is a good indicator of
It is accepted that fresh samples at all positions for each cable, except the little treated samples exhibit smaller $\sigma$ the sampling position. It is seen from the two graphs that the smaller melting range than the fresh samples. It means the treated samples exhibit higher melting point and of the sampling position are shown in Figure 7. It is seen $T_{10}$ crystal, $2.88 \degree C$ where $H$ is the fusion enthalpy per unit volume observed, $T_{mi}$ is the initial melting point, and $T_{me}$ is the ending melting point. The values as a function of the sampling position are shown in Figure 7. It is seen that the treated samples exhibit higher melting point and smaller melting range than the fresh samples. It means the heat treatment promoted an improved thermal performance.

The crystallinity and melting range were calculated with equations (1) and (2):

$$X = \frac{\Delta H_0}{\Delta H_m} \times 100\% \quad (1)$$

$$\Delta T = T_{mi} - T_{me} \quad (2)$$

where $\Delta H_0$ is the fusion enthalpy per unit volume observed and $\Delta H_m$ is the corresponding value of an ideal polyethylene crystal, $2.88 \times 10^3 \text{J} \cdot \text{m}^{-3}$. $T_{mi}$ is the initial melting point, and $T_{me}$ is the ending melting point. The values as a function of the sampling position are shown in Figure 7. It is seen that the treated samples exhibit higher melting point and smaller melting range than the fresh samples. It means the heat treatment promoted an improved thermal performance.

FIGURE 7. Crystallinity and melting range as a function of sampling position for S2 samples. ($\text{■}$, $\text{s}$, $\text{a}$) represent the fresh samples of XLPE-7, XLPE-15, XLPE-30, and ($\text{□}$, $\text{o}$, $\text{△}$) represent the treated samples of XLPE-7, XLPE-15, XLPE-30.

FIGURE 8. Electrical conductivity $\sigma_{DC}$ and dielectric breakdown strength $E_B$ as a function of sampling position for S2 samples. ($\text{■}$, $\text{s}$, $\text{a}$) represent the fresh samples of XLPE-7, XLPE-15, XLPE-30; ($\text{□}$, $\text{o}$, $\text{△}$) represent the treated samples of XLPE-7, XLPE-15, XLPE-30.

In summary, the thermal and electrical performance of the S2 samples were significantly improved when the cables were cycled annealed at 95 °C. In this test, the experimental process of the heat treatment in accordance with the actual operational situation of a cable line. Combining the two different heat treatment experiments, it is verified that retired cables without overheating history can be rejuvenated by giving such an appropriate heat treatment process.

IV. CONCLUSION

This paper presents a further experimental investigation of cable rejuvenation by simulating cable operation on three retired cables with service years of 7, 15 and 30 years. The following conclusions are obtained:

1) The heat treatment on short cables showed the preliminary prospects of this investigation, wherein the thermal and electrical performances of the cable insulation were significantly enhanced. For the thermal performance, the optimum values of the measured factors for the inner, middle, and outer positions were observed when the cables were annealed at 100, 100, and 105 °C. For the electrical performance, the optimum values of the measured factors for the inner and middle positions were observed at the annealing temperatures of 95 or 100 °C, and outer position always shows the best results at the annealing temperature of 105 °C.

2) The optimum annealing temperature for the two short cables was 95 °C, integrate the thermal and electric performance of the entire structure of the cable.

3) The three retired cables annealed at 95 °C exhibited improved thermal and electrical performance at the inner, mid and outer positions of the cable insulation. Therefore, the feasibility of cable rejuvenation by heat treatment was successfully verified.

REFERENCES

[1] J. C. Fothergill, G. C. Montanari, G. C. Stevens, C. Laurent, G. Teysseдре, L. A. Dissado, U. H. Nilsson, and G. Platbrood, “Electrical, microstructural, physical and chemical characterization of HV XLPE cable peelings for an electrical aging diagnostic data base,” IEEE Trans. Dielectr. Electr. Insul., vol. 10, no. 3, pp. 514–527, Jun. 2003.

