Thermal Effect of Short-term Overload on High-voltage Cross-linked Polyethylene (XLPE) Cable Insulation

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Abstract. This paper describes changes on micro-structure and aggregation structure of cross-linked polyethylene (XLPE) with different thermal histories after different times of overheating treatment to analogize the short-term fault or emergency overload in actual operating cables. 5, 10 and 20 times overheating treatment were conducted on a spare cable and a retired cable with service years of 32, whose insulation were analyzed by the diagnostic measurements of Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC) and thermogravimetry (TG). The results show that the spare cable has presented a trend of improvement on the insulation properties after overheating treatment below 20 times, but slight deterioration occurs after 20 times overheating treatment; the retired cable with service years of 32 has presented a trend of degradation on the insulation properties at the first 5 times overheating treatment, and a severe deterioration occurs after 20 times overheating treatment.

1. Introduction
Cross-linked polyethylene (XLPE) has been widely used as an insulating material for high-voltage cables because of its excellent electrical and thermal properties [1~3]. Under its working condition, the cables are subjected to the thermal, electrical, mechanical stresses and environment factors, which eventually leads to the aging phenomenon [4]. It is well evidenced that long-term electric field and thermal field can change the morphology of XLPE insulation deeply and lead to the degradation of the insulation [5]. In the actual operation of the cable, the insulation is influenced by many factors. Therefore, the aging process of the insulation is complicated and the insulation properties can be enhanced in some certain situations.

It is clearly pointed out that the XLPE cable can be superimposed with a large current for a long-term operating temperature of 90°C in AEIC standard [6]. Generally speaking, the threshold temperatures are set as 130°C or 250°C with a limited overheating time for the cross-linked polyethylene cables. The evaluation of this standard ignore the thermal histories on the cables with different service year, or precisely aging status of the cables. On the other hand, most of the research rarely considered the situation of accelerating heat aging in the process of instantaneous changing temperature caused by short-term faults or emergency overload in actual operating cables. Therefore, it is meaningful to conduct a thermal aging to analogize the short-term fault or emergency overload in actual operating cables with different service year to analyze the resistance to overheating situation of the cables with different statuses.
This paper has focused on two cables with different aging statuses to explore the ability to resist the multiple overheating situation. 5, 10 and 20 times overheating treatment in vacuum condition were conducted on a spare cable and a retired cable with service years of 32, whose insulation were analyzed by the diagnostic measurements to observe changes on micro-structure and aggregation structure.

2. Experimental

2.1. Preparation of XLPE Samples
Two XLPE high-voltage cables produced by Japan Showa Cable Factory were selected as experimental objects, including a retired cable which have operated for 32 years and a spare cable at the same period. It can be observed that cables sheath and the insulating layer were not damaged, and there was no water permeation before the thermal aging test. The critical parameters of the cables are listed in Table 1.

Each cable insulation was peeled parallel to the conductor surface, and the tape-like XLPE peels were obtained. Peels near the inner semi-conductive layer were taken as the samples, because these positions of the XLPE endured the most severe electrical and thermal stresses.

| Sample  | Voltage Level (kV) | Conductor Area (mm²) | Conductor Diameter (mm) | Insulation Diameter (mm) | Operation Years |
|---------|-------------------|----------------------|-------------------------|--------------------------|----------------|
| XLPE-0  | 110/63.5          | 700                  | 32                      | 68                       | -              |
| XLPE-30 | 110/63.5          | 700                  | 32                      | 68                       | 1985-2017      |

2.2. Thermal Aging
The samples were divided into 4 groups and thermal aged by three different overloading times. The first three groups were treated by overheated recycling for 5 times, 10 times and 20 times. The last group was untreated group which played a role of reference. The detailed testing conditions are listed in Table 2. The testing samples were set in the aging oven under vacuum condition with the program regulating the temperature curve as shown in Figure 1 measured by the thermo-couple sensors.

The thermal aging includes three phases: transient heating phase of 80 minutes, isothermal phase of 2 hours and cooling phase of 6 hours. These phases characterize the process of superposition of additional current under short-term fault or emergency overload in actual operating condition, the process of insulations’ ability to withstand high temperature and the process of withdrawing superposition current after eliminating short-term fault or emergency overload, respectively.

