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UNDERGROUND POWER CABLE INSULATION ELECTRICAL LIFETIME ESTIMATION METHODS

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Pe durata funcționării, cablurile de energie subterane sunt supuse unor procese de degradare datorită dezvoltării arborescențelor de apă. Drept urmare, durata lor de viață se reduce. În această lucrare sunt prezentate două metode de estimare a duratelor de viață ale izolațiilor din polietilena de joasă densitate ale unor cabluri subterane supuse acțiunii câmpului electric în prezența apei.

Ambele metode sunt bazate pe teste de îmbătrânire accelerată a izolațiilor efectuate (în laborator) în câmpuri de frecvențe ridicate (1...5 kHz) . Prima metodă (A) utilizează câmpuri electrice de intensități egale cu cele din exploatare (nominale), iar cea de-a doua (B) utilizează câmpuri electrice superioare celor nominale. Sunt analizate avantajele şi dezavantajele fiecarei metode şi se arată, în final, ca metoda A este mai eficientă.

During service, underground power cables are subjected to degradations due to the growth of water trees. Therefore, their lifetime is reduced. In this paper, two lifetime estimation methods for low density polyethylene insulated underground cables subjected to electrical fields in the presence of water are presented.

Both methods are based on laboratory accelerated ageing tests using high fields (1...5 kHz). The first method (A) relies on nominal field tests while the second one (B) relies on high intensity field tests. The advantages and disadvantages of each method are presented and the conclusion that method A is more efficient is reached.

Keywords: cables, polyethylene insulation, water trees, lifetime estimation.

1. Introduction

Replacing paper oil power cables insulations with polyethylene ones represented a true revolution in electric power transmission. This was a consequence of the numerous advantages of polyethylene (easy to manufacture,

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very good dielectric properties, low water permeability and maintenance costs etc.).

During service, the polymeric insulations of power cables are submitted to electrical, thermal, mechanical, environmental stresses etc. that contribute to the initiation and development of certain degradation processes. In 1969 Myashita [1] reported water trees presence inside the polyethylene insulations of submersible cables. After that, the inception and development of water trees under the action of variable electric fields in the presence of water with different salt content was studied in many papers [2-7].

Water trees are diffuse areas made from micro-cavities filled with water, connected by very thin channels. They appear in regions with intense electric fields, like the insulation/conductor interface (vented trees, Fig. 1) or in the vicinity of cavities and impurities (bow tie trees, Fig. 2) and start to develop from the areas where the electric field is more intense towards the areas where the electric field is less intense [2], [5].

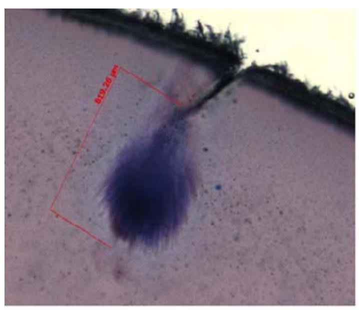


Fig. 1. Vented tree [4].

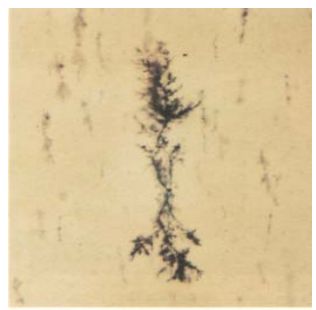


Fig. 2 Bow tie tree [4].

The growth of water trees causes an increase of the electric conductivity, permittivity and dielectric losses in insulations, a local intensification of the electric field, a decrease of the partial discharges inception voltage, a decrease of the dielectric strength and of the breakdown voltage, respectively a premature breakdown of the insulations [5-6].

An important number of medium voltage cables, still in service today suffer from water tree development. Replacing these cables implies huge costs, therefore a diagnostic and life assessment tool is a real necessity [7].

Because all the degradation processes lead to the accelerated insulation ageing, many methods of lifetime estimation based on the accelerated electrical, thermal and mechanical life tests were developed [8-16]. These ageing mechanisms can be done under the action of a single stress factor (single factor ageing) or a multifactor stress (multifactor ageing) [8].

