Dynamic characteristics analysis of XLPE cable charge under different aging degree

Tengfei Zhao1*, Yongjie Nie1, Min Cao1, Pengwu Li1, Jianwei Bai2

1 Electric Power Research Institute, Yunnan power Gird Co., Ltd., Kunming, Yunnan, 650217, China
2 Electric Power Research Institute, Yunnan power Gird Co., Ltd., Kunming, Yunnan, 650217, China
*Corresponding author’s e-mail: nieyongjie@stu.xjtu.edu.cn, 1783748133@qq.com

Abstract. To study the dynamic charge characteristics of XLPE cables. In this paper, a Qt test system is built in the laboratory to test the Qt dynamic charge characteristics of different thermal aging samples, and the current characteristics of different aging degrees are obtained according to the charge test differentiation. The experimental results show that the charge value of unaged sample is about 1100 nC, and the charge value of aged sample is about 2000 nC. At the moment of pressurization, the XLPE cable sheet sample flows through a large instantaneous charging current, and the initial current is more than 10^-9 orders of magnitude. For the unaged sample, the charge accumulation value and conduction current value of H1 and H2 are better than those of F sample. The analysis shows that due to the insufficient aging degree of the sample, the initial aging stage is in the recrystallization stage.

1. Introduction

With the acceleration of urbanization, XLPE cables are widely used in power grid construction due to their good dielectric properties and physical and chemical properties. However, in the actual operating environment, XLPE cable will be subjected to the combined action of electric, thermal and mechanical forces, resulting in a series of irreversible changes in the microscopic chemical and physical structure of XLPE molecular chain fracture, aggregation structure, crystallinity and crosslinking degree, micro-nano scale[1,2]. The change of polymer aggregation structure can change the distribution of trap characteristics in XLPE, which leads to the change of charge injection and transport parameters in the medium, and finally leads to the deterioration of insulation performance of XLPE cables, which seriously threatens the safety of power grid system operation[2,3].

At present, the research on the dynamic characteristics of space charge accumulation and dissipation mainly includes electroacoustic pulse method (PEA method) [4], pressure wave propagation method (PWP method) [5], current integral charge method (Qt method) [6,7], and so on. Li Jianying of Xi’an Jiaotong University measured the charge accumulation characteristics of XLPE cables with different aging forms at different locations by PEA method. The internal and external crystallization morphology of the unaged cable insulation is uneven, the internal crystallization morphology is perfect, and the crystallization rate is high, while the external crystallization morphology is imperfect, and the crystallization rate is low, which is due to the increase of the accumulated charge from the inside to the outside[4]. The principle of space charge measurement by PWP method is to analyze the deformation of the medium caused by elastic pressure wave.
propagation caused by pressure pulse, which leads to the slight change of local electric field, and then induces weak voltage and current signals on the external electrode[8]. Zhang Yewen et al., Tongji University, used PWP method to test the whole and sheet samples of XLPE cables, and compared the space charge results of sheet samples with those of full-size cables. It was found that the data obtained from the inner conductor and the outer layer of the cable were consistent in theory, which proved the effectiveness of the measurement system for signal acquisition from the outer layer of the cable[9]. Nie Yongjie et al. studied the dynamic charge behavior and high-field conductivity characteristics under different electric fields by Qt method. The results show that the threshold field strength of XLPE charge injection is about 10 kV / mm, and the conductivity of XLPE ohmic region is $3.79 \times 10^{-15}$ S / m, which is consistent with the PEA test results[2].

In this paper, the sheet samples of XLPE cables with different aging degrees are prepared in the laboratory. The charge dynamic characteristics of XLPE samples under different electric fields under different aging degrees are studied by current integration method. The current variation characteristics are obtained according to the charge differential measured, which is of certain significance to the evaluation of the insulation state of power cables.

