SOME THEORETICAL ISSUES OF FORMATION AND DEVELOPMENT OF GAS VOIDS IN CROSS-LINKED POLYETHYLENE INSULATION

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It is of great practical importance to study the mechanism of formation of gas bubbles during thermal treatment in the production of medium and high voltage XLPE insulated cables. Experiments show that polymer insulation of cables is very sensitive to these types of defects. Taking this into account, the article developed a mathematical model of the development of gas bubbles in the polymer based on the theory of high elasticity and large mechanical deformation. Based on the mathematical model, the conditions for the development of gas voids were determined, and it was possible to find the critical degree of swelling. It was noted that the values obtained as a result of the theoretical calculations are very important in choosing the optimal technological mode in terms of obtaining homogeneous insulation.

Keywords: polymers,XLPE,voids,elasticity module, thermal treatment, mathematical model.
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INTRODUCTION

Stable, continuous and reliable operation mode of power supply of power units of power stations, industrial enterprises, transportation, utilities and other areas of the agricultures are directly characterized by the reliability of power cables. The reliability and lifespan of cables are determined by the quality of their insulation. Different types of damage occur in cable insulation during both production and operation. During operation, certain electrophysical processes occur in these damages, which causes aging of insulation. As a result, the performance and reliability of the insulation decrease. For this reason, the prevention or minimization of various types of damage in cable insulation is one of the urgent issues for cable manufacturers and operators.

The main types of the aging phenomenon in cable insulation can be noted as following [1,2,3]:

• electrical aging;
• oxidation and heating aging in the insulation;
• aging due to the influence of moisture in the insulation;
• aging due to damages caused by other effects in the insulation.

The most common is electrical aging. This aging is caused by electrical discharges (partial discharge) occurring in the micro-gaps (gas gaps) in the insulation. Due to the effect of discharges, collapsing of molecular bonds in the insulation occur. The breakdown degree and its nature are characterized by the type of insulation material and the nature of the damage.

Currently, in cable technology, especially in the production of 6-500 kV voltage cables, cross-linked polyethylene (XLPE) is used as insulation. These cables have many advantages over oil-impregnated paper-insulated cables [4,5,6,7]. The most important is that depending on the laying conditions, the load carrying capacity must be 15-30% higher due to the higher operating temperature. At the same time, the technology of manufacturing XLPE insulated cables is simple and economically efficient. The operation of these types of cables in about fifty years confirmed their effectiveness. XLPE insulated cables are more reliable and long-lasting in addition to high operational characteristics.

Two modern cable plants in Azerbaijan fully satisfy the country's energy system's demand for this type of cables. TPE insulated power cables produced by both plants are competitive with similar cables from leading western manufacturers.

In addition to all this, unlike impregnated paper insulation, monolithic polymer insulation of cables is more sensitive to various external inclusions (additives), voids and other defects (Figure 1). These defects create a large local electric field intensity in the insulation, lower the breakdown voltage, cause the formation of electric and water trees during operation, as a result of which the insulation aging occurs [8,9]. Just like the variety of foreign inclusions (injuries), the causes of their occurrence are also different. The most common non-homogeneous areas in XLPE insulation are gas voids and moisture. This type of regions can appear in the insulation both before heat treatment and during heat treatment.

Thus, one of the important criteria for evaluating XLPE insulated cables is the electrical strength of the insulation, that is, the electrical strength determines the reliability of the cable as a whole.

The electrical strength of the insulation under alternating and impulse voltages is determined by a number of factors - macro and microdefects of various nature in the insulation system, microvoids, products of thermal destruction, alien particles etc.

There is a high probability of gas voids in the insulation in the production of XLPE-insulated cables. The technological mode should be chosen so that the dimensions of these gaps do not exceed the critical limit that lowers the electrical strength of the insulation.

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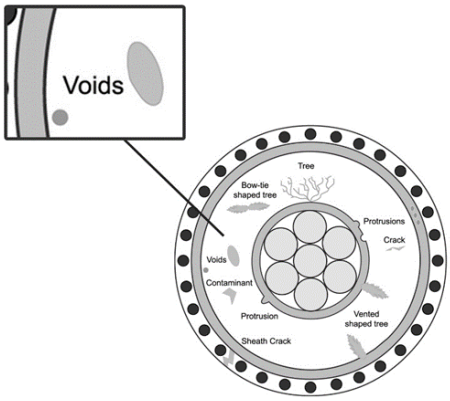

Fig. 1. Different types of defects in XLPE insulation.