In the case of single stress factor, the following models can be remarked:

a) Dakin thermal ageing model [9]

$$D_1 = A_1\exp(B_1/T) \tag{1}$$

b) Mechanical ageing model

$$D_2 = A_2\exp(-B_2\,\sigma) \tag{2}$$

c) Electrical ageing models, respectively inverse power model

$$D_3 = A_3E^{-n} \tag{3}$$

and exponential model

$$D_4 = A_4\exp(-B_4\,E) \tag{4}$$

where $D_{1,2,3,4}$ represent the lifetime of aged insulations at temperature T or electric field E or mechanical strain unit factor σ, and $A_{1,2,3,4}$, $B_{1,2,3,4}$ and n are material constants (dependent on the temperature etc.) [10].

In the case of insulation ageing in an electric field of intensity E and frequency f, the inverse power law (3) may be written as

$$D = AE^{-m}f^{n} \tag{5}$$

where m and n are material constants [11].

For cable insulations electrically aged in the presence of water, lifetime estimation models of water trees inception and development time depending on the strength (E) and frequency (f) of the electric field are presented in [5]. Thereby, for the inception time, the following relation is proposed:

$$t_i = Af^{1}E^{-3.5} \tag{6}$$

where A represents a material constant.

In order to characterize water trees development, the model defined by the following relations is proposed by Dissado [5]:

$$(\frac{L}{r}+1)^{p+1}-1=\frac{\tau}{t_1} \tag{7}$$

$$t_1=\frac{r^{p+1}}{(p+1)\cdot Q\cdot V^{p}} \tag{8}$$

where L represents the water trees length, r – parameter proportional with the curvature radius of the defect where the water tree starts, V – the voltage applied to the sample, Q –Ashcraft constant multiplied by a shape factor, τ – the necessary time for water tree to reach the length L and p – constant which characterizes the dependence between the growth rate of water trees and the electric field strength at its tip [5].

Unfortunately, these models are difficult to implement and do not provide values of the insulation lifetime.

In the case of multifactor ageing, models such as Simoni [12], Ramu [13], Fallou [14], Cygan – Laghari [15], Crine [16], space charge [10], [17], electrical trees [10], partial discharges [18] etc. can be remarked.

In this paper, two methods for electrical lifetime estimation of underground power cables based on accelerated tests in normal (Method A) and high (Method B) electric fields and high frequencies are presented.

2. Electrical lifetime estimation methods

Electrical lifetime estimation methods allow the lifetime estimation of polyethylene insulations of underground power cables subjected to electric field stresses in the presence of water. For this, samples taken from model cables are used. They are insulated with layers of thickness g = 0.5...1 mm of the same polyethylene as the one used for cables and obtained by the same technological process (temperature, pressure etc.).

2.1. Method A

Method A involves performing accelerated ageing in an electric field equal to the maximum field value of the cable insulation during operation ($E_{\max}$), respectively the electric field strength value in the points from the vicinity of the inner semiconductor:

$$E_{\max} = \frac{V}{R_i \cdot \ln \frac{R_e}{R_i}} \ , \tag{9}$$

where V represents the nominal voltage of cable, R_i – the inner radius and R_e – the outer radius of the insulation.

The ageing voltage values of the V_t are determined with the relation:

$$V_t = E_{\max}.r_i.\ln(r_e/r_i), \tag{10}$$

where $r_i = d/2$ represents the conductor curvature of the tested sample and $r_e = r_i + g$ – its outer radius.

The stress factor used in this method is the electric field frequency. In order to reduce the test time, high frequencies (f = 1...5 kHz) are used.

For the lifetime D_f, the following variation with the frequency is considered:

$$D_f = A_f f^{-n} \tag{11}$$

respectively,

$$\lg D_f = \lg A_f - n \cdot \lg f \tag{12}$$

$$y = a_1 - b_1 x \tag{13}$$

where D_f represents the lifetime corresponding to the electric field frequency, A_f is a constant (dependent on the electric field strength and the NaCl concentration in water), $y = \lg D_f$, $x = \lg f$ and a_1, b_1 are material constants.

