

ELECTRICAL LIFETIME ESTIMATION OF UNDERGROUND POWER CABLES

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Abstract

A fast method for lifetime estimation of new polymeric insulations used for underground power cables subjected to an electric field in the presence of water is presented in the paper. Using three fast ageing tests on samples manufactured from the new insulations (low density polyethylene) subjected to higher electric fields and higher frequencies (1...5 kHz), water trees dimensions (maximum length) and breakdown voltage curves versus ageing time were determined. Choosing different values of the end of life criteria, the lifetime lines versus frequency were determined and the insulation lifetimes at nominal frequency used in operation (50 and 60 Hz) were calculated. Finally, the utility of this fast method for underground (medium and high voltage) cables is analyzed.

Key words: power cables, lifetime, polyethylene, water trees, failure

1. INTRODUCTION

Worldwide transport and distribution networks of electricity contain hundreds of thousands of medium and high voltage cables polyethylene insulated. A lot of these cables insulation were manufactured over thirty years ago. So they have consumed their life expectancy (for which they are designed and manufactured). On the other hand, during their manufacture the insulation degradation under the combined action of electric field and water (water trees generation) wasn't taken into account, because this phenomenon was not known. Therefore, nowadays, the cables polymer insulated manufacturers and consumers have two challenges: the estimation of service insulations condition which are not protected against water trees development and manufacture of new cables having insulations with high water trees resistance.

Generally, polymeric cable insulations are subjected during operation to many factors which lead to their degradation in time, respectively to their lifetime reduction (Shirasaka, 2009). Research made in the last decades have shown that 60 % of insulation degradation causes are represented by electrical stresses, 4 % - mechanical stresses, 3-6 % impurities and 40 % - unknown factors (Mamdouh).

In order to estimate the total lifetime, degradation condition and consumed and remained lifetime, many research and models have been done. The proposed models for the lifetime estimation take into account a single stress factor (unifactor) or under the simultaneous action of many factors (multifactor). Among these models the Arrhenius (Montanari, 2002), (Simoni, 1973), (Ramu, 1985), (Fallou, 1979), (Cygan-Laghari, 1990) and (Crine, 1990), inverse power law (Simoni, 1973), space charge model (Montanari, 2002) (Dang, 1996), electrical trees model (Montanari, 2002), partial discharges model (Montanari, 1999) etc. can be remarked. Instead there are few models that refer to the simultaneous action of electric field and water (Dang, 1996).

In 1969 Miyashita (Miyashita, 1969) has found one of the most important electrical cause of lifetime reduction of polymeric power cable insulations, respectively water trees development (Dissado, 1992) (Stennis, 1990). Water trees (Fig. 1) are water filled microcavities connected between them by conductive or semiconductive channels (Nakamura, 2002). Their development lead to the worsening of the electrical properties, reduction of the breakdown voltage (Plopeanu, 2012) (Stancu, 2010), reduction of the partial discharges inception voltage, electrical trees inception and their premature breakdown (Notingher, 2005) (Brinton, 2010) (Hicks) (Fig. 2). So that is absolute necessary to know the water trees resistance of insulations, especially in the case of new polymeric materials use.

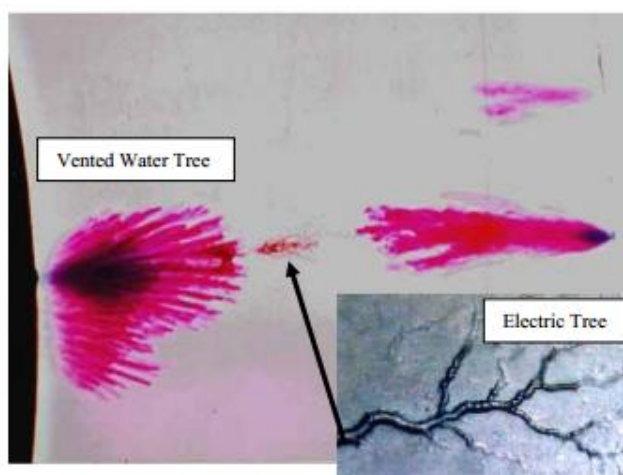


Fig. 1. Electrical trees at the tip of a water trees (Brinton, 2010).