[2] C. D. Green, A. S. Vaughan, G. C. Stevens, S. J. Sutton, T. Geussens, and M. J. Fairhurst, “On the temperature dependence of electrical and mechanical properties of recyclable cable insulation materials based upon polyethylene blends,” presented at the Elect. Insul. Dielectric Phenomena, Oct. 19, 2011. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6232590

[3] F. Aras, V. Alekperov, N. Can, and H. Kırkıç, “Aging of 154 kV underground power cable insulation under combined thermal and electrical stresses,” IEEE Elect. Insul. Mag., vol. 23, no. 5, pp. 25–33, Sep. 2007.

[4] V. Durman, M. Váry, J. Packa, J. Lelák, V. Šály, “Assessment of dielectric properties of cable insulation,” presented at the Int. Sci. Conf. Electr. Power Eng., May 19, 2017. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7967226

[5] W. Gao and Z. Tang, “Characteristic analysis of the insulation state of single-core XLPE Cables,” Adv. Mater. Res., vols. 805–806, pp. 902–905, Sep. 2013.

[6] C. Katz and W. Zenger, “Service aged 69 and 115 kV XLPE cables,” IEEE Trans. Power Del., vol. 14, no. 3, pp. 685–689, Jul. 1999.
[7] B. Wunderlich, *Thermal Analysis of Polymeric Materials*. Berlin, Germany: Springer, 2005, ch. 2. [Online]. Available: https://rd.springer.com/book/10.1007%2F3-540-137476

[8] N. Basu, “Morphological changes during annealing of polyethylene nanocrystals,” *Eur. Phys. J. E Soft Matter*, vol. 35, no. 3, pp. 1–12, 2012.

[9] W. Wang, G. Zhao, X. Wu, and Z. Zhai, “The effect of high temperature annealing process on crystallization process of polypropylene, mechanical properties, and surface quality of plastic parts,” *J. Appl. Polym. Sci.*, vol. 132, no. 46, pp. 42773–42785, Dec. 2015.

[10] Y. Ren, H. Zou, S. Wang, J. Liu, D. Gao, C. Wu, and S. Zhang, “Effect of annealing on microstructure and tensile properties of polypropylene cast film,” *Colloid Polym. Sci.*, vol. 296, no. 1, pp. 41–51, Jan. 2018.

[11] G. Mazzanti, “Analysis of the combined effects of load cycling, thermal transients, and electrothermal stress on life expectancy of high-voltage AC cables,” *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2000–2009, Oct. 2007.

[12] R. Liu and S. Boggs, “Cable life and the cost of risk,” *IEEE Elect. Insul. Mag.*, vol. 25, no. 2, pp. 13–19, Mar. 2009.

[13] Y. Xie, G. Liu, Y. Zhao, L. Li, and Y. Ohki, “Rejuvenation of retired power cables by heat treatment,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 2, pp. 668–670, Apr. 2019.

[14] M. Araoka, H. Yoneda, and Y. Ohki, “Dielectric breakdown of new type polymerized polyethylene using a single-site catalyst,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 3, pp. 326–330, Jun. 1999.

[15] D. Ferrer-Balas, M. MasPOCH, A. Martinez, and O. Santana, “Influence of annealing on the microstructural, tensile and fracture properties of polypropylene films,” *Polymer*, vol. 42, no. 4, pp. 1697–1705, Feb. 2001.

[16] A. Saffar, A. Ajji, P. J. Carreau, and M. R. Kamal, “The impact of new crystalline lamellae formation during annealing on the properties of polypropylene based films and membranes,” *Polymer*, vol. 55, no. 14, pp. 3156–3167, Jun. 2014.

[17] H. Bai, H. Deng, Q. Zhang, K. Wang, Q. Fu, Z. Zhang, and Y. Men, “Effect of annealing on the microstructure and mechanical properties of polypropylene with oriented shish-kebab structure,” *Polyln. Int.*, vol. 61, no. 2, pp. 252–258, Feb. 2012.

[18] V. P. Skorodumov, A. V. Motavkin, and E. M. Pokrovskii, “Determination of the melting point and glass transition temperature of polymers with the lattice model,” *Fibre Chem.*, vol. 37, no. 1, pp. 31–34, Jan. 2005.

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