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Research of Electro-Thermal Aging Process of Cross-Linked Polyethylene

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Abstract. Cable XLPE-insulation operation capability and reliability highly depends on its insulation condition. Statistical analysis showed that more than 70% of cable technological disturbances are insulation breakdowns, caused by insulation aging or poor quality of cable jointing. This paper is devoted to the cable XLPE-insulation aging under the influence of electro-thermal stress. The goal of the research is to develop the technique of cable insulation residual life calculation. Theoretical and experimental research was carried out for this goal. During theoretical research Kuchinsky insulation aging model was considered and statistical research of cable insulation breakdown was performed. Experimental research of cable insulation accelerated electro-thermal aging was carried out. XLPE-insulated cable samples were exposed to the influence of temperature and voltage above rated. The results of theoretical and experimental research showed that partial discharge dependence on electric field has variable coefficients and requires an additional research, taking all possible influencing factors into account.

1. Introduction

XLPE-insulated cables are one of the most widespread elements of electric power systems. It is known that cable insulation is the most destructible element of the cable system. The most frequent cause of technological disturbances on the cable power transmission lines is insulation breakdown. Statistical analysis showed that the cable insulation breakdown is usually 70% or more of all technological disturbances of cable power transmission lines. Cable insulation breakdown is usually caused by insulation aging or by poor quality of cable jointing. Taking this problem into account, a wide spectrum of the cable insulation tests are developed and being applied:

- High voltage VLF test [1];
- Impulse voltage test [2];
- Partial discharge (PD) measurement and analysis [3], [4];
- Insulation resistance measurement [5];
- Tan δ measurement and dielectric response test [6];
- Condition assessment using polarization/depolarization current method [7];
- Reflectometry method [8];
- Cable insulation aging assessment using terahertz waves [9].



The most significant disadvantage of the listed tests is inability of the insulation remaining life prediction. Therefore, insulation materials aging and remaining life determination research continues to be an urgent task.

There are three common types of cable XLPE-insulation aging mechanisms:

- Thermal aging [10], [11];
- Partial discharges [12], [13];
- Electrical and water treeing [14], [15].

Thermal aging has an influence on the cable insulation condition and decreases its electrical strength [16]. However, the recent research [10] showed that thermal aging has to be considered only with the electrical aging effects. Moreover, the other research [17] showed the dominant effect of thermal aging in comparison of the DC stress. Electrical and water treeing significantly effect on the insulation material characteristics, e. g. insulation material conductivity increases [17]. Partial discharges (PD) occur in the insulation defects and lead to their growth and insulation breakdown. Usually these defects are electrical treeing [18], insulation impurities [2] and cavities in the cable joints [19]. All listed mechanisms deteriorate the insulation and lead to the insulation electrical strength decrease. This paper is devoted to the problem of insulation aging and insulation electric strength decrease during operation.

2. Insulation aging simulation

2.1. Mathematic model

Cable insulation remaining life is to be calculated using the data of insulation degree of degradation and statistical data of insulation breakdowns. Cable insulation degradation degree determination is possible using the insulation aging mathematic models [20] and monitoring of the insulation destruction factors [21]. In spite of insulation aging models diversity, in the literary sources wasn't found the model taking all factors into account. Not all of them were considered on their trustworthiness. So in this paper mathematic insulation aging model, proposed by Kuchinsky, is considered [22]:

$$\tau_o = AE^{-n} \exp\left(\frac{W_a}{kT}\right) \quad (1)$$

where W_a – Arrhenius activation energy, k – Boltzmann constant, T – absolute temperature, E – electric field, A – constant.

The main idea of Kuchinsky model is multiplication of partial discharge influence and thermal effect on the insulation. So the formula (1) is based on two formulas: partial discharge power dependency on the electric field:

$$P_q = BE^{-n} \quad (2)$$

and Arrhenius equation, calculating the chemical reactions rate constant:

$$K = K_0 \exp\left(\frac{W_a}{kT}\right) \quad (3)$$

But the proposed model cannot be used for the insulation remaining life calculation without improvement and transformation. The basic parameter determining the insulation remaining operation life is insulation destruction degree. It is to be determined using the formula of no destructed molecules number of the insulation material:

$$N(t) = N_0 e^{-C \cdot B \cdot E^n \cdot K_0 \cdot \exp\left(\frac{W_a}{kT}\right) \cdot t} \quad (4)$$

where C – parameter, depending on cable size, $t = \tau_0$ if $N(t)$ has critical value and insulation operation is not recommended.

