Development of Cable Space Charge Measurement Device through Using Pulse Electro-acoustic Method

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Abstract: The existence and accumulation of space charge within the cable insulation pose great threat to the conductance characteristics, aging and breakdown of polymer power cables. Hence, it is of significance to study the distribution and accumulation of space charge. In the paper, the basic principle of pulse electro-acoustic (PEA) is presented and a new device that can be used for measuring the cable sample PEA space charge is developed. It is possible for the device to measure cables with different insulation thicknesses and radius thanks to the use of flat electrode. The system is used to test a new 10kV XLPE cable and a 10kV XLPE cable which has been in service for 20 years. It is found that the space charges accumulated in the cable which has been running for a long time are more than the new one under the same test conditions.

Key words: pulse electro-acoustic method (PEA), space charge, flat electrode, stray capacitance, data processing

Introduction

The XLPE electric cable is widely used in the high voltage transmission line and medium-low distribution network thanks to a series of advantages, including good electric performance, high breakdown field strength and simple to install and maintain. However, people always focus on the insulation aging and breakdown problem under long-term condition. The distribution and movement of space charge have big effect on the characteristics such as conductance, aging and breakdown. It is widely accepted that space charge and electric field distortion is one of main causes for insulation aging and breakdown.

The development of space charge research is based on space charge measurement technology. The non-destructive measurement technology especially advances the development of space charge research and equipment production. Non-destructive methods include pressure wave expansion, laser intensity modulation and pulse electro-acoustic (PEA) method. Of them, the pulse electro-acoustic is the most widely applied method in the world.

Because cable insulation is thick, many problems will arise when PEA method is adopted to conduct the test. For instance, electrode form, applied DC voltage, pulse high voltage’s amplitude, steepness, repetition...
frequency, pulse width selection and cable insulation's multi-layer structure and thickness have an effect on the attenuation of acoustic signals. How to deal with measured original signals to get space charge distribution of the sample?

In the paper, basic principles of PEA is presented and a new type of PEA space charge measuring device is developed to conduct the tests for new cables and cables that have been in service for 20 years.

1. Basic Principle of Measuring Space Charge via PEA

The principle is based on the following four assumptions:

1) Space charges are evenly distributed in the direction of interface while the distribution of space charges in the sample is one-dimension function along the direction of thickness; 2) Waveforms of acoustic pulses generated by space charges are the same as applied high voltage pulses and the amplitude is proportional to quantity of charges within the area; 3) the speed of frequency component is the same and the amplitude does not change; 4) the principle of linear superposition can be used when two or several acoustic waves interact.

The basic principle of PEA is as follows: it is assumed that there exists space charge \( p(t) \) in the sample with the thickness of \( d \). An electric pulse is applied between upper electrode and lower electrode and the width of pulse is represented by \( t_w \). When the pulse acts on the small sheet of space charge represented by \( \Delta z \), an acting force will generate. Under the influence of force, space charge moves slightly. The movement will send out a acoustic pulse, which transmits to the piezoelectric sensor through sample and electrode. The piezoelectric sensor converts all signals within the section into input voltage signals \( u_s(t) \) of pre-amplifier, which are input into the oscilloscope.

The output signal of pre-amplifier is proportional to distribution of space charge and induced media interface charge.

\[
u_s(t) = K \frac{U_p}{d}(\sigma_A + \sigma_C + u_{sa}Q(v_{as}(t - \tau_1)))
\]

Where:

- \( K \) - proportion coefficient
- \( U_p \) - amplitude of high voltage pulse
- \( \sigma_A \) - interface charge induced on the upper electrode
- \( \sigma_C \) - interface charge induced on the lower electrode
- \( Q \) - space charge
- \( u_{sa} \) - voltage signal induced by space charge in the media
- \( v_{as} \) - the speed of acoustic wave transmitting through the media
- \( \tau_1 \) - transmission time of wave in the sample
- \( t_d \) - one shock pulse

Based on the formula, it is found that output signal of pre-amplifier is in linear relation to the distribution of space charge and induced interface charge. Hence, the PEA method can be
used to measure the space charge in the media.

It is assumed that the diameter is much smaller than the length of cable, and the distribution of space charge is one dimension and changes only in the direction of radius. All interfaces must be vertical to the radius of cables and contact closely. Therefore, the above-mentioned one-dimensional mode shown in Fig.1 can be used.

![Fig.1 Basic principle of PEA in the measurement of cable samples](image)

2. Test

2.1 Test device system

The measuring electrode of test device adopts flat electrode. This kind of device can measure space charges in the polymer cables with different thicknesses of insulation. The diagram is shown in Fig.2. The measuring electrode is 18mm thick. Under the measuring electrode is shielding box, which contains piezoelectric sensor and amplifier. Parameters of DC high voltage pulse power source are as follows: the amplitude is -4.8kV; the pulse width is 50ns; repetition frequency is 91.5Hz. The amplifier parameters are in the following: the band width is 0.3-600MHz and gain is 64dB.