![Figure 1. Temperature curve of overheating thermal aging test changed with time (one cycle)](image-url)
Table 2. Introduction about the testing conditions of cable samples

| Sample | Aging temperature /°C | Overloading number | Overloading time/h |
|--------|------------------------|--------------------|-------------------|
| A-0    | 130                    | 0                  | 0                 |
| A-5    | 130                    | 5                  | 10                |
| A-10   | 130                    | 10                 | 20                |
| A-20   | 130                    | 20                 | 40                |
| B-0    | 130                    | 0                  | 0                 |
| B-5    | 130                    | 5                  | 10                |
| B-10   | 130                    | 10                 | 20                |
| B-20   | 130                    | 20                 | 40                |

2.3. Diagnostic Measurements

The Fourier transform infrared spectroscopy (FTIR), the differential scanning calorimetry (DSC) measurement, X-ray diffractometry and the breakdown field strength measurement were adopted to analyze the properties changes on the specimens after the thermal effects.

Micro-structure change of the samples was analysed by the VERTEX 70 infrared spectrometer manufactured by German. Each sample was tested at 32 scans in the range of 400-4000 cm\(^{-1}\).

Aggregation structure changes on the specimens were analyzed by the DSC NETZSCH-DSC 214 instrument manufactured by German. 5 mg specimens were prepared to the test with the program of two heating phases and a cooling phase under nitrogen atmosphere to avoid thermal degradation. The temperature was increased from 25 to 140°C at a rate of 10°C /min and maintained at 140°C for 5 min, and then cooled to 25°C. This scanning was repeated twice per measurement, and the first cooling and second heating phases were analyzed in this paper.

Thermo-stability on the specimens were analyzed by thermos-gravimetric analyzer (type: NETZSCH TG 209 F1 Libra) to measure the TG weight loss curve of XLPE insulation. During the experiment, the temperature was set from 30°C to 800°C at a heating rate of 10°C/min, and the weight loss of each sample with increasing temperature was observed. In a single experiment, the sample weighed 5 mg.

3. Results and Discussions

We define the sample of spare cable and the retired cable which have operated for 32 years as A and B with corresponding overheating number. That means A-0, A-5, A-10 and A-20 for the spare cable with different overheating numbers; B-0, B-5, B-10 and B-20 for the retired cable which have operated for 32 years with different overheating numbers.

3.1. Result of FTIR Spectroscopy Measurement

XLPE is a high molecular polymer whose methylene groups (-CH\(_2\)) are the most characteristic group of XLPE. This absorption peak appears at a wavelength of 720 cm\(^{-1}\), and it is confirmed by the peaks that locate at 1471 cm\(^{-1}\), 2856 cm\(^{-1}\) and 2937 [7]. Dicumyl peroxide (DCP) is commonly used as cross-linking agent and its by-product mainly consists of acetonelone, cumyl alcohol and \(\alpha\)-methylstyrene. The corresponding characteristic groups of these compounds are phenylenyl, carbonyl 3371 cm\(^{-1}\), respectively [8]. In addition, absorption peaks ranging from 1700 cm\(^{-1}\) to 1800 cm\(^{-1}\) can be considered as the thermo-oxidative products [9]. In this range, carboxylic acid absorption appears at 1701 cm\(^{-1}\), ketone absorption locates at 1718 cm\(^{-1}\) and aldehyde absorption situates at 1741 cm\(^{-1}\). The peak at 1635 cm\(^{-1}\) is assigned to the unsaturated groups absorption, which can indicate the molecular decomposition process. In order to judge the oxidation and decomposition situation of each samples under the different equivalent accelerated aging test condition, carbonyl index and double band index were chosen for research. The indexes are shown in Table 3.

Figure 2 (a) shows the FTIR spectrum of the spare cable after 5, 10 and 20 overheating treatment. It can be seen that obvious absorption peaks appear in the range of 1600 cm\(^{-1}\)~1760 cm\(^{-1}\) in the untreated sample XLPE-0. The main reason for this phenomenon may be attributed to the introduction of a large amount of impurities during the production of the cable. As the number of overheating treatment
increases, the intensity of the absorption peaks in the range of 1500~1680 cm\(^{-1}\) have increased gradually. On the contrary, the intensity of absorption peaks in the range of 1680~1760 cm\(^{-1}\) have decreased comparing with XLPE-0. This situation is ascribed to a reduction of volatile impurities and a conversion of groups under the thermal effects.

