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Research Article

DC Electrical Ageing of XLPE under Hydrostatic Pressure

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The experimental electrical ageing, of cross-linked polyethylene films 100 μm thick, was investigated under high hydrostatic pressure of 300 bar and at atmospheric pressure. The tests are conducted on direct current (dc) for up to 1000 h ageing and at temperature of 70°C. The use of the Weibull statistic, with the estimation of confidence bounds at 90%, has shown that the hydrostatic pressure has a real effect on the lifetime. These lifetime data are qualitatively analyzed with the inverse power model. It was found that thermally activated process is able to describe the pressure effect on the electrical ageing of XLPE.

1. Introduction

Since the advent of synthetic polymer development, cross-linked polyethylene (XLPE) has become the commonly used insulating material for modern high-voltage extruded cables, due to a combination of low material and processing costs, reliability, and appropriate electrical and mechanical properties [1, 2]. This widespread use of XLPE may be attributed also to a maximum operation temperature of 90°C, emergency temperature of 130°C, and a short circuit maximum temperature of 250°C [3, 4].

However, it is well known that, under service conditions, these insulators will likely undergo a graduation deterioration in performance as a dielectric material that can ultimately lead to failure. Consequently, the study of this phenomenon, namely, electric ageing, or a long-term dielectric breakdown, of these materials, is necessary. The interest of such a study is double: on the one hand, it allows the evaluation of the time to breakdown or lifetime of these insulators under the effect of the considered stresses; on the other hand, it looks for a correlation between the ageing process and the stresses causing it.

The main purpose of our work has therefore been to examine the effect of hydrostatic pressure, on the electrical ageing, by a dc voltage, on insulators used in submarine cables. We have already investigated this effect on other insulators polymers [5]. This paper gives the long-term performance of XLPE films at a temperature of 70°C and two pressures: 1 and 300 bar. These parameter values (300 bar and 70°C) can be considered as the real use conditions of the submarine cables.

2. Experimental Procedure

2.1. Materials under Study. The samples, which were 100 μm thick films of XLPE, were cut from unaged cables. The insulation thickness was precisely controlled by micrometer. The principal characteristics of these XLPE specimens are given in Table 1. Commercial confidentiality denied us knowledge of the manufacturing procedure.

2.2. Experimental Setup. The purpose of our work is to show the effect of hydrostatic pressure on the electrical ageing, by a dc voltage, on XLPE and that is why the experimental study has been carried out at two pressures: 1 bar and 300 bar and the temperature of 70°C. The latter can be considered as the temperature of XLPE insulator in service condition.

The experimental setup is classically composed of a dc generator of 100 kV, a measuring cell, and a detection system.

The samples were placed into the measuring cell composed of five high-voltage relays and five pairs of electrodes. Electrodes are made with stainless steel following Rogowsky profile. The same dc voltage (ranging from 14 to 50 kV) was applied to each specimen (they were tested in parallel). When a dielectric breakdown occurred in a sample, a positive

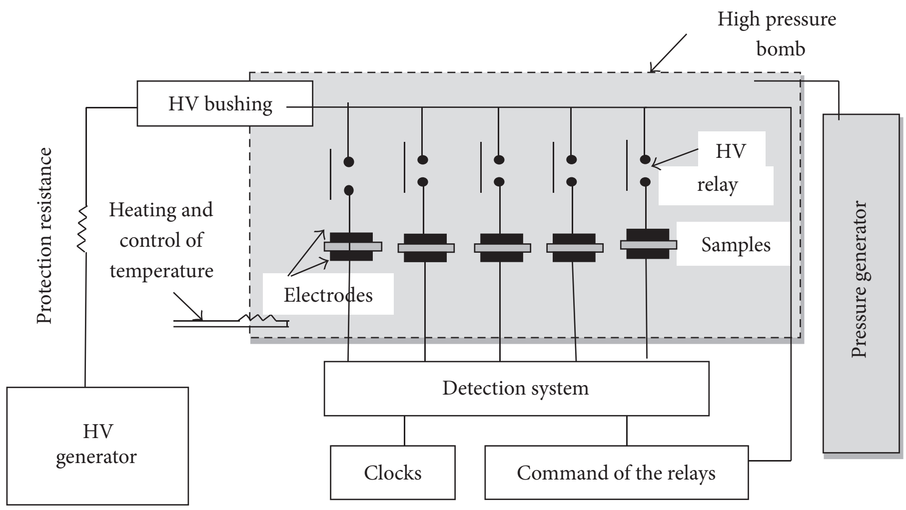

Figure 1: Electrical ageing measurement setup under hydrostatic pressure.