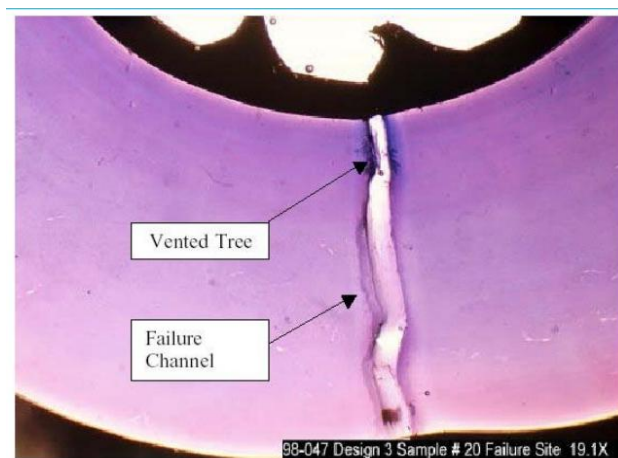


Fig. 2. Water trees leading to the insulation breakdown (Hicks).

In order to estimate the insulation lifetime, fast tests (laboratory accelerated ageing tests) whose duration and cost need to be minimized are required. Taking into account these requirements, in this paper a new method for the estimation of the electrical lifetime of medium and high voltage cables by conducting tests on model cables in high fields and high frequencies is proposed.

2. MODELS FOR LIFETIME ESTIMATION

The lifetime of an insulation system is defined as the time where, under the action of stress factors (electrical, mechanical, thermal, environmental etc.) the value of a property modifies and exceeds a limit value called end of life criteria. In order to estimate the insulations lifetime many methods were defined, based on fast ageing where one or many stress factors are used.

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

- a) Dakin thermal ageing model (Montanari, 2002)

$$D_1 = A_1 \cdot \exp(B_1/T) \quad (1)$$

- b) Electrical ageing models, respectively inverse power law

$$D_2 = A_2 E^{-n} \quad (2)$$

and exponential model

$$D_3 = A_3 \cdot \exp(-B_3 E). \quad (3)$$

- c) Mechanical ageing model

$$D_4 = A_4 \cdot \exp(-B_4 \sigma), \quad (4)$$

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.) (Fallou, 1979) (Cygan, 1990).

In the case of multifactor ageing can be remarked:

- a) *Simoni's Model*

In Simoni's model, the ageing rate R describes the thermal-electrical ageing process. Simoni's expression for the combined ageing rate originates from thermodynamics:

$$R = A \exp\left(-\frac{B}{T}\right) \exp\left(\left(a + \frac{b}{T}\right)f(E)\right) \quad (5)$$

where $f(E)$ is an unspecified function of the electric field E , T is the temperature and, a , b , A and B are material constants. Simoni's model is fashioned after this rate equation. The rate equation expresses

the influence of an electric field on a thermally activated process (thermal ageing). The exact form of this influence is, however, not described.

Simoni suggests that $f(E) = \ln(E/E_0)$, E_0 being a reference gradient below which no electrical ageing takes place. Based on the choice of $f(E)$ Simoni has deduced a life model for thermal-electrical ageing, here called Model 1, which is compatible with the inverse power model for electrical ageing:

$$L(T, E) = L_0 \exp \left(-B\Delta \left(\frac{1}{T} \right) \left(\frac{E}{E_0} \right)^{-N} \right), E \geq E_0 \quad (6)$$

where L_0 is time-to-breakdown at room temperature and $E = E_0$, $N = n - b\Delta(1/T)$, n is a constant, and $\Delta(1/T) = 1/(T - T_0)$.

