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CALCULATION OF THE LIFETIMES OF POWER CABLES POLYMERIC INSULATIONS

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Estimating the lifetimes of energy cable insulations before their commissioning and calculating the consumed lifetimes after a certain period of operation, as well as the remaining lifetimes, are extremely important issues for cable manufacturers and users. This paper proposes a method for calculating insulations lifetimes, taking into account their electrical and thermal stresses, which could be constant and/or variable during their operation. Calculations performed on a single-phase cable insulated with cross-linked polyethylene (XLPE) show that the values of estimated and remaining lifetimes decrease, while those of consumed lifetimes increase with the electric field intensity and operating temperature.

Keywords: power cables, insulation lifetimes, remaining lifetimes

1. Introduction

The use of thermoplastic polymers (low-density polyethylene (LDPE) and high-density polyethylene (HDPE), polyvinyl chloride (1950)) or thermoset polymers (silicone rubbers, Ethylene-Vinyl Acetate (EVA), cross-linked polyethylene (XLPE 1970)) for manufacturing the insulation of power transmission cables, both for alternating current (AC) and direct current (DC), has become predominant in recent years [1]. This is due to their superior manufacturing technology, electrical, mechanical, and environmental resistance characteristics, as well as their relatively long lifetimes (up to 50-80 years [2]). In operation, the insulations are subjected to combined electrical, thermal, mechanical, and environmental stresses. As a result, the insulations undergo various chemical and physical degradation processes which deteriorate their electrical and mechanical characteristics, leading to aging and reduction of their lifetimes. Evidently, the risk of failure is anticipated to increase with service age [3]…[8].

In general, the assessment of conditions and the estimation of cable insulations lifetimes are based on establishing diagnostic factors (tensile elongation at break [9], water trees dimensions [3] [6], breakdown voltage [3], dielectric strength [2], DC conductivity [10], DC resistance [5], loss factor [3] [5] [10],

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accumulated space charge [6] [12], polarization/depolarization currents [4] [11], partial discharge level [13], etc.) and end of life criteria (reduction or increase in the initial value of the parameter chosen as the diagnostic factor) [5]. In [10], it is shown that changes in the values of DC conductivity and the loss factor measured at low frequencies are very sensitive in the case of electrical degradation due to thermal aging. In [6], it is shown that insulations aging can be characterized by the increase in water trees dimensions and their associated space charge. In a study presented in [2] on XLPE insulations of 15 kV cables in service for 4 to 26 years, dielectric strength is used as a diagnostic factor, showing that the probability of a failure occurring in a short time is less than 1% if the dielectric strength value falls below 8 kV/mm. In [14], the maximum length of water trees is considered a diagnostic factor, and a method for estimating the remaining lifetime based on the values of this parameter is proposed. The effects of thermal, mechanical, electrical stresses, radiation and water have been mainly considered, and various models have been established to calculate the estimated lifetimes corresponding to simple and/or combined stresses of the insulations. A presentation of these models can be found in [7] [9] [13] [15] …[19]. It should be noted that the influence of mechanical stresses on their lifetimes is less studied [18], and that numerous studies on the effects of radiation and the environment (especially water) were conducted at the end of the last century [6] [11] [14].

The most used models for estimating the lifetimes of insulations take into account single-factor thermal [7] [18] or electrical [17] stresses and two-factor thermal+electrical stresses [17] [19] [20] [21] [22], and the estimated lifetimes are determined based on accelerated laboratory tests, allowing the estimation of lifetimes generally under constant stresses. As the cable loads in operation and therefore the operating temperatures are variable [8], methods for determining the lifetimes under such stresses are needed [23] [24]. This paper presents such a method, namely the determination of the lifetimes of XLPE cable insulations considering simultaneous constant and variable electrical and thermal stresses. It is shown that the consumed and remaining lifetimes are strongly influenced by the values of the electric field intensity and the insulation temperatures.

2. Lifetimes

2.1. Case of Thermal Stresses

2.1.1. Estimated Lifetime

Considering that the cable insulations in operation function at a constant temperature T and that the rates of thermal degradation phenomena satisfy the Arrhenius equation, the thermal lifetimes of the insulations can be calculated using the equation:

$$L(T) = A\,exp(E_a/kT) \quad (1)$$

where $Le(T)$ represents the estimated lifetime at temperature T (in K), A is a material constant (lifetime for $T \rightarrow \infty$), E_a is the activation energy, and k is the Boltzmann constant [20] [23] [25].