Table 1: Main characteristics of XLPE under study.

Density	0.923
Melting point (°C)	110
Rate of crystallinity	40
Tensile strength (MPa)	17
Elongation (%)	450
Water content (ppm)	100
Dielectric constant ε_r (1 MHz)	2.3
Loss factor	$5 \cdot 10^{-4}$

pulse was generated across the detection system by which the applied voltage was immediately removed for this sample and the breakdown time value, t_i, was recorded.

For high-pressure measurements (300 bar), the measuring cell was placed into a high-pressure bomb with a working volume of 9500 cm^3, where the pressure was obtained by a diaphragm compressor using gaseous nitrogen as the transmitting fluid. At atmospheric pressure (1 bar), the measuring cell was immersed into a chamber filled with silicone oil to avoid flashover and partial discharge effects.

For all measurements, the desired temperature was obtained, with stability of 1°C, by the use of heating resistance of 1600 W.

A schematic drawing of the experimental setup, under hydrostatic pressure, is shown in Figure 1.

3. Results and Discussion

Experimental results were obtained at 1 and 300 bar, for a temperature of 70°C in the range of an electrical field of 140–450 kV·mm^{-1} and for up to 1000 h of ageing. For each value of field, only five specimens were aged since it takes a relatively long time to perform one measurement.

3.1. Statistical Analysis. To assess the results for the breakdown of polymeric insulation, the use of statistical method is often required. Weibull distribution is now widely accepted which is based on the fact that the failure of the whole system depends on the failure of the weakest point in the system [6, 7]. The two-parameter Weibull distribution is given by

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right], \qquad (1)$$

where t is the measured breakdown time; $F(t)$ is the probability of failure at time less than or equal to t; α is the scale parameter ($\alpha > 0$) and represents the time for which the failure probability is 63.2%; and β is a shape parameter and a measure of the spread of the data.

The time to breakdown data and tolerance bounds on percentiles, of the two-parameter Weibull distribution, were then fitted using an exact approach based on the maximum likelihood method [8].

Figures 2 and 3 give examples of the application of the Weibull distribution to our experimental data. The same types of graph were obtained for the other values of electrical fields. They show that the 90% confidence bounds (for 1 and 300 bar) do not overlap, indicating that the two sets of data are different significantly.

Even though the distribution of Weibull does not offer any physical mechanism of electric ageing, it remains essential for the analysis of the experimental data and the description of the effect of a parameter (pressure in our case). To explain the effect of pressure on the electrical ageing of XLPE, we try to model the experimental lifetime data. The models suggested in the literature are of two types: macroscopic and microscopic. The first one or phenomenological one can be considered as global description of ageing, while the second one is based on a physical approach.

3.2. The Inverse Power Law Model. The inverse power law model is an empirical model, but it is commonly used for a

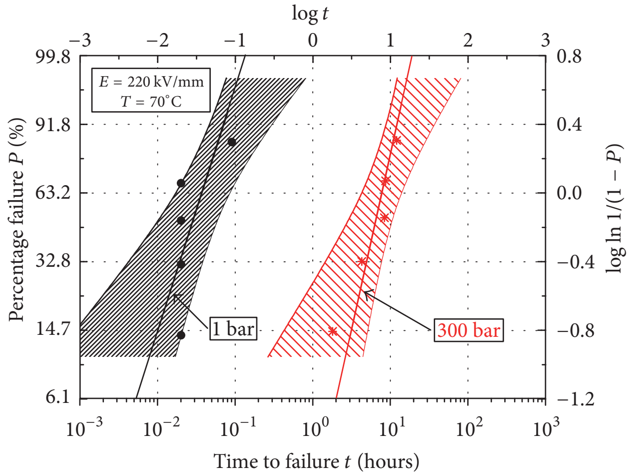

FIGURE 2: Weibull plot of the electrical ageing data of XLPE at 220 kV/mm and 70°C.