2. Experiment

2.1 Sample preparation

Select 10kv XLPE power cable. XLPE samples with thickness of about 0.5 mm were prepared along the axial direction of the cable by J / Q strip XLPE cable insulation cutting machine, and the samples were placed in distilled water for ultrasonic cleaning to remove pollutants on the surface of the samples. Referring to the test method IEC-60811-1-2 (2000-07) provided by the International Electrotechnical Commission, the above samples are placed in the DKN412C air aging test box for accelerated thermal aging test. Because the temperature of the cable is about 90 °C, the temperature used for this aging is 135 °C, a series of thermal aging samples are obtained. Table 3 - 1 shows the detailed information of different thermal aging samples.

| Old time (h) | Temperature (°C) | Numbering |
|-------------|------------------|-----------|
| 0           | 0                | F         |
| 120         | 135              | H1        |
| 168         | 135              | H2        |
| 504         | 135              | H3        |

2.2. Test method

The device diagram of Qt measurement system is shown in Fig. 1. The whole Qt system is composed of high voltage DC power (30 kV), Qt test device, electrode, communication module, voltage control module, data acquisition and control. The charge quantity of sheet sample was tested by three electrode structure. Test wiring using Qt placed in the high voltage side for testing. The Qt charge dynamic distribution curve of test sample under different voltage is realized by computer pressure and data acquisition control. The test voltage is from 2 kV to 18 kV, and the test step is 2 kV. Each test voltage was pressurized for 300 s, and the test system was discharged for 5 s before and after the test of each group of samples to prevent the influence of residual charge on the experimental results. Data acquisition is set to collect charge data every 2s.
2.3. Data Extraction and Calculation

2.3.1. Charge calculation

An integral capacitance (Cint) between the high voltage outlet and the test sample is used to form the test circuit. When the voltage is applied, the current flowing through the test sample and the integral capacitor Cint is the same, that is, the derivative of the charge on the sample to time is the same as that on the integral capacitor Cint. Therefore, the charge information on Cint also reflects the charge information on the sample. The charge quantity Q(t) is shown by the initial charge quantity Q0, the cumulative space charge quantity Qspac (t) and the leakage current charge quantity Qleak (t), as shown in the formulas (1) and (2).

\[ V_q(t) = \frac{q(t)}{C_{int}} = \frac{1}{C_{int}} \int_0^t I(t) dt \]  

(1)

\[ Q = Q_0 + \int_0^t I_{spac}(t) dt + \int_0^t I_{leak}(t) dt \]

= \int_0^t \left( I_0 + I_{spac}(t) + I_{leak}(t) \right) dt

(2)

2.3.2. Current calculating

The current is calculated by the charge differential, as (3).

\[ I(t) = \frac{dQ_0}{dt} + \frac{d\int_0^t I_{spac}(t) dt}{dt} + \frac{d\int_0^t I_{leak}(t) dt}{dt} \]

= \int_0^t \left( I_0 + I_{spac}(t) + I_{leak}(t) \right)

(3)

I0 is composed of conduction current, current generated by space charge and leakage current.
3. Experimental results and analysis

3.1 Effect of thermal aging on charge dynamic characteristics of XLPE aging samples

Fig. 2 shows the variation of XLPE charge with time under different thermal aging conditions. It can be observed from the figure that the surface of the sample is charged instantaneously after pressurization, and the surface charge is formed at the interface between the electrode and the sample. With the increase of pressurization time, the charge on the surface of the sample tends to be stable. With the increase of compression strength, the charge accumulation on the sample surface increases. When the applied voltage reaches 12kv, the slope of the curve increases gradually. By comparing figure 2 (d) and figure 2 (a), the surface instantaneous charge accumulation of unaged sample H1 under 18 kv voltage is 1100 nC, and it is found that the surface instantaneous charge accumulation of sample H3 under 18 kv voltage is 2000 nC, which is significantly higher than that of unaged sample. By comparing figure 1 (b), (c) and figure 1 (a), it can be observed that when the pressure is 18 kv, the surface instantaneous charge accumulation is roughly the same, about 1100 nC. The slope of H1 charge change curve of the sample is smaller than that of the unaged sample, which is because the aged sample is in the early stage of thermal aging.
3.2. Effect of Thermal Aging on Current Characteristics of XLPE Aging Samples

![Graphs showing current versus time for different conditions](image)

Figure 3. Current versus time curve of XLPE sample under different thermal aging conditions.