From (1), the lifetime equation is obtained:

$$\ln L_e(T) = a + b/T \quad (2)$$

where $a = \ln A$ and $b = Ea/k$.

If the lifetime value corresponding to the insulation operating at nominal stresses (L_0) is known, the estimated lifetime at temperature T ($Le(T)$) can be calculated using the equation:

$$L_e(T) = L_0 \exp\left[b\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \quad (3)$$

where T_0 is the nominal operating temperature of the insulation [26].

Knowing the values of parameters a and b from (1), the value of L_0 can be calculated as:

$$L_0 = \exp(a).\exp(b/T_0) \quad (4)$$

Thus, to calculate the lifetime corresponding to the insulation operating at any constant temperature T, the values of parameters a and b (or E_a) are needed. To determine these, the three-temperature method (recommended by IEC 60216-1/2001 [27]) or the activation energy method (presented in [28]) can be used.

2.1.2. Consumed and Remaining Lifetimes

2.1.2.1. Operation at Constant Temperature

If a cable has operated for a time interval Δt at a constant temperature T, the consumed lifetime in Δt ($L_c(T)$) is:

$$L_c(T) = \Delta t \quad (5)$$

The remaining lifetime $L_r(T)$ is the difference between the estimated lifetime and the consumed lifetime:

$$L_r(T) = L_e(T) - \Delta t \quad (6)$$

2.1.2.2. Operation at Variable Temperature

If the operating temperature of the insulation varies over time ($T = T(t)$), the quantities L_c and L_r are calculated by numerical integration. The relative consumed lifetime in unit time of the insulation corresponding to the cable operating at nominal temperature T_0 (L_{cr0}) is (from (1)):

$$L_{cr0} = \frac{1}{L_e(T_0)} = \frac{1}{A}\exp(-\frac{b}{T_0}) \quad (7)$$

and the relative consumed lifetime of the insulation in an interval Δt ($L_{cr}(\Delta t)$) is:

$$L_{cr}(\Delta t) = \frac{1}{A}\int_0^{\Delta t} e^{-b/T(t)} dt \tag{8}$$

The consumed lifetime in Δt ($L_c(\Delta t)$) is:

$$L_c(\Delta t) = L_{cr}(\Delta t).\ L_e(T_0) \tag{9}$$

and the remaining lifetime is:

$$L_r(\Delta t) = L_e(T) - L_c(\Delta t) \tag{10}$$

If equation (3) is used for the calculation of L_e, the equation becomes, for $L_{cr}(\Delta t)$:

$$L_{cr}(\Delta t) = \frac{1}{L_0}\int_0^{\Delta t} e^{\frac{b[T(t)-T_0]}{T(t).T_0}} dt \tag{11}$$

The integrals in equations (8) and (11) are calculated using a numerical (approximate) method. For example, the time interval Δt is divided into N equal subintervals $\Delta t_1 = \Delta t/N$, and the areas of the trapezoids determined by the functions $f(t) = \exp(-b/(T(t))$ – for (8) and $f(t) = \exp[b(T(t)-T_0)/(T(t).T_0)]$ – for (11) are summed.

2.2. Case of Electrical Stresses

It is considered that the insulations function at the nominal temperature T_0. According to IEC 61251, for calculating the estimated electrical lifetime, the inverse power law can be used:

$$L_e(E) = C.\ E^{-n} \tag{12}$$

where $L_e(E)$ represents the lifetime corresponding to an electric field intensity of E, while C and n are two material constants [15], [29].

The parameter n is called the voltage endurance coefficient (VEC) and takes values depending on the electric field intensity: between 8 and 15 according to [29] or between 2.5 and 27 according to [17].

For calculating $L_e(E)$, the following relationship is also used:

$$L_e(E) = L_0(E/E_0)^{-n} \tag{13}$$

where L_0 represents the lifetime of insulation under nominal operating conditions (for $T = T_0$ and $E = E_0$) [30], [31], and $n = 7$ for cables with polymer insulation [32].