As an alternative, Simoni has proposed that $f(E) = E - E_0$. The life model based on this alternative (denoted Model 2) is compatible with the exponential model for electrical ageing (see Equation (3)):

$$L \frac{1}{A} \exp \left(\frac{B}{T} \right) \exp \left(- \left(a + \frac{b}{T} \right) (E - E_0) \right), E \geq E_0 \quad (7)$$

Simoni's Model 1 resembles a pure multiplication of the expressions for single electrical and single thermal ageing (Montanari, 2002) (Cygan, 1990).

b) Ramu's Model

Ramu's model is obtained from a multiplication of classic single stress rates. The model accounts for synergy effects by treating the constants of the inverse power law as temperature dependent. Ramu's model is given by Equation (8):

$$L(T, E) = c(T) E^{-n(T)} \exp \left(-B\Delta \left(\frac{1}{T} \right) \right) \quad (8)$$

$$c(T) = \exp \left(c_1 - c_2 \Delta \left(\frac{1}{T} \right) \right), n(T) = n_1 - n_2 \Delta \left(\frac{1}{T} \right)$$

where $c_{1,2}$ and $n_{1,2}$ are constants (Montanari, 2002) (Ramu, 1985).

c) Fallou's Model

Fallou has proposed a semi-empirical ageing model based on the exponential model for electrical ageing:

$$L = \exp\left(A(E) + \frac{B(E)}{T}\right), E > 0 \quad (9)$$

where $A(E) = A_1 + A_2E$, and $B(E) = B_1 + B_2E$ must be determined experimentally from time-to-breakdown curves at constant temperatures (Montanari, 2002).

d) Crine's Model

Crine proposes that the time to cross the energy barrier is the lifetime of the insulation. It is at this point that Crine's approach becomes questionable (Montanari, 2002). Crine says that the time for a single passage of the energy barrier is equal to the mean time of passage that can be described by thermodynamic relations:

$$L = \left(\frac{b}{k_B T}\right) \exp\left(\frac{\Delta G}{k_B T}\right) \csc h\left(\frac{e\lambda E}{k_B T}\right) \quad (10)$$

h being the Planck constant, k_B the Boltzmann constant, ΔG is the free energy of activation, λ is the distance between A and B , and e is the charge of the particle taking part in the ageing process (Montanari, 2002).

It should be noted that if the electric field is zero, Crine's model is not defined. Crine's model is not compatible with single thermal ageing as was the case for Simoni's model. The parameters ΔG and h are functions of temperature and remain unspecified by Crine (Crine, 1990) (Dang, 1996).

3. ELECTRICAL LIFETIME ESTIMATION

In the case of ageing in an electric field of strength E and frequency f , the inverse power law (Equation (2)) can be written as follows:

$$D = AE^{-m} f^{-n} \quad (11)$$

where m and n are material constants (Dang, 1996). The values of m and n are given in (Starr, 1961).

For electrical stresses at nominal fields (equal to those in service) and high frequencies, equation (11) can be written as:

$$D_f = A_f f^{-n} \quad (12)$$

where $A_f = AE^{-m}$ is a material constant dependent on the electric field strength.

Performing tests in an electric field of strength E at three frequencies ($f_{1,2,3}$) and choosing as diagnostic factor the property P , the $P(\tau)$ or $p(\tau) = P(\tau)/P_i$ characteristics for three frequencies can be drawn (τ being the ageing time and P_i the initial value ($\tau = 0$) of P) (Fig.3).