But electric field and temperature in the cable insulation depend on time. Therefore, insulation destruction rate is to be calculated:

$$v(t) = -\frac{dN(t)}{dt} = c \cdot B \cdot E^n \cdot K_0 \cdot \exp\left(-\frac{W_a}{kT}\right) \cdot N_0 \cdot e^{-c \cdot B \cdot E^n \cdot K_0 \cdot \exp\left(-\frac{W_a}{kT}\right) \cdot t} \quad (5)$$

In this case the no destructed molecules number of the insulation material is to be computed using the formula:

$$N(t) = N_0 - \int_0^t v(t) dt \quad (6)$$

This equation allows calculating the no destructed molecules number on the basis of the integrated influences on the insulation. The obtained dependence on time is to be extrapolated using least squares method. It allows determining the $N(t)$ empiric function and the time to the insulation critical destruction and insulation breakdown probability increase. The cable XLPE-insulation critical degree of destruction is to be determined using the insulation breakdown statistical analysis and simulation.

2.2. Statistical analysis and simulation of the insulation breakdown

Statistical simulation of the cable insulation breakdown was carried out using the computer program developed for this goal. The main idea of the simulation was to represent the insulation as a three-dimensional massive of cells (molecules) with proportions of cable insulation size. It was assumed that the insulation breakdown occurs when 80% of the molecules in one line between cable core and screen are destructed. Every moment of time one random molecule is destructed. The result of breakdown simulation allowed determining the insulation breakdown probability dependence on the insulation degradation degree (figure 1).

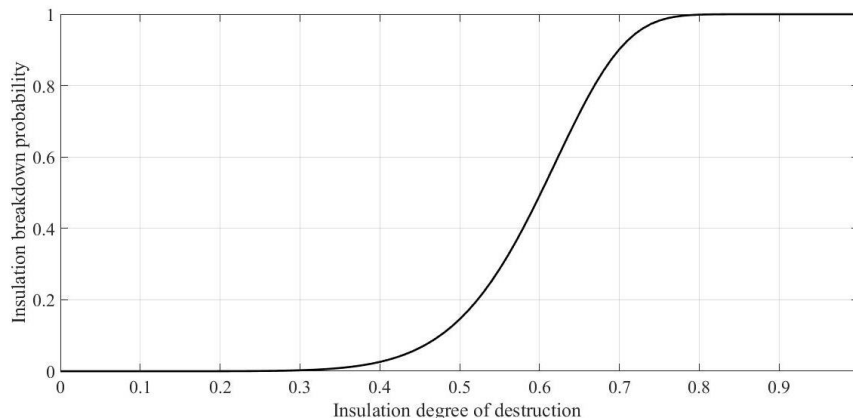


Figure 1. Insulation breakdown probability dependence on insulation degree of destruction.

Obtained characteristic shows that insulation breakdown probability is less than 1% if the insulation is less than 35% destructed. Cable operation until 35% of the insulation destruction is mostly safe. But operation with more than 35% material destruction tends to periodical insulation breakdowns because of the insulation defects occurrence. Therefore, it is recommended to operate cables until their 35% insulation degradation.

3. Experimental research

Experimental research of electro-thermal cable XLPE-insulation accelerated aging was carried out. To exclude the effects of insulation water absorption the insulation samples were aged in a dry air. Experimental setup was developed for this goal (figure 2). It consists of asbestos-cement pipe containing cable samples, tubular electric heating elements for 1 kW in summary and basaltic heat insulation. Insulation samples were 6 kV jointed cables. During experimental research insulation samples were exposed to the heating and AC 50 Hz voltage. Temperature inside the experimental

setup was maintained at the level of 100°C using electronic scheme with a symistor and temperature sensor. This temperature was chosen because of the cable sheath melting with a temperature about 105-110°C. AC voltage was obtained using testing transformer up to 100 kV. Experimental samples voltage was periodically increased from 10.8 kV to 50 kV. The experiment time was 2500 h. Partial discharge power were periodically calculated on the basis of measurement.