For a cable with a nominal voltage of $U_f/U_l = 64/110$ (kV/kV) (Fig. 1), its XLPE insulation has an inner radius $R_i = 12.5$ and an outer radius $R_e = 30$ mm, and the activation energy $E_a = 1.24\ldots 1.36$ eV [33], [34]. In the absence of water trees and space charge [35], the electric field at a point with coordinates $r \in [R_i, R_e]$ ($E(r)$) can be determined by the relationship [6]:

$$E(r) = -\frac{U_f}{r \ln \frac{R_i}{R_e}} \quad (14)$$

The values obtained are: $E(R_i) = E_i = 5.85$ MV/m and $E(R_e) = E_e = 2.44$ MV/m.

In the following, under nominal conditions ($E_0 = E_i = 5.85$ MV/m and $T_0 = 90$ ºC), the lifetime of the insulation is considered $L_0 = 40$ years [32].

It should be considered that, after a certain period of operation, a layer of space charge with a thickness l_s, has accumulated in the insulation, which locally modifies the values of E [6], [36]. Calculations presented in [6] show that the emergence of a layer of space charge with a density of 0.106 C/m^3 leads to an increase in E_i by 1.1 times if $l_s = 0.1$ mm and by 1.94 times if $l_s = 1$ mm. The simultaneous presence of a layer of charge with $l_s = 0.35$ mm and a water tree of equal length to l_s results in an increase in the value of E at certain points in the cable insulation of approximately 1.6 times [36].

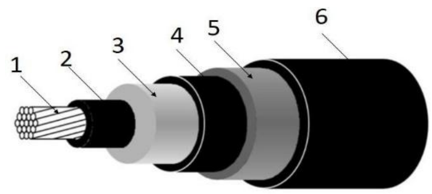

Fig. 1. Extruded power cable: 1 - Conductor; 2 - Inner semiconductor; 3 – Insulation (XLPE); 4 - Outer semiconductor; 5- Metal sheath; 6 - Jacket ("oversheath") [46]

Consequently, the cables lifetimes will be reduced compared to those that would result in the absence of space charge and water trees. On the other hand, the existence of space charge leads to the existence of a residual electric field even after the cable is de-energized [6], [36].

Therefore, if a cable has been in operation for a time interval Δt under voltage U (respectively in the field E), the consumed lifetime is $L_c(E) = \Delta t$, and the remaining lifetime is $L_r(E) = L_e(E) - L_c(E)$. However, if during the interval Δt the cable was de-energized for a period $\Delta t'$, the consumed lifetime $L_c(E)$ is greater than $\Delta t - \Delta t'$, and the remaining lifetime $L_r(E)$ is less than $L_e(E) - \Delta t'$.

2.3. Case of Simultaneous Electrical and Thermal Stresses

2.3.1. Estimated Lifetime

For calculating the estimated lifetime, it is considered that both electrical (E) and thermal (T) stresses act simultaneously and are constant over time. On the other hand, mechanical stresses and environmental effects are neglected, as well as the variation of the parameter n with temperature. Under these conditions, the estimated lifetime $L_e(E,T)$ is calculated using the following relationships:

$$L_e(E,T) = L_0\left(\frac{E}{E_0}\right)^{-n}\exp\left(\frac{b}{T}\right) \tag{15}$$

$$L_e(E,T) = L_0\left(\frac{E}{E_0}\right)^{-n}\exp\left(-b\frac{T-T_0}{T.T_0}\right) \tag{16}$$

The value of L_0 is determined based on the estimated lifetime corresponding to operation under nominal stresses (E_0, T_0), respectively $L_e(E_0, T_0) = L_0 = 40$ years. Furthermore, for calculating the estimated lifetime, only equation (16) is used.

2.3.2. Consumed and Remaining Lifetimes

2.3.2.1. Operation under Constant Stresses

If the cable insulation operates under nominal stresses (E_0, T_0) for a time interval Δt, the consumed lifetime is

$$L_c(E_0, T_0) = \Delta t \tag{17}$$

and the remaining lifetime is:

$$L_r(E_0, T_0) = L_e(E_0, T_0) - \Delta t \tag{18}$$

2.3.2.2. Operation under Variable Stresses

In the case where the cable voltage and load are not constant during the operating interval Δt, the quantities E and T are functions of time, namely $E = E(t)$ and $T = T(t)$. Knowing the values of the applied voltage to the cable in the most stressed areas of the insulation and the temperature for different values of t (i.e., $U_f(t)$) and $T(t)$), the variation curves of E and T in Δt can be plotted.