Considering the P_n value as the end of life criteria (respectively $p_n = P_n/P_i$), the $Q_{1,2,3}$ points are obtained, with the coordinates $f_{1,2,3}$ and $\tau_{1,2,3}$, respectively in logarithmic coordinates $Q'_1(\lg f_1, \lg \tau_1)$, $Q'_2(\lg f_2, \lg \tau_2)$, $Q'_3(\lg f_3, \lg \tau_3)$. The $Q'_{1,2,3}$ points are situated on the lifetime line with the equation:

$$y = a + bx \quad (13)$$

where $y = \lg D_f$, $x = \lg f$ and $b = -n$ (Fig. 4).

Using the lifetime line equation, the lifetime of an insulation subjected to an electric field of strength E , at a frequency f , can be determined.

In the present paper the dimensions (length, diameter) of water trees and the breakdown voltage V_{br} were used as diagnosis factors. If the breakdown voltage is used, in (ASTM D-149) is stipulate that a reduction with 50 % of it initial value $V_{br,0}$ (due to some ageing factors) implies the cable replacement (for safety reasons). For this reason, $V_{br,eol} = 0.5 V_{br,0}$ was considered as the end of life criteria. Because the breakdown voltage is direct dependent on the trees length (Notinger, 2005) the maximum length l_{wmax} was used.

For the end of life criteria three values of trees lengths were considered, considering that if the water trees lengths exceed a third of insulations thickness, then the insulations suffer a breakdown (with a probability which depends on these lengths) (Bloom, 2006).

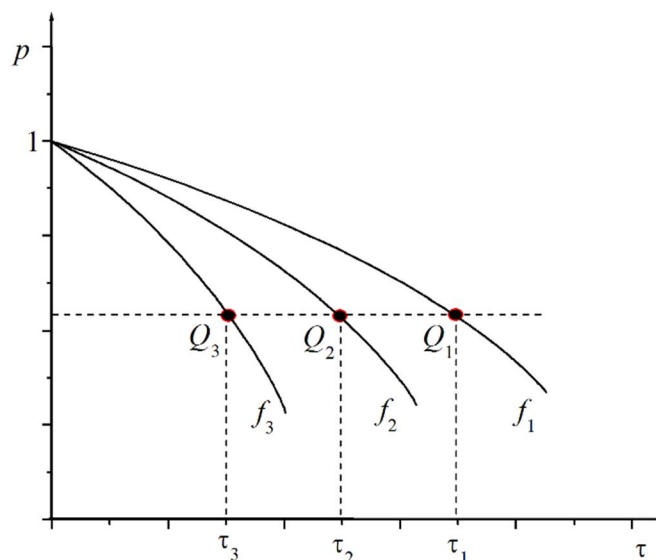


Fig. 3. The variation of property p with ageing time τ .

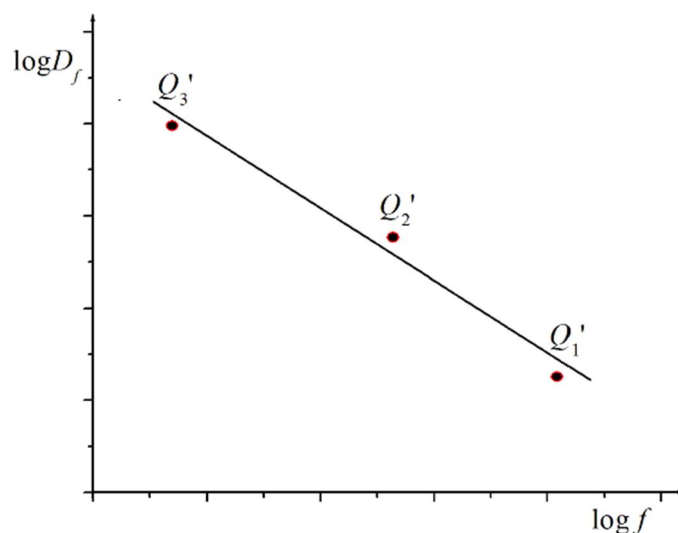


Fig. 4. Lifetime line.