In order to determine the insulation lifetime, 3 groups of 6 samples are subjected to an electric field (in the presence of water with NaCl in a concentration of 0.1 mol/l) at three frequencies $f_{1,2,3}$ for ageing times τ between 0 and 12 days. As diagnosis factors of the ageing condition, the water trees maximum or average length, their concentration, breakdown voltage etc. can be chosen.

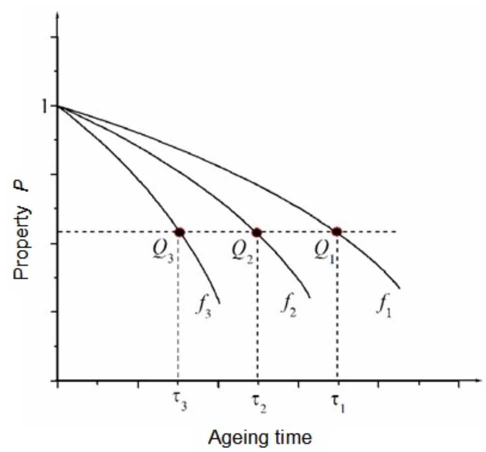


Fig. 3. The variation of property P with ageing time τ.

Considering as diagnosis factor the parameter P, the characteristics $P(\tau)$ or $p(\tau) = P(\tau)/P_i$ for the three frequencies (P_i being the initial value of P, and τ – the ageing time) are drawn (Fig. 3).

Considering the value P_n as the end of life criterion (respectively $p_n = P_n/P_i$) the $Q_{1,2,3}$ points with the coordinates $\tau_{1,2,3}$ and $f_{1,2,3}$ (in logarithmic coordinates $Q'_1(\lg f_1, \lg \tau_1)$, $Q'_2(\lg f_2, \lg \tau_2)$, $Q'_3(\lg f_3, \lg \tau_3)$) are obtained. The points $Q'_{1,2,3}$ determine the lifetime line (Fig. 4) whose parameters a and b depend on the chosen life criterion value.

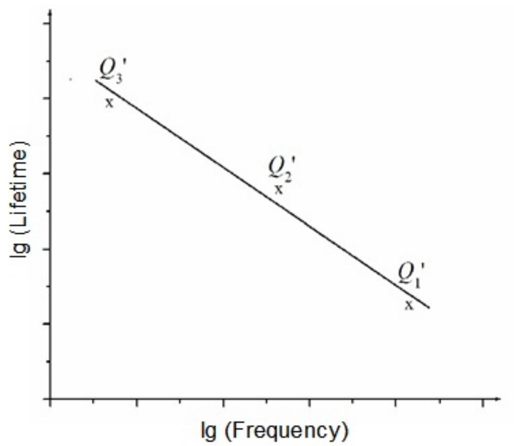


Fig. 4. Lifetime line.

Using equation (13), the insulation lifetime in an electric field of maximum value E_{max} at any frequency f can be determined.

2.2. Method B

The method B is based on a multifactor ageing, using as ageing factors (simultaneously) the frequency and the electric field strength. For the electric field E, three values are chosen ($E_{t,1,2,3}$), higher than the maximum value used in operation E_{max} (computed with the relation (9)). The values of the samples ageing voltages ($V_{t\ 1,2,3}$) are calculated with the relation (10), where E_{max} is replaced by $E_{t\ 1,2,3}$.

Starting from equation (3), it can be written that:

$$D_V = A_V\, V^{m} \tag{14}$$

respectively,

$$\lg D_v = \lg A_V - m \cdot \lg V \tag{15}$$

$$y = a_2 - b_2 x \tag{16}$$

where D_V represents the lifetime corresponding to the applied voltage, and A_V, a_2 and b_2 are material constants (depending on the electric field frequency and NaCl concentration in water).