For calculating the consumed and remaining lifetimes in Δt, the insulation wear under nominal conditions and the insulation wear in the time interval Δt are defined.

a) The relative consumed lifetime per unit time of the insulation (wear) corresponding to the cable operation under nominal conditions (L_{cr0}) is:

$$L_{cr0} = \frac{1}{L_e(E_0, T_0)} = \frac{1}{L_0} \tag{19}$$

b) The relative consumed lifetime in the interval [0, Δt] ($L_{cr}(\Delta t)$) in the case of variable stresses $E_r(t) = E(t)/E_0$ and $T(t)$ is calculated using the following relationships:

$$L_{cr}(\Delta t) = \frac{I(\Delta t)}{L_0} \tag{20}$$

$$I(\Delta t) = \int_0^{\Delta t} f(t)\,\mathrm{d}t \tag{21}$$

$$f(t) = [E_r(t)]^n \exp\left[b\frac{T(t) - T_0}{T(t).T_0}\right] \tag{22}$$

Since the function $f(t)$ is not generally integrable, the calculation of the integral $I(\Delta t)$ (equation (21)) is done through an approximate method. In this regard, the time interval $[0, \Delta t]$ is divided into N equal subintervals of width $\Delta t'$, and in each subinterval i, the function $f(t)$ is approximated by a polynomial of degree 4 (Fig. 2) [24].

The integral I is calculated as the sum of the areas of the N trapezoids determined by the points $P_i(t_i, 0)$, $Q_i(t_{i+1}, 0)$, $R_i\ (t_i, f(t_i))$ and $S_i(t_{i+1}, f(t_{i+1}))$ (Fig. 2), respectively:

$$I(\Delta t) = \sum_{i=1}^{i=N} I(i) \tag{23}$$

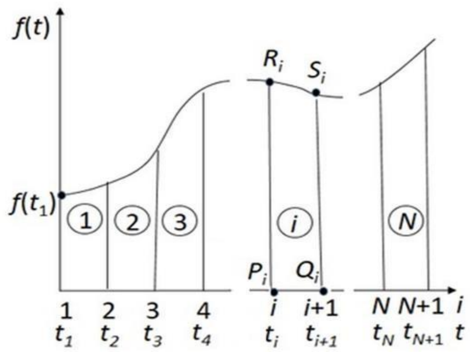

Fig. 2. Regarding the calculation of the integral I [24]

where $I(i) = (f(t_i) + f(t_{i+1})).\ \Delta t'/2$ [6].

The consumed lifetime in $[0,\Delta t]$ ($L_e(E,T)$) is:

$$L_c(\Delta t) = L_0.L_{cr}(\Delta t) \tag{24}$$

and the remaining lifetime is:

$$L_r(\Delta t) = L_0 - L_c(\Delta t) \tag{25}$$

3. Results

The calculation of the lifetime values was performed for the XLPE insulation of the cable presented in Section 2.2, considering the activation energy value $E_a = 1.27$ eV (i.e., $b = E_a/k = 14725$ K) and $n = 7$ [32].

3.1. Estimated Lifetime

Using equation (18), the estimated lifetime $L_e(E,T)$ values were calculated for different values of the electric field intensity E (respectively, the relative field

$E_r = E/E_0$)) and temperature T. Some of the results are presented in Figures 3 and 4.

Fig. 3 shows the variation of the insulation lifetime with the insulation operating temperature for $E_r = 1$ and $E_r = 1.1$. It is observed that an increase in insulation temperature (due to cable overload) results in a considerable reduction in the estimated lifetime values, for any electric field (Fig. 3). For example, if the T rises from 95 to 105°C, the lifetime decreases by approximately three times, results consistent with those presented in [37]. On the other hand, if the insulation operate at temperatures lower than the nominal temperature, the lifetime takes very high values. Thus, for $E = E_0$, L_e is approximately 3.2 times greater when operating at 80°C compared to operating at 90°C, and about 39 times greater when operating at 60°C.