The proposed method in this paper assumes performance of fast ageing in an electric field higher than the maximum value used in operation ($E_{\max}$), respectively the value of the electric field strength in points from the inner semiconductor vicinity.

$$E_{\max} = \frac{U_n}{r_i \cdot \ln \frac{r_e}{r_i}} \quad (14)$$

where U_n is the nominal voltage of cable, r_i – the inner radius and r_e raza – the outer radius of insulation.

The second factor of stress is the frequency of the electric field. For a more reduction of time tests high values of the frequency, respectively $f = 1...3$ kHz are chosen.

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

4. EXPERIMENTS

Tests were performed on samples taken from model cables (having the inner radius of insulation $r_i = 0.55$ mm and outer radius of insulation $r_e = 1.35$ mm) of insulation thickness $g = 0.8$ mm. The length of each sample is $l = 50$ cm. In order to develop water trees, groups of 3 samples were subjected to the simultaneous action of the electric field and water (Fig. 5). On a 1 cm length, the ends of cables were

stripped and introduced in metallic balls in order to avoid the electric discharges which may appear at high voltages. To reduce the inception time of water trees but also the test time, the following methods were used:

- a) Creating superficial defects on the outer surface of cable insulation. For that each sample was covered with abrasive paper type P240 and pressed with a force $F = 1$ tf during 2 minutes;
- b) Using high electric fields of effective values E_t superior to maximum value from operation (calculated with the relation (14)) and high frequencies (1, 2 and 3 kHz). The test voltage values V_t were calculated with the relation:

$$V_t = E_t r_i \ln \frac{r_e}{r_i} \quad (15)$$

After ageing for each sample the breakdown voltage was determined according to (Finnish Electrotechnical Standards Association SFS 5791/1994-10-10 12/20 kV PAS pct. 6.1.4).

After failure, the samples were put into a pot with a solution of Rhodamine and placed in an oven, where they were maintained for 48 h $T = 60$ °C. After this conditioning, from each sample, 5 slices taken and the dimensions (length, diameter) of trees were measured (Stancu, 2010).

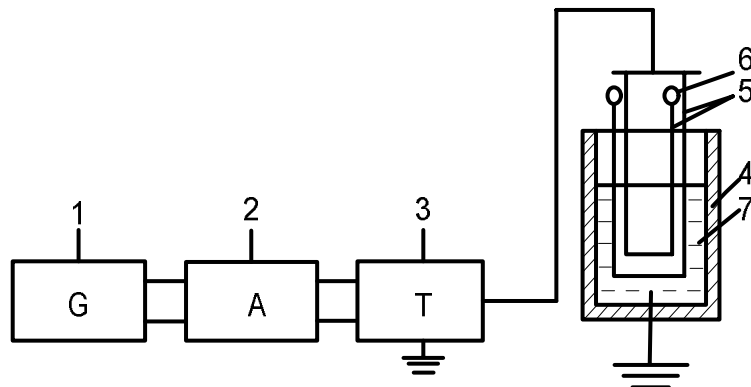


Fig. 5. Setup used for water trees development: 1- Tektronix CFG 253 voltage generator, 2- Amplifier, 3- High frequency transformer, 4- Ageing cell, 5- Samples, 6- Metal balls to avoid discharges, 7- Water/NaCl solution.

5. RESULTS. DISCUSSIONS

In Table 1 the maximum values of trees lengths but also the breakdown voltage obtained for different ageing times for a test voltage $V_t = 5$ kV, which corresponds to a test field $E_t = 4$ MV/m are presented.

It can be seen an increase of maximum length of trees and a reduction of breakdown voltage values with the ageing time and frequency of the electric field.

Table 1. Characteristics of water trees (maximum length l_{wmax} and breakdown voltage V_{br}).