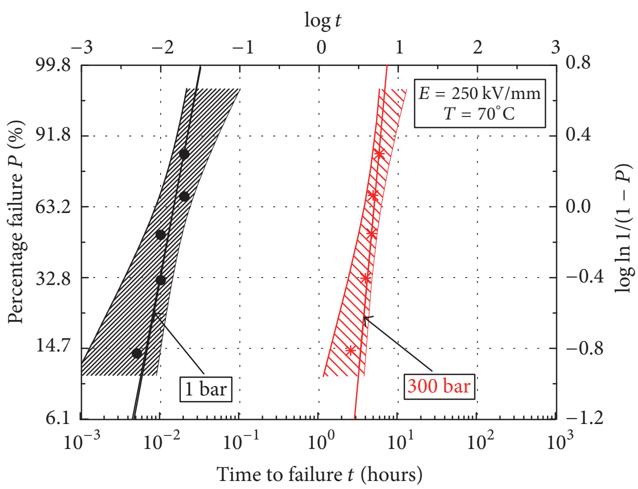

FIGURE 3: Weibull plot of the electrical ageing data of XLPE at 250 kV/mm and 70°C.

qualitative analysis [9, 10]. It is given by the following relationship:

$$t = kE^{-n}, \tag{2}$$

where t is the time to breakdown (usually it is a Weibull scale at 63.2% probability); E is the applied electrical field; k is a constant; the exponent n is the voltage endurance coefficient whose value depends on the compound, additives, and manufacturing procedures [11].

The inverse power law is considered valid, if the data being plotted on log-log graph fits a straight line.

Figure 4, which gives the fit of our experimental data, for the two considered pressures, shows the following:

(i) The reduction of the life exponent n, with pressure, is from n (1 bar) = 18 to n (300 bar) = 12. The recommendation, for testing high-voltage dc extruded cables systems, gives lower limit of ageing parameter n equal to 10 [12].

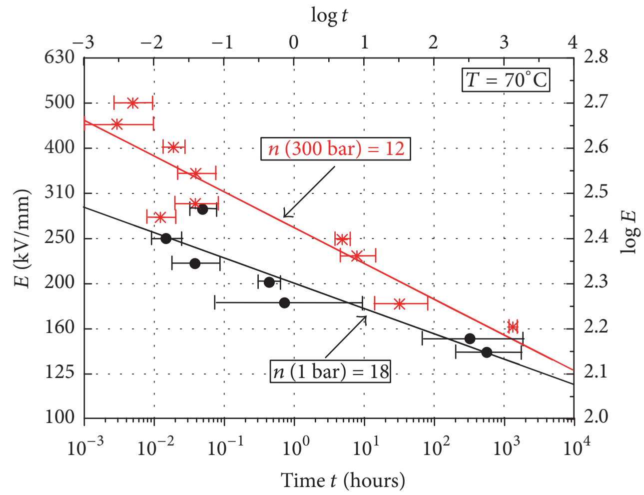

FIGURE 4: Representation of the ageing data of XLPE, according to the inverse power model, at 1 and 300 bar and 70°C. The bars to each line in this plot are 90% confidence limits.

(ii) The life curve at 300 bar is shifted towards the high fields.

3.3. Application of Crine's Model. The inverse power law model has no clear physical basis; it allows a qualitative analysis but does not give information on the origin of the breakdown processes [13]. Among the physical theories studied in our bibliography, it seems that Crine's model is adapted the most to describe our results.