In this case, three sets of ageing tests (on three groups of 6 samples) at frequencies $f_{1,2,3}$ and voltages $V_{1,2,3}$ for different ageing times τ are performed. As diagnosis factors, the same parameters as in Method A are used.

Choosing as diagnosis factor the parameter P, the three sets of characteristics $P(\tau)$ for frequencies $f_{1,2,3}$ and voltages $V_{1,2,3}$ are drawn. The end of life criterion is established, the coordinates of points $Q_{4,5,6}$, $Q_{7,8,9}$, $Q_{10,11,12}$ are determined (by the curves $P(\tau)$ and the end of life line) and electrical lifetime lines in logarithmic coordinates are drawn ($x = \lg V$ and $y = \lg D$) (figure 5).

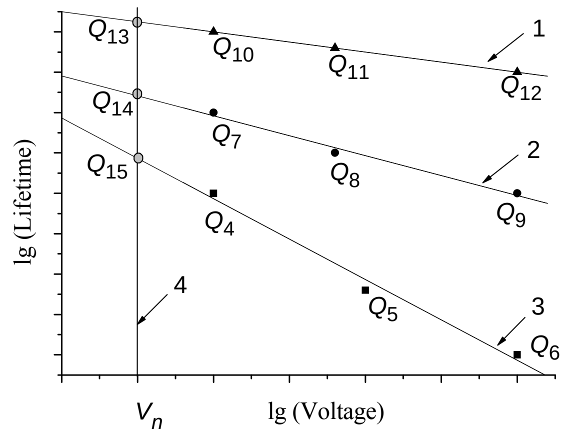


Fig. 5. Lifetime variation with the voltage for the frequencies f_1 (1), f_2 (2), f_3 (3) and the nominal voltage line V_n(4).

Using the lifetime lines (curves 1, 2 and 3, Fig. 5) and the vertical line $V = V_n$ (line 4, Fig. 5) the lifetime values which correspond to the nominal voltage V_n are determined, respectively the points Q_{13} ($\lg f_1$, $\lg \tau_1$), Q_{14}($\lg f_2$, $\lg \tau_2$), Q_{14}($\lg f_3$, $\lg \tau_3$). Then a lifetime line variation with the frequency is drawn (similar to the one from Figure 4) and the values of the parameters a_3 and b_3 of its equation are determined:

$$y = a_3 - b_3 x \tag{17}$$

where $x = \lg f$, $y = \lg D_V$, and a_3, b_3 are material constants.

Using equation (17), the lifetime value for $f = 50$ Hz and nominal voltage V_n is determined.

3. Experiments

3.1. Samples

The experiments were performed on model cables (miniature cables), manufactured by IPROEB Bistrita Company (using the same technology as for signaling cables), made of a copper round conductor with the diameter D_i = 1.2 mm and low density polyethylene insulation (used for cables with the nominal voltage V_n = 72 kV, outer diameter of the insulation d_e = 49 mm and insulation thickness g_{ins} = 10 mm) and thickness g = 0.8 mm (having the inner radius r_i = 0.6 mm and the outer radius r_e = 1.4 mm). From model cables, 220 samples having 50 cm in length were taken. On the outer surfaces of the samples superficial defects were made, by pressing them (with abrasive paper) with a CARVER press at 9.8 kN, for 2 minutes [19]. All samples were thermal conditioned for 72 h at a constant temperature $T = 60\ ^0$C.

3.2 Set-ups

For water trees development, the set-up presented in figure 6 was used [20], and the breakdown tests were made with the set-up presented in [21]. The ageing values vary between 0 and 300 h.