![Figure 2](image)

**Figure 2.** FTIR spectrum of each sample before and after the overheating thermal aging test. (a): the spare cable; (b): the retired cable with service years of 32

| Sample | Carbonyl index (I\textsubscript{1741/1471}) | Double band index (I\textsubscript{1635/1471}) |
|--------|----------------------------------|----------------------------------|
| A-0    | 0.146                            | 0.048                            |
| A-5    | 0.041                            | 0.111                            |
| A-10   | 0.041                            | 0.072                            |
| A-20   | 0.065                            | 0.091                            |
| B-0    | 0.028                            | 0.047                            |
| B-5    | 0.009                            | 0.079                            |
| B-10   | 0.009                            | 0.098                            |
| B-20   | 0.023                            | 0.198                            |

**Table 3.** Carbonyl and double band indexes

From the changes on the carbonyl index and the double band index in Table 3, the following regularities can be found: the carbonyl index has decreased comprehensively after overheating treatment, but the values have ascended monotonously with the overheating times increases. It indicates the overheating treatment have promoted the process of impurities volatilization in the preliminary phase of thermal aging. Subsequently, the thermal oxidative degradation has played a dominant part gradually in the XLPE insulation with the numbers of overheating treatment increases.

In the inspection on double band index, we can also find that the decomposition process of the samples to generate a certain quantity of broken molecular chains occurred distinctly after overheating treatment. Figure 3 (b) displays the FTIR spectrum of the cable with service years of 32 after 5, 10 and 20 times of overheating treatment. We can observe that absorption peaks intensity of the untreated sample in the range of 1720~1800 cm\(^{-1}\) is weaken than the spare cable’s. it may be explained by the fact that the cable with long-term operation was basically free of the volatile impurities and thermal oxidation was not distinct in a relatively low-temperature operating condition. As the number of overheating treatment increases, the intensity of the absorption peak in the range of 1500~1680 cm\(^{-1}\) increases monotonously, while the intensity of the absorption peaks in the range of 1720~1800 cm\(^{-1}\) decreases properly.

We can also figure the regularities from the changes on carbonyl index and double band index in Table 3. The double band index among the samples shows a linear ascending trend with the increasing
times of overheating treatment, which indicates the crystalline morphology of the insulation has been basically stable in the long-term actual operation process, and thermal degradation dominates in the case of overheating treatment, aggravating the destruction of the molecular chains. In the aspect of carbonyl index, it declines preliminarily after 5 and 10 times of overheating treatment. Subsequently, abrupt increase occurs after 20 times of overheating treatment. The drop on carbonyl index is probably attributed to the transformation of the groups under the thermal effects. The elevation on carbonyl index indicates the dominant role of thermo-oxygen degradation.

3.2. Result of DSC Measurement

With the results of DSC measurement, two phases were analyzed, including the heating and cooling phase, which can be used to analyze crystalline structure and the ability of recrystallization among the samples. Figure 3 and Figure 4 show the heating and cooling phase thermograms of each sample.

Figure 3 (a) shows the DSC heat flow curve of heating phase on the spare cable samples. It can be observed that the endothermic peak of all the samples drifts to higher temperatures after the overheating treatment. But the melting range of each sample is enlarged at the same time. This phenomenon is mainly attributed to the nucleation and development of crystalline structure have not reached steady state. With the thermal effect activating the adequate motion of macromolecular chains, the scission of tie molecules traversing the amorphous regions have rearranged into the lattice to increase crystallinity [10, 11]. From the results of FTIR, it can be deduced that the generation of broken chains and small molecular chains would also promote the formation of secondary crystal to increase crystallinity.

Figure 3 (b) shows the DSC heat flow curve of heating phase on the retired cable samples. It can be seen that endothermic peaks gradually drift to a lower temperature with the numbers of overheating treatment increases. During the long-term operation of the retired cable, the development of the internal crystalline nucleus and crystals basically have reached the steady state. That means the potential of crystalline structure to recrystallize to better one has been declined. Therefore, the deterioration of the crystallite structure becomes more distinct as the overheating treatment increases with the phenomenon of the melting range expanding.
Figure 3. DSC spectrum of heating phase before and after the accelerated thermal aging test. (a): the spare cable; (b): the retired cable with service years of 32.