This electrical life model, presented in the last three decades and modified later, assumes that electrical ageing is thermally activated process [13–17]. It was the first model to use the thermodynamic concept associated with the theory rate to describe ageing process [18]. Indeed, the energy parameter controlling the rate of ageing is the free energy change $\Delta G = \Delta H - T\Delta S$, where ΔH and ΔS are the activation enthalpy and entropy [19]. Thus, a free energy barrier ΔG shall be crossed for the system to pass from the unaged state to the aged state. Under the action of electrical field, the barrier ΔG decreases with the square of the field due to an electromechanical modification of the intrinsic free energy barrier. Then, the insulation life under dc high field E is given by

$$t \approx \left[\frac{h}{2kT}\right] \exp\left[\frac{\Delta G - (1/2)\,\varepsilon_0 \varepsilon_r \Delta V E^2}{kT}\right], \tag{3}$$

where h and k are the Planck and Boltzmann constant, ΔV is the activation volume, ε_0 and ε_r are the permittivity of free space and the dielectric constant of polymer, respectively.

This model suggested that the main ageing factor is the Maxwell stress induced by the field [17, 20]. Under the action of low and moderate electrical field, the nanocavities (the free volume of polymers) will be compressed by this compressive Maxwell stress. In this case only some nanocavities will be deformed and those located near chain ends and in the amorphous phase are more likely to be the first to be deformed. When a given number of nanocavities have been entirely

Table 2: Parameters of Crine's model for the ageing of XLPE at 70°C.

Pressure (bar)	ΔG (J)	ΔV (m^3)
1	$2{,}3 \cdot 10^{-19}$	$1{,}2 \cdot 10^{-25}$
300	$2{,}35 \cdot 10^{-19}$	$0{,}837 \cdot 10^{-25}$

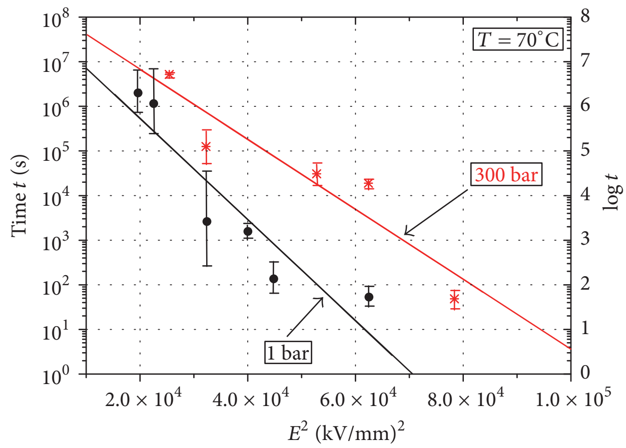

Figure 5: Representation of the experimental data of the XLPE at 70°C, according to Crine's model.

deformed, the amorphous phase is then significantly deformed and weak Van der Waals attraction bonds are broken; then the ageing process will considerably accelerate. The activation volume is then the inverse of the concentration of completely deformed nanocavities.

This model envisages a linear relation between E^2 and the logarithm of time (3), which we obtained with our results on Figure 5. Table 2 gives the value of ΔV and ΔG deduced from the slope and intercept, respectively, in these plots.

The free energy and the activation volume values deduced from experimental results (Table 2) seem in good agreement with existing data [17, 20].

The increase of ΔG, with pressure, can be attributed to the term $P\Delta V$ which appears in the relation of ΔG ($\Delta G = \Delta H - T\Delta S = \Delta E - T\Delta S + P\Delta V$) and which is generally negligible at atmospheric pressure [21]. The deformation of the barrier has been also reported by Crine and David [22]. They found that under a hydrostatic pressure P the barrier is deformed symmetrically (the original and final states are equally deformed by the energy term $P\Delta V$).

The decrease of ΔV with the pressure can be explained by the fact that the hydrostatic pressure induces a compression which reduces the free volume of the polymer; it has been reported that the hydrostatic pressure can change the free volume and the morphology of polymers [23].

4. Conclusion

The pressure effect on the electrical ageing of XLPE films has been investigated. The experimental measurements were carried out at pressures of 1 and 300 bar, at temperature of 70°C, in the range of an electrical field of 140–450 kV/cm, and for up to 1000 hours of ageing. The results were analyzed by Weibull's statistic with a confidence bounds of a 90% level. The inverse power law model gives a qualitative analysis: the hydrostatic pressure delays the electrical ageing of this XLPE in the time domain considered. The ageing process of this polymer could be explained by Crine's model based on the concept of thermally activated degradation and the existence of nanocavities. We assume that both of them can be influenced by an increase of hydrostatic pressure.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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