The above-mentioned suggests that the reasons for the appearance of gas gaps and other inhomogeneous areas in the insulation in the production of polymer, including woven polyethylene insulated cables, and modern methods for their determination have been studied in detail.

At the same time, the development conditions and kinetics of gas voids formed due to dissolved gases during thermal treatment of insulation have not been sufficiently studied. The study of the growth conditions of gas bubbles and the influence mechanism of some technological parameters that play an important role in their development is very relevant from a practical and theoretical point of view. This article is devoted to the analysis of the development mechanism of gas bubbles that appear during thermal processing of XLPE insulation.

The achieved results can be useful in calculating the optimal technological mode for obtaining monolithic cable insulation.

DEVELOPMENT CONDITIONS OF GAS VOIDS

The reasons for the formation of dissolved components during the technological regime in polymer insulation can be divided into three groups:

• the first group includes substances dissolved in the material before thermal treatment - moisture, air, solvents, etc. belongs to.

• the second group includes substances released in the material during heat treatment - by-products of the construction reaction, decomposition products of organic peroxides, products resulting from the destruction of the polymer.

• the third group includes gases dissolved in the polymer when technological heat treatment is carried out at high pressure.

When peroxide is used in the cross-linking process of polyethylene, the release of methane and acetophenone gases is characteristic. Technological thermal processing is carried out in a nitrogen (N_2) environment at high pressure, in this case, additional nitrogen gas is dissolved in processed polyethylene.

At high temperatures, these gaseous products cause gas bubbles to form in polyethylene. In these bubbles, under certain conditions, ionizations - partial discharges occur and finally the insulation breakdowns. It should be taken into account that since the structure is heterogeneous, there are ionization centers with radius r in the polymer. Therefore, let's look at the mechanism of the growth of the air gap of radius r, which is already present in the polymer.

The equilibrium pressure of vapors (gases) dissolved in the material is a function of temperature and concentration, i.e. P = f (V,T). The dependence of equilibrium pressure on concentration is expressed by Henry's law [13].

$$P = \frac{U}{h} \tag{1}$$

where, U - the concentration of gases dissolved in the material, kg/m^3; h- is the solubility coefficient, kg/Pa·m^3.

It is known that the gases cannot be infinitely dissolved in the polymer, that is, at a certain value of the concentration (at a given pressure and temperature), the polymer-gas equilibrium is established (saturated solution).

The growth of a gas bubble in a polymer melt can occur if the equilibrium pressure is greater than the pressure of the region surrounding the air gap (ambient pressure). Therefore, the growth condition of gas bubbles will be as follows:

$$P = \sum P_i \geq P_0 \,, \tag{2}$$

where, ∑Pi is the total equilibrium pressure of gases dissolved in the substance; P0 is the pressure in the polymer in the region where the gas bubble develops.

In the production of XLPE insulated cables in modern technological equipment, the peroxide cross-linking process is carried out at high temperatures (300 - 3600 C), and at this time polyethylene becomes highly elastic. In the case of high elasticity, the properties of polymers obey large elastic mechanical deformation laws [14,15]. In the simplest case, the following statement is true for a tensile specimen:

$$\sigma = \frac{G}{2}(\lambda - \lambda^{-2}), \tag{3}$$

where, $\lambda = l/l_0$; l_0 – the length of the sample until tension; l – the length of the sample after stretching (steady state); G- the modulus characterizing the elasticity property, Pa; σ – mechanical stress in tension, Pa (considering the cross-sectional area in the non-tensile state).

In the theory of large elastic mechanical deformation [15], the expression of the dependence of the dimensions of the spherical cavity (in this case, the gas cavity) located in a large block of material on the pressure inside it was obtained:

$$P = \frac{G}{2}(5 - 4\lambda^{-1} - \lambda^{-4}), \quad (4)$$

where, P- pressure; G- elasticity of the polymer (modulus of displacement); λ - is the degree of swelling of the sphere, $\lambda = r/r_0$, r_0 is the initial radius of the sphere, r is the radius in the deformed state. Equation (4) was experimentally confirmed in [15].

Modulus G is one of the quantities that play a key role in the development of the sphere.