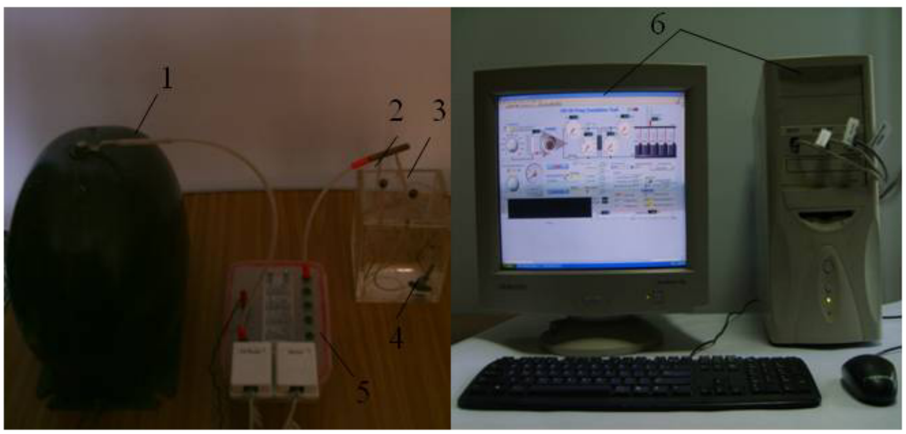


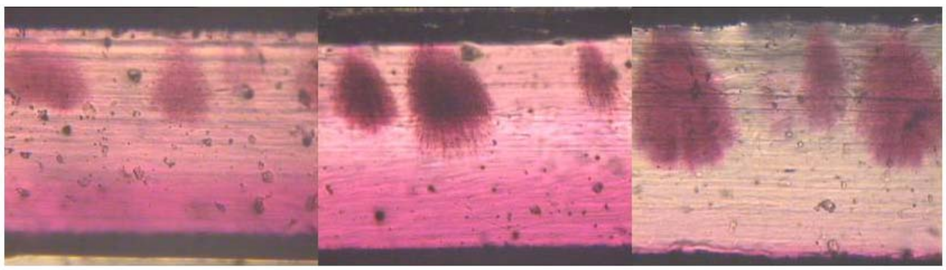
Fig. 6. Set-up for the accelerated growth of water trees: 1 - Transformer; 2 - HV; 3 – Cable samples; 4 - LV; 5 – Separators; 6 – Data acquisition system.

4. Results. Discussions

4.1. Method A

Based on the cable dimensions and nominal voltage, the maximum value of the electric field ($E_{\max}$ = 9.6 kV/mm - using relation (9)) and the model cable samples test voltage value (V_t = 5 kV - using relation (10)) were calculated. Then the samples were subjected to voltages of 5 kV and frequencies of 1, 1.5 and 2 kHz. After certain ageing time values τ, the voltage was stopped and three samples were immersed in a rhodamine solution for 48 h, after which 5 slices were taken from each sample and the water trees dimensions were measured. On other 3 samples, the breakdown voltage was determined and the average value was compared with the one obtained in (unaged) samples without water trees.

It was found that, under the action of the electric field and in the presence of water, water trees develop in insulations, and their dimensions increase with the ageing time τ (fig. 7). On the other hand, the breakdown voltage values V_{br} were considerably reduced with τ, for all values of the ageing frequency f (Fig. 8).



a) b) c)

Fig. 7. Water trees obtained in polyethylene samples after 24 h (a), 48 h (b) and 72 h (c).

According to the current standards [22 - 23], in polymeric power cable insulations, if the breakdown voltage decreases with more than 50% from the initial value obtained for the same unaged cable, it is considered that the insulation is no longer in conformity with the minimum safety requirements and that the cable must be taken out of service. Consequently, as the breakdown voltage for unaged samples is $V_{br,0}$ = 38 kV, for the end of life criterion, the value $V_{br,eol}$ = 19 kV was decided.

Using the $V_{br}(\tau)$ curves and the end of life criterion line, the coordinates of the points $Q_1(f_1, \tau_1)$, $Q_2(f_2, \tau_2)$ and $Q_3(f_3, \tau_3)$ are determined (fig. 8) and the lifetime line is drawn in logarithmic coordinates (according to (11)), of equation:

$$y = a_1 - b_1 x \tag{18}$$

where $x = \lg f$ and $y = \lg D_f$, and the constants a_1 and b_1 were determined using the Origin software (a_1 = 4.37061 and b_1 = 0.76348).