<i>Ageing time</i> [h]	<i>Frequency</i> [kHz]	<i>Maximum length</i> [μm]	<i>Breakdown voltage</i> [kV]
0	-	-	39
72	1	267	23.6
144	1	300	15.9
288	1	450	12.6
48	2	240	22.3
96	2	323	15.9
144	2	375	13.1
24	3	200	25
48	3	300	14.6
72	3	350	12.2

Using the data from Table 1 the variation curves of maximum length of trees l_{wmax} but also the breakdown voltage with the ageing time τ for the three values of frequency: 1, 2 and 3 kHz (Figs. 6 and 7) are drawn. If the maximum length of water trees are chosen as diagnosis factors, the end of life criteria were: ELC1 = 290 μm (36 % from insulation thickness), ELC2 = 400 μm (50 % from insulation thickness) and ELC3 = 440 μm (55 % from insulation thickness) according to (Bloom, 2006). For the breakdown voltage, the end of life criteria was ELC4 = 19 kV (50 % from $V_{br,0}$) according to (ASTM D149).

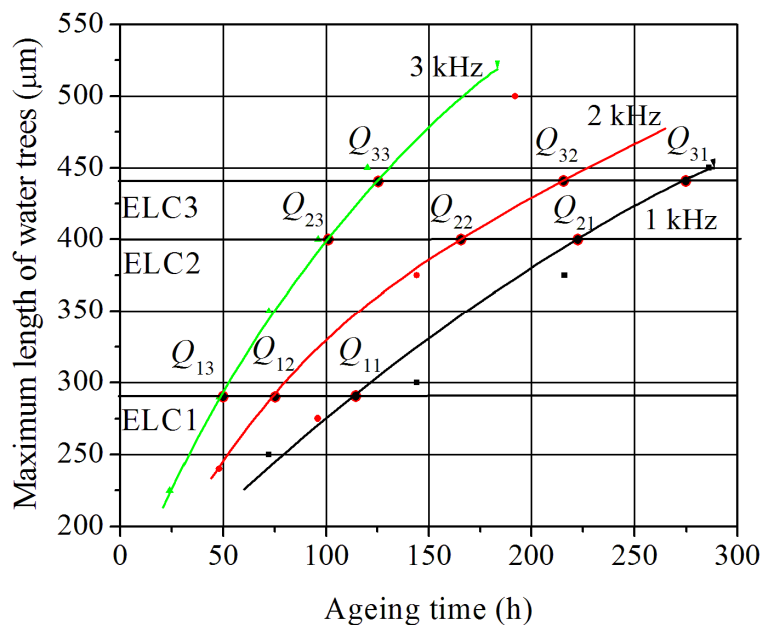


Fig. 6. Variation of maximum length of trees with the ageing time for 1, 2 and 3 kHz.

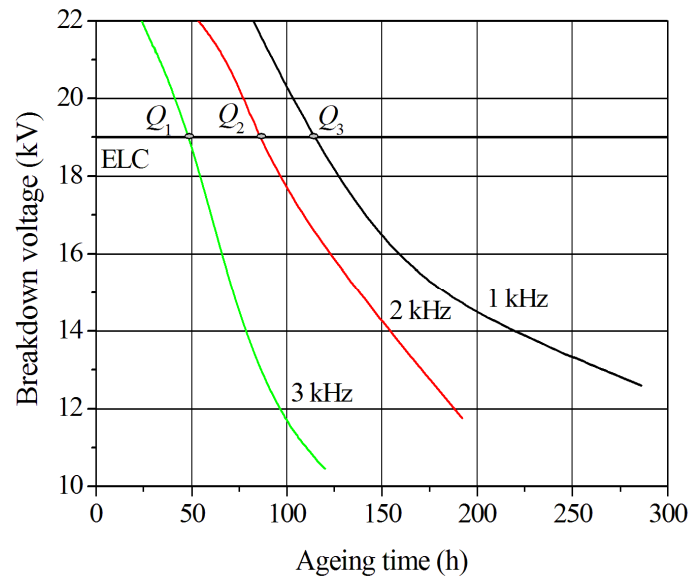


Fig. 7. Variation of breakdown voltage with the ageing time for 1, 2 and 3 kHz.