The value of G depends on the degree of cross-linking of molecules and is determined by the following formula [16].

$$G = 2\rho\frac{RT}{M_{av}}, \quad (5)$$

where, ρ- density of PE, kg/m³; T-temperature, K; R-gas constant, C/mole·K; $M_{av}$is the average molecular weight of the polymer chain located between two adjacent building points. The value of M_{av} is inversely proportional to the number of transverse bonds in the XLPE.

If the initial radius of the gas cavity (r_0) is very small, then it is necessary to add the pressure accumulator that takes into account the effect of surface tension to the right side of equation (4):

$$\Delta P = \frac{G}{2}\left[5 - 4\left(1 - \frac{\alpha_g}{r_0 G}\right)\lambda^{-1} - \lambda^{-4}\right] \quad (6)$$

where α_g - is the surface tension of the polymer.

For a thin-walled spherical bubble, equation (6) becomes:

$$\Delta P = 2G(\frac{t_0}{r_0})(\lambda^{-1} - \lambda^{-4}), \quad (7)$$

where t_0 - is the thickness of the sphere wall.

Taking into account pressures inside the sphere (4) and surface tension (6), we can write the development condition of the gas void inside the highly elastic polymer:

$$P - P_0 = \frac{G}{2}(5 - 4\lambda^{-1} - \lambda^{-4}) + \frac{G}{2}\left[5 - 4\left(1 - \frac{\alpha_g}{r_0 G}\right)\lambda^{-1} - \lambda^{-4}\right] \quad (8)$$

After some transformations, we get:

$$\frac{P-P_0}{G} = \frac{5}{2} - 2\left(1 - \frac{\alpha_g}{2r_0 G}\right)\lambda^{-1} - \frac{\lambda^{-4}}{2} \quad (9)$$

or

$$P - P_0 = \frac{2\alpha_g}{r_0\lambda} + G(5 - 4\lambda^{-1} - \lambda^{-4}) \quad (10)$$

When λ=1, the pressure in the gas space depends only on the surface tension. If
$P-P_0 < 2\alpha_g/r_0$, then the gas gap will not grow.

If $1 - \frac{\alpha_g}{2r_0 G} > 0$, then the gas bubble with radius r_0 will grow to the limit calculated by formula (6). Here $\Delta P = P - P_0$, P_0 is the pressure of the medium surrounding the polymer, and P is the pressure inside the gas bubble.

If $\frac{2(P-P_0)}{G} < 5$, then the size of the initial gas bubble grows to the limit determined by the formula(9).

If the condition $\frac{2(P-P_0)}{G} \geq 5$ is met, the gas bubble should grow to infinity. In reality, gas bubble growth is limited by the allowable value of the relative tensile elongation of the cross-linked polyethylene, or the polymer collapses when the mechanical strength of the polymer is low (case of poor cross-linking).

If $1 - \frac{\alpha_g}{2r_0 G} < 0$, the growth of the gas bubble occurs only if the condition $\frac{2(P-P_0)}{G} > 5$ is met, and with a certain probability (as in hot liquids). In this case, the probability of bubble growth can be determined by a method analogous to the theory of bubble formation in heated liquids [16].

It is clear from the analysis that the growth rate of the bubble depends on the modulus of elasticity G of the polymer, the surface tension force α_g and the starting radius r_0. The average surface tension of hydrocarbons and other organic substances is about $3\cdot10^{-2}$ N/m. The value of the modulus of elasticity depends on the amount of PDK to which PE is added. It has been determined experimentally that when ≈1.8-2% PDK is added to PE, the value of G is around ≈10^5 - 10^6 N/m² [12]. Thus, at the average value of the α_g/G ratio, $r_0 = 1.5\cdot10^{-7}$ m is obtained. Accordingly, as long as the pressure inside the sphere is greater than the pressure of the polymer surrounding it, all gas bubbles larger than 10^{-7} m in size will grow in any case. In order to satisfy the condition $\alpha_g/2Gr_0 < 1$, r_0 must be < $1.5\cdot10^{-7}$ m. This condition is not met in technical materials.