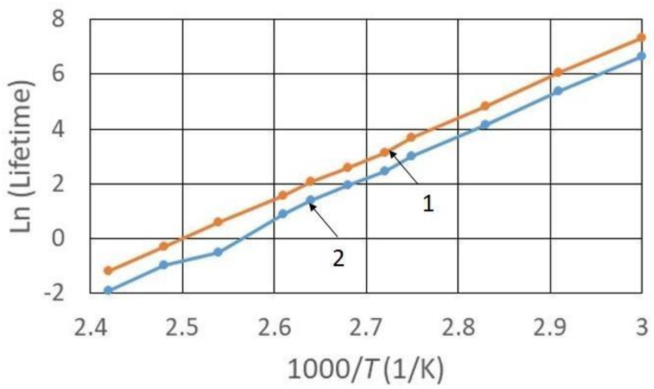

Fig. 3. Variation of the estimated lifetime with temperature T for $E_r = 1$ (1) and $E_r = 1.1$ (2)

The increase in the electric field (as a result of the increase in the applied cable voltage or the separation of the space charge) also leads to a reduction in the lifetime values (Fig. 4). Thus, the lifetime is reduced by approximately 3.5 times if E_r increases from 1 to 1.2, and by 17 times if E_r increases to 1.5. Of course, the presence of these stresses over the entire operating interval is unlikely.

3.2. Consumed and Remaining Lifetimes

For the calculation of consumed and remaining lifetime values, the known values considered were $T_0 = 90$°C, $L_0 = 40$ years, $n = 7$, $b = 14725$ K, T and E_r at different times t within $\Delta t = 24$ hours. As shown in [8], as a result of insulation aging, dielectric losses increase with operating time (with 35% after 30 years). Consequently, for the same cable load at I_n, the maximum temperature in the insulation increases significantly (for a cable of 110 kV and 900 A - from 62°C to 121°C) [8]. Therefore, the temperature variation curves in the interval Δt differ from day to day due to both variable loading and/or changes in the electric field and loss factor (i.e., dielectric losses). Through online measurements, temperature values were determined after each subinterval of $\Delta t' = 1$ hour over two different days, 1

($T_1(t)$) and 2 ($T_2(t)$) (Fig. 5), and for the electric field, two cases were considered: a) $E_r(t) = E_{r0} = 1$ and b) the variation of $E_r(t)$ shown in (Fig. 6).

For the calculation of consumed and remaining lifetimes, it was considered that within each subinterval i ($i = 1,\ldots, 24$) of Δt, $E_r(t)$ varies linearly with t (i.e., $E_{ri}(t) = p_i + q_i t$), and $T(t)$ varies parabolically with t (i.e., $T(t) = r_i + s_i t^2$) (Fig. 7). For any given subinterval i, determined by the times $t_i = i.\ \Delta t'$ and $t_{i+1} = (i+1)\Delta t'$, the parameters p_i, q_i, r_i and s_i were determined based on the values of E_r and T at the extremities of the subinterval, using the relations (26)…(29):

$$p_i = \frac{E_r(t_i)t_{i+1} - E_r(t_{i+1})t_i}{t_{i+1} - t_i} \tag{26}$$

$$q_i = \frac{E_r(t_{i+1}) - E_r(t_i)}{t_{i+1} - t_i} \tag{27}$$

$$r_i = \frac{T(t_{i+1})t_i^2 - T(t_i)t_{i+1}^2}{t_i^2 - t_{i+1}^2} \tag{28}$$

$$s_i = \frac{T(t_i) - T(t_{i+1})}{t_i^2 - t_{i+1}^2} \tag{29}$$

The function $f(t)$ used for the calculation of the integral $I(i)$ from equation (25) can be presented as:

$$f_i(t) = \left(p_i + q_i t\right)^n \exp\left[b\frac{r_i + s_i t^2 - T_0}{T_0\left(r_i + s_i t^2\right)}\right] \tag{30}$$