Using the curves from Figure 6 and the end of life criteria values the points coordinates $Q_{i1,2,3}$ (respectively, $f_{1,2,3}$ and $\tau_{i1,2,3}$) were determined. Then, the logarithmic coordinates of points $Q'_{i1,2,3}$ (respectively, $\log f_{1,2,3}$ and $\log \tau_{i1,2,3}$) but also the coefficients of lifetime lines equations $y = a_i + b_i x$, $i = 1, 2, 3$ (where $x = \lg(f)$ and $y = \lg(D)$) were calculated. The lifetime lines are presented in Figure 8.

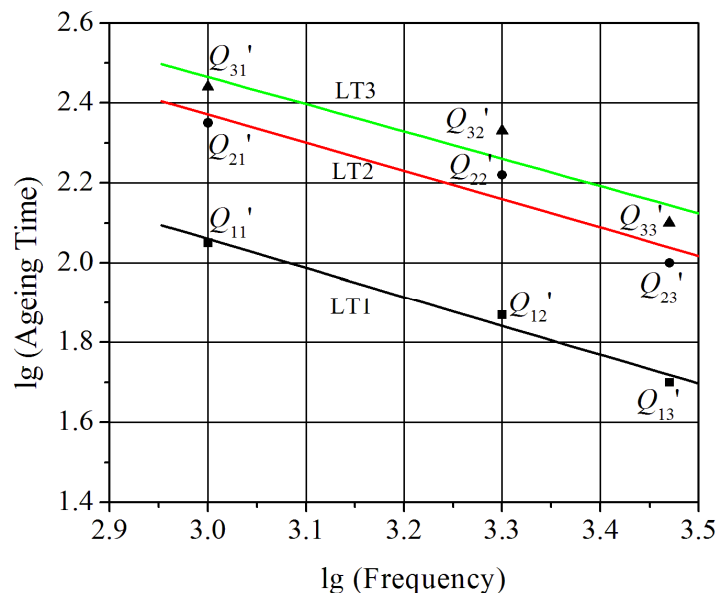


Fig. 8. Lifetime lines for ELC1 = 0.29 mm (LT1), ELC2 = 0.4 mm (LT2) and ELC3 = 0.44 mm (LT3).

Using the $V_{br} = f(\tau)$ curves which corresponds to the end of life criteria $ELC4 = 19$ kV, the points coordinates $Q_1(f_1, \tau_1)$, $Q_2(f_2, \tau_2)$ and $Q_3(f_3, \tau_3)$ were determined and the lifetime line of equation $y = a_i + b_i x$ at logarithmic scale were drawn (Fig. 9).

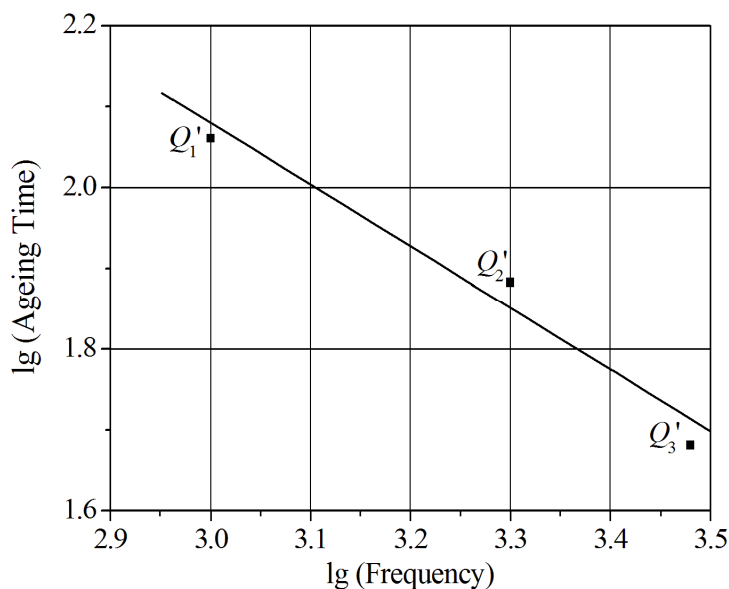


Fig. 9. Lifetime line for $ELC4 = 19$ kV.