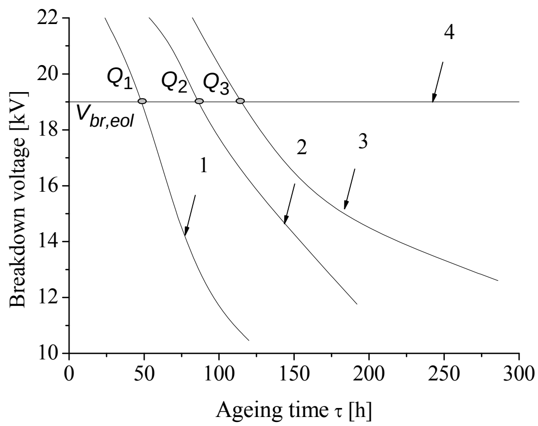


Fig. 8. Breakdown voltage variation with ageing time for $f = 3$ kHz (1), $f = 2$ kHz (2), $f = 1$ kHz (3) ($V_{br,eol} = 19$ kV (4)).

Using equation (18), the samples lifetime can be determined for any frequency. For example, for $f = 50$ Hz, the lifetime $D_{50} = 1174.89$ hours (48.95 days) was obtained.

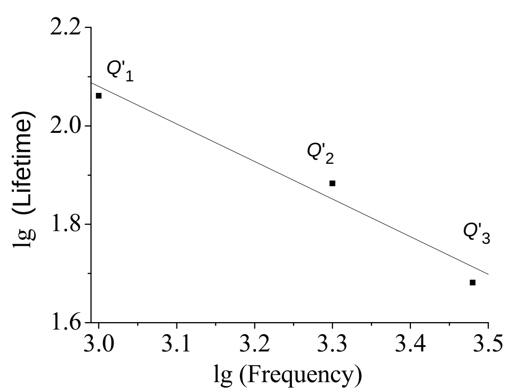


Fig. 9. Lifetime line variation with frequency.

To verify the results presented above, ageing tests at $f = 50$ Hz were done, for $\tau = 49$ days, after which the breakdown voltage was determined. The obtained value was $V_{br50,ex} = 18.7$ kV, differing with only 1.6% from the chosen value of the end of life criterion ($V_{br,eol} = 19$ kV).

4.2. Method B

For Method B, three sets of accelerated ageing were performed (on groups of three samples) at the frequencies $f = 1$, 1.5 and 2 kHz and values of the electric fields $E_{t\,1,2,3}$ = 11.8, 13.76, 15.73 kV/mm, for various ageing times τ = 24 ... 220 h. The samples ageing voltage values (determined with the equation (10) where $E_{\max}$ is replaced with $E_{t1,2,3}$) were $V_{t1,2,3}$ = 6, 7 and 8 kV.

For the lifetime estimation, the breakdown voltage V_{br} was chosen as a diagnosis factor. The breakdown voltage variation curves with ageing time $V_{br}(\tau)$ are presented in figures 10 .... 12.

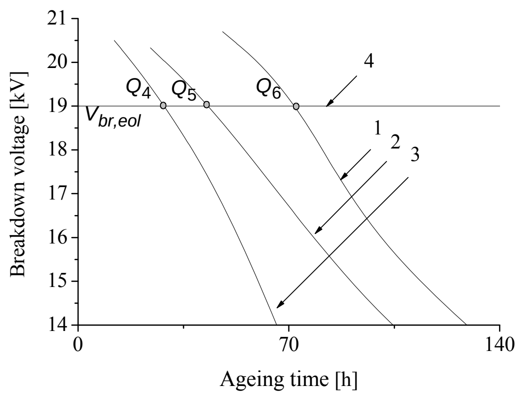


Fig. 10. Breakdown voltage variation with ageing time for V_{t1} = 6 kV (1), V_{t2} = 7 kV (2), V_{t3} = 8 kV (3) ($V_{br,\,eol}$ = 19 kV (4), f_3 = 2 kHz).