Measurements carried out in cable factories on ready-made XLPE insulated cable samples showed that it is possible to have bubbles with a diameter of (10^{-4} - 10^{-5}) m in the insulation. Therefore, the condition $\alpha_g/2G \cdot r_0 << 1$ is always satisfied. In this case, we write the following approximate expression from equation (9).

$$\frac{P-P_0}{G} = \frac{5}{2} - 2\lambda^{-1} - \frac{\lambda^{-4}}{2} \qquad (11)$$

As you can see, surface tension can be neglected in this case. In this case, the condition $P - P_0 > 5G$ is unacceptable, because the growth of bubbles becomes more intense.

The process is carried out at high pressure so that bubbles do not grow during the construction process, in $\lambda=1$. For the case with $\lambda=1$, we get from (11). $P - P_0 \leq 0$ or $P \leq P_0$

Apparently, in order for the bubble not to grow, the external pressure must be greater than the total pressure of the gases dissolved in the polymer.

The growth of the initial gas bubble with radius r_0 is conditioned by the following probability [17].

$$W = \exp(-\frac{Q}{kT}) \qquad (12)$$

where, k-Boltzmann constant; Q- is needed energy for bubble growth; T is the temperature.

Taking into account that the degree of swelling of the bubble λ depends on the equilibrium pressure inside it, P, on the pressure in the growth region (external pressure) P_0, on the modulus of elasticity of the material G and on the surface tension α_g, the critical value of the degree of swelling can be written for λ_{cr}:

$$\lambda_{cr} = \frac{2(1-\frac{\alpha_g}{2Gr_0})}{(\frac{5}{2}-\frac{P-P_0}{G})}, \qquad (13)$$

At the beginning of the cross-linking process, at high temperature ($300\text{-}360^0$) C, the polymer becomes molten, and the value of G becomes very small. In this case, the critical value of the degree of swelling of the sphere can be calculated analogously to the formation and development of bubbles in heated liquids [17], i.e.

$$\lambda_{cr} = \frac{2\alpha_g}{r_0(P-P_0)}, \qquad (14)$$

accordingly, the critical radius $r_{cr} = \lambda_{cr} \cdot r_0$

$$r_{cr} = \frac{2\alpha_g}{(P-P_0)}, \qquad (15)$$

For gas bubble growth, the residual value of equilibrium pressure ($P\text{-}P_0$) should be close to the value of $2\alpha_g/r_0$.

If we take $\alpha_g = 3 \cdot 10^{-2}$ N/m for polymers in the highly elastic case, the equilibrium pressure should be $P\text{-}P_0 = 10^5$ Pa for the growth of the initial bubble with radius r_0.

As can be seen from (15), the critical radius of the bubble depends on the properties of the material and external conditions.

After the thermal treatment process (cross-linking process), the cooling process should be carried out at high pressure to prevent the growth of gas voids. As the temperature decreases, the vacuum pressure P decreases.

During cooling, the value of the modulus of elasticity increases sharply (several orders) in the region of transition from the highly elastic state to the amorphous-crystalline state ($105\text{-}115^0$ C) of the cross-linked polyethylene. Accordingly, at temperatures below 100^0 C, the growth of microgas bubbles in the polymer is impossible due to the large value of the modulus of elasticity of polyethylene. Therefore, the cooling mode should be selected so that the temperature of the polymer should be below 100^0 C, even in places close to the conductor. However, during operation, the temperature in certain areas of the insulation may exceed 100^0 C for various reasons (for example, in short circuits). In this case, the growth of gas bubbles is possible. Therefore, in cases where the thickness of the insulation is large, especially in XLPE-insulated cables with a rated voltage of 110 kV and higher, gas products dissolved in the insulation should be removed from the insulation. For this purpose, the cable should be kept for certain time in an environment with a temperature of ($80\text{-}90^0$) C. At this time, dissolved gases are removed from the insulation by way of diffusion.

The obtained results are very important in terms of calculating the optimal technological heating mode.

RESULT

The mechanism of formation of gas bubbles in the insulation during thermal treatment in the production of XLPE insulated cables has been determined.

Based on the theory of high elasticity and large mechanical deformation, a mathematical model of the development of gas voids in polyethylene in the state of high elasticity was developed.

Considering various factors, the growth conditions of gas voids were determined.

A mathematical expression was obtained to determine the critical degree of swelling of gas cavities. According to this expression, it is possible to determine the development condition of gas spaces. The obtained results can be useful in choosing the optimal technological mode in terms of obtaining monolithic insulation in the production of XLPE insulated cables.

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