Knowing the values of coefficients a_i and b_i the lifetime values for different frequencies (as example, for 50 and 60 Hz) were calculated (Table 2). Analyzing the data presented in Table 2 it can be remarked that, if the lengths of trees are used as diagnosis factor, higher end of life criteria implies higher lifetime.

Table 2. Values of coefficients a_i and b_i and lifetime at 50 (D_{50}) and 60 Hz (D_{60}).

<i>ELC</i>	a_i	b_i	D_{50} [days]	D_{60} [days]
<i>ELC1</i>	4.24	-0.72	43.2	37.2
<i>ELC2</i>	4.49	-0.7	83.2	73
<i>ELC3</i>	4.51	-0.68	94.2	83
<i>ELC4</i>	4.37	- 0.76	48.9	43.4

In order to validate the model used to calculate the lifetime, 3 samples were chosen and subjected to an electric field of intensity $E_t = 4$ kV/mm and frequency $f = 50$ Hz. Samples were subjected to the electric field action in the presence of water until failure. The failure occurred at 49 days after starting the experiment. This value was considered as experimental obtained lifetime.

Comparing the value experimental obtained (49 days) with those obtained with the theoretical model (respectively, 43.2 days – in the case of maximum length of water trees chosen as diagnosis factor (end of life criteria ELC1) and 48.9 days (in the case of breakdown voltage as diagnosis factor) small differences between them can be remarked, which validates the goodness of presented theoretical model.

The obtained experimental lifetime values, but also the ones resulted from the proposed model are very reduced comparative with the lifetimes of underground real cables (30-40 years). This is due, firstly, to material used in experiments: a low density polyethylene recommended for low voltage cables, uncrosslinked and without water trees retardants. But, according to (omnexus) water absorption of low density polyethylene is 0.01 % compared to only 0.005 % for crosslinked polyethylene. On the other hand, the salt content from water used in our experiments (0.1 mol/l) is much higher than the salt content from soil which cables come into contact. According to (Wu, 2008) the salt content from soil varies between 0 and 0.05 mol/l for a slightly saline soil, so half of the one considered in our experiments. It is well known that the development growth rate of water trees increases considerably with the salt content from water which insulation come into contact. A high salt content leads to a fast ageing of tested samples insulations, so it will result a reduced lifetime.

Performing defects of the samples surfaces which come into contact with water a local important increase of the electric field is produced (Stancu, 2009). For this reason, the inception time of water trees are much reduced and the development growth rate are higher in the case of tested samples than in real cables (which not have such defects). Therefore the lifetime values obtained in this paper cannot be extrapolated to real cables. But the proposed method is very useful for cables manufacturers, because allows very quickly informations regarding the water trees resistance of some new materials and comparing the results with those obtained on materials already used in cables manufacturing.

6. CONCLUSIONS

The method proposed in this paper allows the lifetime estimation of new polymeric insulations subjected to electric field action in the presence of water.

The frequency increase of the electric field determines an increase of water trees dimensions and a reduction of the breakdown voltage of polyethylene insulations.

The curves $l_{wtmax} = f(\tau)$ and $V_{br} = f(\tau)$ obtained by fast tests using high frequencies allow determination of insulations lifetime lines but also estimation of its value at normal operating frequency of power cables (50 and 60 Hz).

The ageing tests performed at 50 Hz confirmed the lifetime values obtained using the lifetime lines resulted for short testing times at higher frequencies.

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