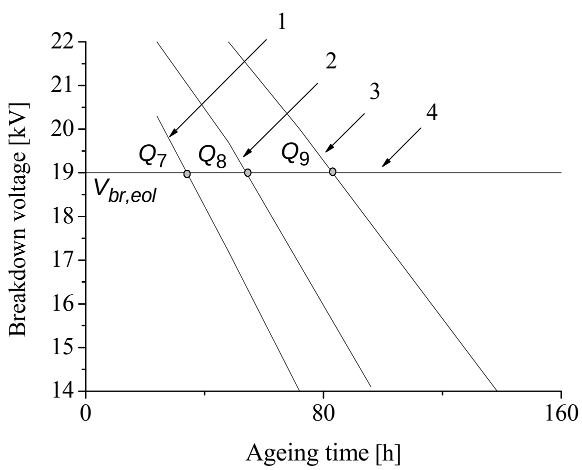


Fig. 11. Breakdown voltage variation with ageing time for V_{t1} = 6 kV (1), V_{t2} = 7 kV (2), V_{t3} = 8 kV (3) ($V_{br,\,eol}$ = 19 kV (4), f_2 = 1.5 kHz).

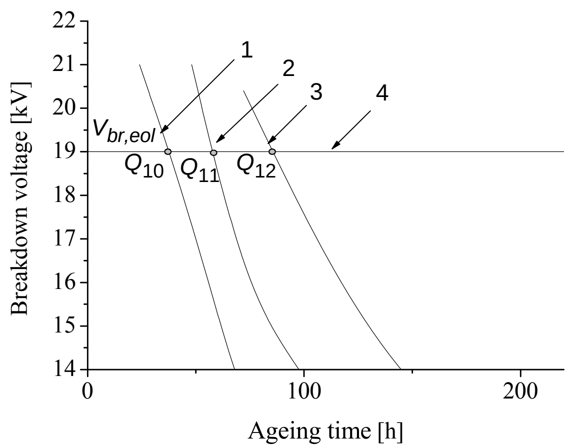


Fig. 12. Breakdown voltage variation with ageing time for V_{t1} = 6 kV (1), V_{t2} = 7 kV (2), V_{t3} = 8 kV (3) ($V_{br,\,eol}$ = 19 kV (4), f_1 = 1 kHz).

The end of life criterion was chosen the same as the one corresponding to Method A ($V_{br,eol}$ = 19 kV).

Based on the $V_{br}(\tau)$ curves and the end of life criterion line, the coordinates of the points $Q_{4,\ldots12}$ were determined (Table 1) and then, the lifetime lines corresponding to the three frequencies (1, 1.5 and 2 kHz) were drawn in logarithmic coordinates ($x = \lg V$ and $y = \lg D_V$) (fig. 13) .

Using the lines from figure 13, the lifetime values corresponding to the nominal voltage were determined V_n, respectively the coordinates of the points Q_{13} ($\lg f_1$, $\lg \tau_1$), Q_{14}($\lg f_2$, $\lg \tau_2$), Q_{14}($\lg f_3$, $\lg \tau_3$).

Table 1

The coordinates of the points $Q_{4\text{-}12}$ (V_t, τ)

Point	f	V_t [V]	τ [h]
Q_4	2	6000	72
Q_5		7000	43
Q_6		8000	28
Q_7	**1.5**	6000	83
Q_8		7000	54
Q_9		8000	34
Q_{10}	1	6000	92
Q_{11}		7000	58
Q_{12}		8000	37

Using the coordinates of the intersection points, a variation function of the lifetime with the ageing frequency for the nominal voltage V_n is determined:

$$y = a_3 - b_3 x \tag{19}$$

where $x = \lg f$ and $y = \lg D_V$, and the constants a_3 and b_3 were determined using the Origin software ($a_3 = 4.04439$ and $b_3 = 0.58349$).