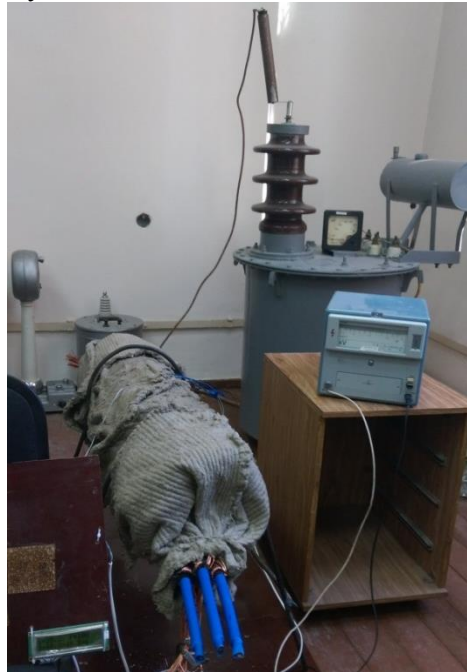


Figure 2. Experimental setup.

The results of experiment showed sufficient difference of PD power for different measurements. Therefore, this research allows only determining the range of PD power dependences on electric field (figure 3), and the parameters B and n (2) are variables on different factors, e. g. insulation moisture, temperature etc.

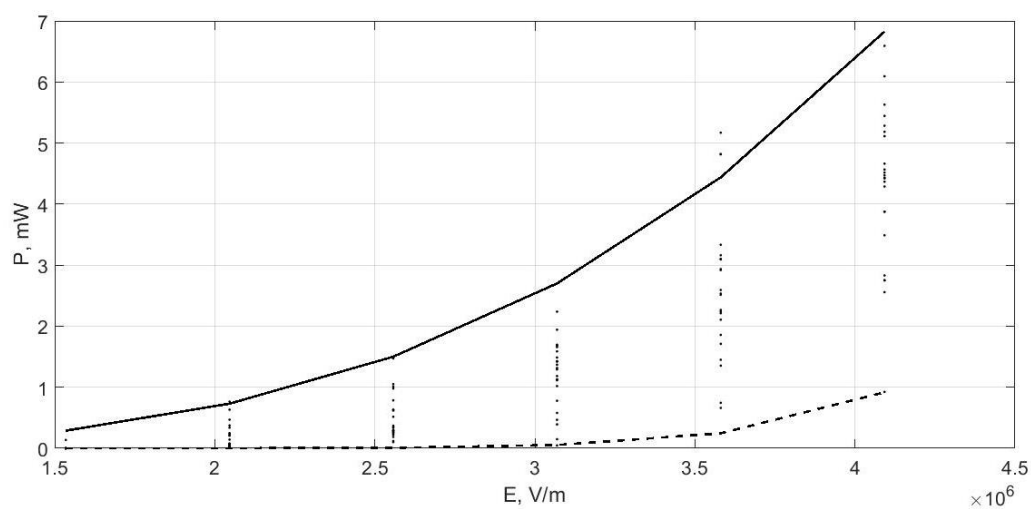


Figure 3. PD power dependence on electric field.

4. Results and discussion

Theoretical research of the insulation aging process consisted of Kuchinsky mathematic model considering and statistical simulation of the insulation breakdown. Kuchinsky insulation aging model was transformed and improved to calculate the insulation residual life. Statistical simulation of the insulation breakdown allowed determining the critical insulation destruction rate. 35% of the insulation destruction or more leads to periodical insulation breakdowns. It is recommended to carry out the predictive maintenance to reduce the number of short circuits caused by insulation breakdown. Experimental research showed a significant difference of PD power for different measurements. This result shows that PD power dependence on electric field has variable coefficients. Their determination requires a research, taking all possible factors into account.

5. Conclusion

Cable XLPE-insulation remaining life calculation model based on Kuchinsky insulation aging model is proposed. Insulation voltage and temperature monitoring during operation allows calculating its residual life. The obtained experimental results showed that PD power function has variable coefficients. Their determination requires a research, taking all possible influencing factors into account. The experimental data and experience are to be used to improve the proposed mathematic model for its possibility of residual life calculation of any type and voltage class of XLPE-insulated cables.

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