To reduce the approximation error of the integral $I(i)$, each subinterval i is divided into N_2 subintervals of width $\Delta t'' = \Delta t'/N_2$, forming N_2 curvilinear trapezoids with smaller areas, characterized by the points $P_j(t_j, 0)$, $Q_j(t_{j+1}, 0)$, $R_j\ (t_j, f_i(t_j))$ and $S_j(t_{j+1}, f_i(t_{j+1}))$ (Fig. 8). The area of the curvilinear trapezoid j in subinterval i is:

$$A_{i,j} = (f_i(t_{i,j}) + f_i(t_{i,j+1},)).\ \Delta t'' /2 \tag{31}$$

and $I(i)$ is:

$$I(i) = \sum_{j=1}^{i=N_2} A_{i,j} \tag{32}$$

3.2.1. Variable Temperature and Constant Field

Considering $E_r(\mathrm{t}) = 1$, $t \in [0, \Delta t]$, the consumed lifetime in $\Delta t = 24$ hours (L_c) and the remaining lifetime (L_r) were calculated using the measured temperature values on two distinct days, 1 ($T_1(t)$) and 2 ($T_2(t)$) (Fig. 5). The temperature values are close to the nominal operating temperature (90°C), although under emergency loading, it can reach 130°C [20]. Each subinterval i of Δt ($i = 1,\ldots N_1$) was divided into $N_2 = 10$ subintervals j of width $\Delta t'' = 6$ minutes, and the areas $A_{i,j}$ (equation (31)), the integrals $I(i)$ ($i = 1,\ldots N_1$) (equation (32)), the integral $I(\Delta t)$ (equation (23)), the relative consumed lifetime L_{cr} (Δt) (equation (20)), the consumed lifetime $L_c(\Delta t)$ (equation (24)), and the remaining lifetime (equation (25)) were calculated.

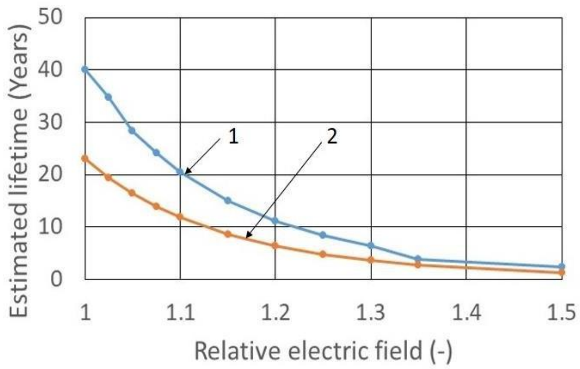

Fig. 4. Variation of the estimated lifetime with the relative electric field intensity E_r for T_1 = 90 ºC (1) and T_2 = 100 ºC (2)

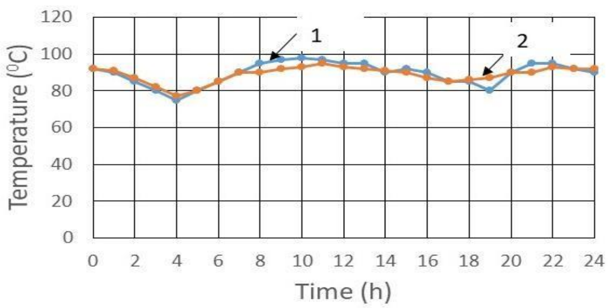

Fig. 5. Time variations of temperature in the days 1 ($T_1(t)$, curve 1) and 2 ($T_2(t)$, curve 2)

The time variations of the consumed lifetime in Δt, for both temperature variation curves ($T_{1,2}(t)$), are presented in Fig. 9 (curves 3 and 4). It can be observed that, in both cases, the values of L_c increase over time. These increases are more significant for T_1 (curve 3) than for T_2 (curve 4), because approximately 63% of the time in [0, Δt], T_1(t) >$T_2(t)$.

If the electrical and thermal stresses are the same every day, then the consumed lifetime in one year would be L_c (year) = 1.14 years for T_1 (14% higher than in the case of operation at the nominal temperature T_0 = 90°C) and only 0.96 years for T_2 (4% lower than in the case of operation at the nominal temperature T_0).

The remaining lifetime after one year of operation at the nominal field E0 would be L_r (year) = 38.86 years for T1 and 39.04 years for T2.

3.2.2. Constant Temperature and Variable Field

In this case, it was considered that the temperature remains constant and equal to the nominal temperature T_0 (90°C), while the electric field varies according to Fig. 6. The time variations of the consumed lifetime in Δt are presented in Fig. 10. It can be observed that the values of L_c increase rapidly over time, and after 24 hours, L_c reaches 42,961 hours, which is approximately 1.79 times higher than that corresponding to nominal stresses (i.e., 24 hours). If the electrical and thermal stresses are the same every day, then the consumed lifetime in one year would be L_c (year) = 1.79 years, which is approximately 75% higher than in the case of operation at the nominal temperature T_0 .The remaining lifetime after one year of operation at the nominal temperature would be L_r (year) = 38.21 years.