![Fig.2 Effect of external shielding layer on the stray capacitance](image)

To facilitate the acquisition of PEA signals, one resistive divider module is added to output DC high voltage pulse and low voltage pulse signal, the waveform and frequency of which are the same as high voltage pulse. This low voltage pulse signal serves as the trigger signal of measuring PEA signal. The cycles of LV pulse signal, HV pulse signals and PEA signals are the same and time difference is a fixed value.

2.2 Sample

The test adopts two kinds of samples: ① 10kV XLPE cable which left the factory soon; ② 10kV XLPE cable which has been in service for 20 years. The main insulation of both cables is 3.5mm thick; the internal and external shielding layers are 0.8mm thick; the length of sample is 65cm. In order to prevent the cable core from discharging to external shielding layer; external shielding layer is eliminated from the place where the sample cable is not in contact with electrode. The
appearance of electrode device and sample are shown in Fig.3. The oscilloscope adopts DP04034 model to acquire original data. Its basic parameters are listed below: band width is 350MHz and sample frequency is 2.5 GHz. Before the test, -50kV voltage is applied to two cables for 24 hours to accumulate space charge.

![Image of Fig.3 Measuring electrode](image)

**Fig.3 Measuring electrode**

### 2.3 Test results

Considering that the used electrode is flat, the measuring electrode should be grounded. Hence, when the cables are placed on the electrode, external shielding layer to ground stray capacitance has a certain effect on the test. The contact part between cable and electrode is incased in a layer of aluminum foil, which is 100um thick to lessen the effect of stray capacitance on the test.

The measuring waveform at applied -30kV voltage is shown in Fig.4.

![Image of Fig.4 Effect of aluminum foil on measuring signal](image)

**Fig.4 Effect of aluminum foil on measuring signal**

The added aluminum foil reduced the effect of cable on stray capacitance. It can be found that interference signals in the front of PEA signal lessen obviously. Besides, there is a certain time delay in PEA signal with or without aluminum foil. The charge peak value turns narrow and the amplitude of interface charge’s output voltage signal increases.

Fig.5 presents PEA signals at different DC voltage.
Fig. 5 PEA signals at different DC voltage

The measured signals cannot reflect the distribution of space charge in the cable samples. Hence, it is necessary to analyze actual data. The space charge distribution after data processing is shown in Fig. 6.

Fig. 6 Space charge distribution on the cable after data processing (at -50kV DC voltage)

3. Discussion

As the applied DC voltage increases, there is a growing trend towards the space charge in the cable sample’s electrode interface and body. Generally speaking, the insulation material (such as polyethylene) can be composed of two parts: ① under the influence of high field strength ( > 30kV/mm), the trapping charge carrier injected from electrodes which are in contact with media or movable charge carrier, which is called same polarity charge; ② under the influence of low field strength, impurities in the media ionize and shift, leading to the generation of space charge, which is called hetero-polarity charge. The maximum applied voltage in the test can reach -50kV. So, hetero-polarity charge plays a prominent role.

In the pure polyethylene sample, little space charges build up. However, some additives (such as antioxidant, voltage stabilizer and catalyst) will be added during the production of XLPE cables. These additives, byproducts during the process of cross-linking and impurities are main causes of hetero-polarity space charge accumulation. Through the comparison of test results of two sample cables, it is found that the space charges accumulated in the new cable are less than the one which has been in service for 20 years under the same test conditions.

The electric field strength of main insulation layer and internal shielding layer interface is the highest. Owing to the influence of aging, space charge will further distort and field strength enhances. It is easiest to lure and develop electric tree and water tree. Therefore, conducting space charge tests for cables with different service periods can determine the aging degree of main insulation and evaluate its insulation conditions and residual life.
4. Conclusions

A set of space charge measuring system is produced based on PEA method in the paper. The new and old 10kV XLPE cables are measured and compared. Conclusions are made as follows:

1) The new flat electrode used in the test can be utilized to conduct the space charge tests for cables with different insulation thicknesses and radius.

2) A layer of 100um aluminum foil is added at the external shielding layer of cable to reduce the effect of stray capacitance between cable sample and flat electrode on the PEA signals. Interference signals decrease obviously. Besides, there is a certain time delay in PEA signal with or without aluminum foil. The charge peak value turns narrow and the amplitude of interface charge's output voltage signal increases.

3) The PEA signals measured in the cable samples tend to grow as the applied DC voltage increases.

4) The space charges accumulated in the cable which has been running for a long time are more than the new one under the same test conditions. Hence, conducting space charge tests for cables with different service periods can determine the aging degree of cables.