Using equation (19) the lifetime values for any ageing frequency are determined. Therefore, for $f = 50$ Hz a lifetime of 1146 hours is obtained.

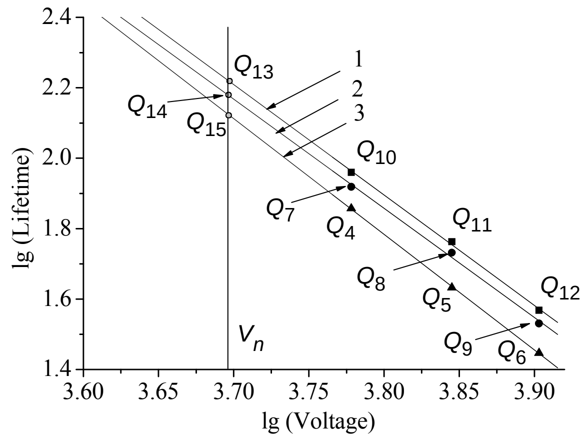


Fig. 13. Lifetime line variation with the applied voltage for f_1 = 1 kHz (1), f_2 = 1.5 kHz (2) f_3 = 2 kHz (3) and the line corresponding to the nominal voltage V_n (4).

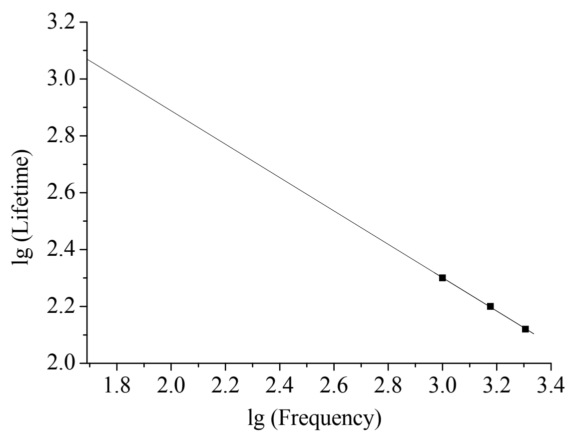


Fig. 15. Lifetime variation with the frequency of the applied voltage for a cable operating at nominal voltage.

From the analysis of the two lifetime values (obtained with A and B methods), for a 72 kV LDPE insulated cable, results a minor difference between them (2.5 %). On the other hand, for obtaining the cable lifetime using Method A, 55 samples were necessary, and the test duration was 1800 h. In the case of Method B, 165 samples were used, and the test duration was 2800 h. Consequently, Method B requires higher material consumption and longer (approximately 1.5 times) testing times (therefore, more energy). Therefore, the usage of accelerated ageing voltages (superior to the cable nominal voltage) and high frequencies (Method B) leads to the increase of ageing time and cost. It can be stated that in the case of high frequencies, Method A is more adequate.

On the other hand, if a more stronger high voltage high frequency water trees development set-up can be used and the values of the test voltage are much bigger that the voltage corresponding to E_{max}, testing times may significantly decrease and Method B may become more efficient than Method A (although, due to the high fields used, it would involve more drastic security measures).

5. Conclusions

Methods A and B presented in this paper allow the lifetimes estimation of LDPE cable insulations that are subjected to the electric field in the presence of water with various salt concentrations.

The use of intense fields and/or high ageing frequencies (1…5 kHz) allows the growth of water trees with relatively large dimensions in short ageing times (3-4 days).

The increase of ageing time determines a considerable increase in water trees dimensions and a reduction of the breakdown voltage of power cables polyethylene insulations.

Both new methods proposed allow a quick estimation of the electrical lifetime of underground power cable insulations (the values obtained differing by less than 3 %).

Method A has the advantage of a small number of samples, the decrease with approximately 1.5 times of testing times and the smaller amount of energy used than Method B.

The experimental verification of the new methods shows that the differences between the estimated breakdown voltage and the experimental one are below 2 %.

The lifetime values obtained for the tested polyethylene show that this material is not suitable for insulating underground power cables.

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