3.2.3. Variable Temperature and Variable Field

In this case, it was considered that both the electric field and temperature vary over time in Δt (Fig. 5 and 6). The time variations of the consumed lifetimes are presented in Fig. 9, curves 1 and 2. It can be observed that, at any moment, the values of L_c are higher than those obtained in the case of variable temperatures and constant field E_0, as well as those obtained in the case of constant temperature and variable field. If the electrical and thermal stresses are the same every day, then the consumed lifetime in one year would be L_c (year) = 2.23 years for T_1 (2.23 times higher than in the case of operation at the nominal temperature T_0 = 90°C) and 1.83 years for T_2 (1.83 times higher than in the case of operation at the nominal temperature T_0). The remaining lifetime after one year of operation at the nominal field E_0 would be L_r (years) = 38.86 years for T_1 and 39.04 years for T_2. The estimated lifetime L_0 = 40 years would be reached in 17.9 years for T_1 and 21.9 years for T_2. Therefore, the increase, over certain periods of time, in electrical and thermal stresses beyond nominal stresses, leads to a drastic reduction in the values of remaining lifetimes.

It should be emphasized that for the calculation of all lifetimes, the value of the activation energy E_a was considered constant. However, this decreases due to the consumption of antioxidants [19], [41], leading to a reduction in the estimated and remaining lifetime values and an increase in consumed lifetime. Therefore, based on electrical measurements (absorption- resorption currents [4, 5, 42-43], resistivity, loss factor, etc.) the activation energy in the cable operation process should be evaluated. Under the action of the electric field, electrical trees [44] and water trees [6], [45-46] can develop, which contribute to premature aging and degradation of the polymer insulations of cables. These phenomena should be taken into account by introducing additional factors into the equations for calculating the estimated lifetimes. On the other hand, in the case of cables used in nuclear power plants, the effect of radiation should be taken into account, which contributes not only to the intensification of chemical degradation reactions of insulations, but also to the increase of antioxidant consumption [19],[47]. Therefore, consumed lifetimes increase and remaining lifetimes decrease.

In this paper, a procedure for calculating the remaining lifetime due to variable thermal and electrical stresses has been presented. However, it should be noted that the cable user does not necessarily want to know when a cable has consumed its entire technical lifetime, but rather when the cable needs to be replaced (i.e., "remaining life management"). In this case, besides technical criteria, economic and strategic criteria also intervene [24]. The modifications of these lifetime calculation relations did not take into account the changes in the characteristics of cable insulations due to mechanical stresses (vibrations, etc.) and ambient environment (radiation, oxygen, water, etc.), which accelerate aging processes and increase consumed lifetimes, especially in the case of submarine cables [37-39].

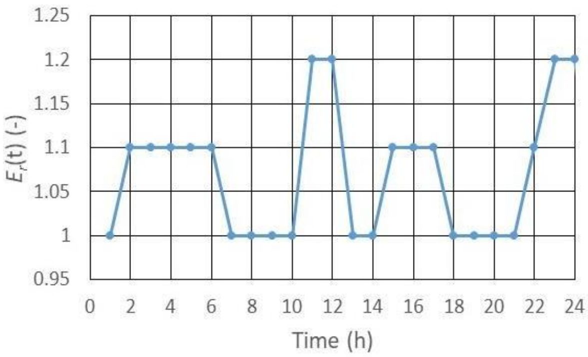

Fig. 6. Time variation of the relative electric field (E_r(t) in the interval: [0, Δt]

Also, the effect of polarity reversal events as electrical transients in addition to thermal transients on the electrothermal lifetimes [40] was not considered. The modifications of these calculation relationships will be presented in a future paper.