Figure 4. DSC spectrum of cooling phase before and after the accelerated thermal aging test. (a): the spare cable; (b): the retired cable with service years of 32.

Figure 4 (a) shows the DSC heat flow curve of cooling phase on the spare cable samples. It can be seen that the heat flow curves drift to lower temperature after 5 times and 10 times of overheating treatment, but slightly drifts to high temperature after 20 times of overheating treatment comparing to untreated one (A-0). This phenomenon indicates the deterioration on re-crystalline structure occurs in the beginning of the overheating treatment but has been improved after 20 times of overheating treatment, which reveals the cable insulation has not reached steady state with high potential to recrystallize for better forms.

Figure 4 (b) shows the DSC heat flow curve of cooling phase on the retired cable samples. Abrupt elevation in enthalpy of crystallization and diminution in degree of super-cooling can be associated with the increase of broken chains and small molecular chains after overheating treatment, which is prone to generate large quantities of secondary crystalline structure.

3.3. Result of TG Measurement

Table 4 shows the critical parameters obtained from TG measurement, where $T_0$ is the initial weight loss temperature, which characterizes the first melting parts of the secondary or imperfect crystalline structure; $T_{50\%}$ is the temperature at 50% weight loss of the samples; and $T_p$ is the peak value of DTG, which characterizes the temperature corresponding to the most violent reaction of weight loss.

It can be seen from Table 4 that the thermal stability of the insulation is enhanced after 5 times of overheating treatment of the spare cable insulation, which is manifested by an increase in $T_0$ and $T_p$. However, the thermal stability of the samples has been slightly decreased with the increasing of the overheating treatment of 10 and 20 times. We can also find that the $T_p$ is increased distinctly after 5...
and 10 times overheating treatment, which demonstrates the main crystalline structure becomes more compact.

From Table 4, there is a distinct regularity can be found. The crystalline structure of the cable with service years of 32 has basically reached the steady state. The parameters of $T_0$, $T_{50\%}$, and $T_p$ exhibit a linear decrease with the overheating times increases. This phenomenon can be ascribed to the aggravation of destruction on the macromolecular chains of the samples to generate more broken chains and small molecular chains, which form a large quantity of incompact crystals with thin lamellar thickness under the overheating process. Therefore, the thermal stability of the samples has been declined with the overheating times increases.

Table 4. Critical parameters obtained from TG measurement

| Sample | $T_0$ (°C) | $T_{50\%}$ (°C) | $T_p$ (°C) |
|--------|------------|----------------|------------|
| A-0    | 445.9      | 464.4          | 468.7      |
| A-5    | 446.9      | 464.0          | 470.1      |
| A-10   | 445.2      | 463.7          | 470.9      |
| A-20   | 443.6      | 462.2          | 469.3      |
| B-0    | 450.1      | 467.6          | 473.5      |
| B-5    | 449.1      | 466.1          | 472.8      |
| B-10   | 448.3      | 465.8          | 471.0      |
| B-20   | 447.0      | 464.2          | 470.3      |

4. Conclusion
This paper describes changes on micro-structure and aggregation structure of a spare cable and a retired cable with service years of 32 after different times of overheating treatment to analogize the short-term fault or emergency overload in actual operating cables. Distinct differences on the changing trend between these two cables indicate the thermal history plays a decisive role on the resistance to overheating treatment of the cable. Following conclusions can be made:

1) The spare cable has presented a trend of improvement on the insulation properties after overheating treatment below 20 times, but slight deterioration occurs after 20 times overheating treatment;
2) The retired cable with service years of 32 has presented a trend of degradation on the insulation properties at the first 5 times overheating treatment, and a severe deterioration occurs after 20 times overheating treatment.

Therefore, it can be deduced that the spare cable has a high potential to resist multiple overheating situation below 20 times due to the integrate structure of XLPE macromolecular chains and the unstable status of the crystal nucleus and crystalline structure; On the contrary, the retired cable with service years of 32 can hardly resist multiple overheating over 10 times. This kind of cables should avoid multiple overheating situation in the actual operating condition.

5. Acknowledgments
This research is truly supported by the foundation item: The Technical Projects of China South-ern Power Grid (No. GDKJXM20172797).

6. Reference
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