Fig. 3 shows the variation of XLPE current with time under different thermal aging conditions. It can be observed from Fig. 3 that the current magnitude of the sample is about $10^{-9}$ to $10^{-10}$. In this process, the current can be divided into three parts. The first is the instantaneous charging current generated by the pressure, called instantaneous charging current, the order of magnitude is more than $10^{-9}$. The instantaneous charging current gradually decays with the change of time. Due to the polarization of XLPE medium, an absorption current gradually decreases with the increase of pressure time, which is related to the relaxation time of the medium. In this process, the charge of the integral capacitor $C_{int}$ increases nonlinearly, and finally becomes a stable conductance current, which remains at the order of $10^{-7}$. With the increase of electric field, the conductivity current of XLPE sample increases. With the increase of thermal aging time, the conductivity current of XLPE samples also gradually increases. By comparing Fig. 3 (b), (c), (d) and (a), it can be found that the conductance currents of H1, H2 and H3 samples decrease instead of increasing compared with those of the unaged samples, which is inconsistent with the theoretical results. This is because the aging degree of the test sample is not enough, and it is in the physical aging stage at the early aging stage. When the XLPE sample is in the early stage of aging, re-crosslinking reaction will occur, resulting in the increase of the crystallization area of the sample, the increase of the deep trap density, and the decrease of the shallow trap density. Then, the carriers captured by the shallow trap will lead to the decrease of the conductivity current.
4. Discuss
The ratio of $Q(t)$ at $t = 14$ s and $t = 314$ s is used as the criterion to judge the charge injection and accumulation, as shown in Formulas (4):

$$K = \frac{q(314s)}{q(14s)}$$

Figure 4. Curve of Charge Variation of XLPE Sample with Electric Field Strength under Different Thermal Aging Conditions.

Fig. 4. Curve of Charge Variation of XLPE Sample with Electric Field Strength under Different Thermal Aging Conditions. $k$ is the rate of charge change $q(14s)$ is the initial charge, $q(314s)$ is the termination charge. Figure 4 is the comparison of the charge change rate of XLPE cable samples with aging time of 120h, 168h and 504h. It can be observed from the diagram that the charge variation of unaged sample is the largest, the charge variation of H1 sample is the smallest, and H2 and H3 are between the two. Compared with the unaged sample, when the electric field intensity is lower than 20 kV / mm, the charge change rate is greater than 1 and less than 1.2. This is because at this time and under low field strength, space charge injection dominates. When the electric field strength is greater than 25 kV / mm, the $k$ value is greater than 1.2, the leakage current is dominant. In addition, it can be observed from Fig. 4 that the $K$ value of specimen numbered as H series is less than that of specimen F, which is because the aging degree of this aging specimen is insufficient at the early aging stage. This may be due to the recrosslinking reaction in XLPE due to the effect of oxygen or heat at the initial stage of thermal aging (physical aging stage). Oxidative radical RO· and peroxy radical ROO· produce aging products such as ketones, aldehydes, esters and carboxylic acids through disproportionation reaction. The recrystallization process makes the imperfect crystal perfect, and makes the XLPE sample have better insulation performance [10].

5. Conclusion
In this paper, the current integration method is used to conduct experiments on XLPE sheet cable samples at different aging stages to study the influence of thermal aging on the charge accumulation and dielectric properties of XLPE cables. The following conclusions are obtained:

1) At the moment of pressurization, the sheet sample of XLPE cable will be charged instantaneously, resulting in charge accumulation. The charge value of unaged sample is about 1100 nC, and the charge value of aged sample is about 2000 nC. In the instant of compression, the sheet sample of XLPE cable flows through a large instantaneous charging current, and the initial current is more than $10^{-9}$ orders of magnitude.
2) With the increase of applied voltage, the charge accumulation and conduction current of XLPE cable sheet samples increase significantly. Compared with the unaged samples, the charge accumulation value and conduction current value of H1 and H2 samples are better than those of F samples. This is due to the re-crosslinking reaction of XLPE samples at the early stage of thermal aging, the crystallization area increases, the deep trap density increases, and the shallow trap density increases.

3) The slope of the charge change curves of H1, H2 and H3 samples is smaller than that of the unaged samples. The charge does not accumulate significantly relative to the pressure moment, and the current increases relative to the unaged samples. Due to the insufficient aging degree of the aging samples used in this experiment, they are caused at the initial stage of aging and the subsequent experiments will be carried out.

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