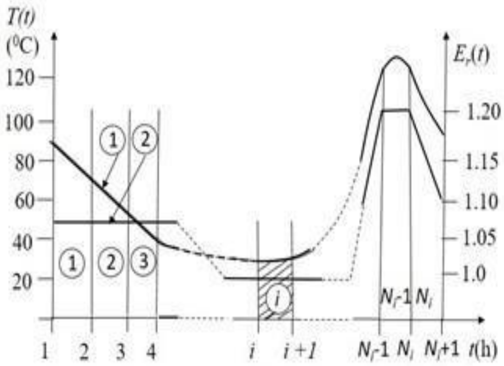

Fig. 7. Regarding the approximation of the functions $T(t)$ (1) and $E_r(t)$ (2) and the calculation of the parameters p_i, q_i, r_i and s_i

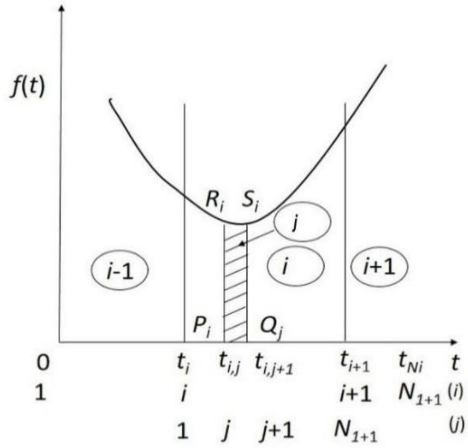

Fig. 8. Regarding the calculation of the integral $I(i)$

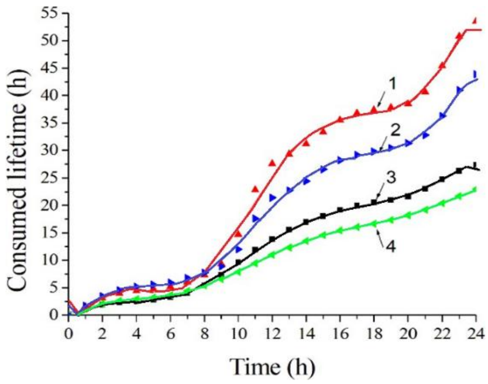

Fig. 9. Time variation of the consumed lifetime (L_c) in the interval Δt = 24 hours for $E_r(t)$ and $T_1(t)$ (curve 1, red), $E_r(t)$ and $T_2(t)$ (curve 2, blue), $E_r(t)$ =1 and $T_1(t)$ (curve 3, black), and $E_r(t)$ =1 and $T_2(t)$ (curve 4, green)

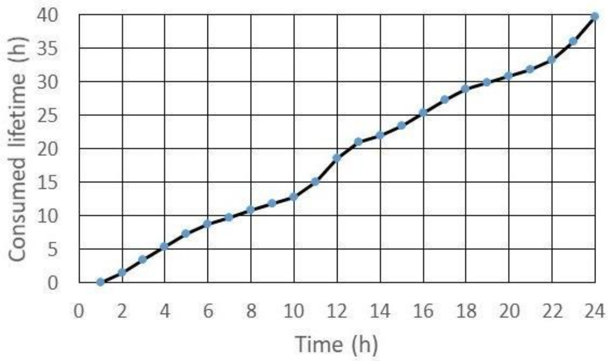

Fig. 10. Time variation of the consumed lifetime (L_c) in the interval Δt = 24 hours for constant temperature (T_0 = 90 °C) and variable field

4. Conclusions

Considering the known estimated lifetime for the operation of energy cables at nominal stresses, this paper presents a method for calculating the estimated lifetimes at thermal and electrical stresses constantly different from nominal ones, as well as the consumed and remaining lifetimes corresponding to variable thermal and electrical stresses over time. Increasing the operating temperature by 5°C above the nominal operating temperature (90°C) results in a reduction of the estimated lifetime from 40 to 23 years, while increasing the electrical stress by 10% above the nominal stress leads to a reduction in the estimated lifetime by approximately 70%.

In the case of lower operating temperatures, the estimated lifetimes of polymer insulations can reach very high values (425 years for T = 70°C). The occurrence of under- and overloads during cable operation leads to time-variable insulation temperatures compared to the nominal temperature. Measuring the temperature values over time allows for a more accurate calculation of the consumed and remaining lifetimes of the insulations, based on which a remaining life management can be established.

Consumed lifetimes increase, and remaining lifetimes decrease compared to the estimated ones with the increase, relative to nominal values, of temperature and electric field intensity. Calculating lifetimes taking into account mechanical stresses and ambient environment will be presented in a future paper.

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