JOURNAL OF SUSTAINABLE ENERGY VOL. 5, NO. 2, JUNE, 2014

UNDERGROUND POWER CABLES MAINTAINABILITY– THE BIODETERIORATION OF EXTERNAL POLYMERIC JACKETS AND ITS INFLUENCE ON INSULATION AGEING

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Abstract – Long time (5 year observation) monitoring results of nine underground power lines (20kV. three-phase. 9 x 3 = 18 cables) are presented. From the experimental data it can be concluded that the cable insulation ageing is a complex process occurring in more successive steps. in which the first and decisive is the external polymeric layer's biodeterioration caused especially by *Aspergillus niger* and *Penicillium funiculosum. A*lso be concluded that cables insulation aging can be prevented by cathodic protection of the cables' metallic screen. and already partially aged insulated cables can be rejuvenate to a limited extent. The obtained results validate the proposed model for the degradation mechanism of the buried cables.

Keywords: power cables. polyethylene biodeterioration, insulation aging, molds, *Aspergillus niger*, *Penicillium funiculosum*.

1. INTRODUCTION

In the perspective of the sustainable development the problem of providing reliable urban utilities, including electric power, is of a particular importance.

The buried power network is exposed to corrosion (metallic parts) and/or to deterioration (nonmetallic parts) [1, 2, 3]. The soil from urban environments is an electrolytic medium characterized by moisture, salinity, acidity, presence of microorganisms, mechanical vibrations (caused by road transport), electromagnetic pollution in DC (produced by trams, subway, etc.) and/or in AC (produced by three-phased power system) [4].

During operation, the underground power cables are exposed to the operating environment's specific stressors (physicochemical and microbiological aggression of soil) and those due to operation (operating voltage, currents etc.). Simultaneous and synergistic action of these factors leads to aging of cable insulation, and their failures in extreme situations.

The safe operation of the power distribution grids is determined primarily by insulation condition of medium voltage (6 – 110kV) underground power cables [3, 5].

Preventing damage is possible through intelligent and preventive diagnostic studies, respectively by remaining life time estimations. An estimation requires knowledge of both the amplitude of degradation and intensity of stress factors at the evaluation date. A correlation between the evolution of functional parameters (such as electrical resistance of cable insulation) and stress factors intensity should be established [6 - 10].

Previously we have studied (in laboratory) the biodeterioration of different polyethylene (PE) sorts used in buried urban grids [10 – 13]. From these studies, it appears that the resistance to mold growth of the PE is limited. Similar results are reported in [14].

The purpose of this paper is to establish the correlations between the factors that determine the aggressiveness of soil and the speed of deterioration process of polymeric jacket and the insulation ageing of 20kV power cables. It is also proposed to set a minimum for soil/metallic screen and metallic screen/conductor wire resistances which ensure a safe operation of cables.

2. EXPERIMENTAL

In order to establish the correlations between environmental factors and the deterioration state of cables on a route (at intervals of cca. 50m) of nine 20 kV buried power lines UPL the resistivity and acidity (pH) of soil at depth of 0.7m were determined). Also soil samples were taken to identify representative species of mold which were present.

The soil samplings were done in sterile vials. Samples were processed working with the methods [15] applied in microbiology, then being periodically observed, analyzed, separated and isolated to identify species.

The investigated UPL cables were monitored by periodic measurements of soil/metallic screen resistance R_{ms-s} (show the deterioration stage of polymeric jacket). metallic screen/conductor wire resistance (show the aging state of the insulation) and of corrosion potential E_{corr} (show the corrosion state of metallic screen).

Soil resistivity – ρ – measurements were made with a special equipment type. MI 2086 EUROTEST 61557 (METREL).

Soil acidity – measurements were made as follows: a sample of soil about 50 g was collected in a glass, over it was added 100 ml water, it was then mixed and after 5 minutes of sedimentation, a pH indicator paper (Merck) was immersed into the sediment solution.

R_{ms-s} and R_{ms-cw} measurements were made at 5 kV, with a FLUKE 1550B megaohmmeter.

E_{corr} measurements were made with Cu/CuSO$_4$ reference electrode and a digital multimeter type HC81.

3. RESULTS AND DISCUSSION

Table 1. shows the nine UPLs and the results of investigations of cable's status since monitoring began.

For the evaluation the annual average rate of cables polymeric jacket degradation k for the time elapsed from cable burial date to initial measurement, it is considered for a new cable the insulation resistance value between screen and soil $R_{0ms\text{-}s}$ has a value in the range 23MΩ ≤ $R_{0ms\text{-}s}$ ≤ 27MΩ – average value $R_{0ms\text{-}s}$ = 25MΩ. With dates from table 1 is calculated k. expressed in MΩ/years (1):

$$k = \frac{R_{0ms-s} - R_{ms-s}}{n} \tag{1}$$

where n is the time of the operation of cable, respectively $n = t - t_0$; t = year of first investigation (2008) and t_0 = year of cable burial. For investigated cables, shown in Table 1., the average calculated values of k are presented in Table 2.

Table 1. The investigated UPL and the results of initial determinations (September 2008)

UPL N^0 Long Burial year	$^*\rho$ [Ω·m]	*pH	**Representative moulds species**	**Phas**	E_{corr} [$V_{Cu/CuSO4}$]			$R_{ms\text{-}s}$ [MΩ]	$R_{ms\text{-}cw}$ [MΩ]	***Remarks***
					End **A**	End **B**	Average			
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
UPL 1. L= 0.4 km 2005	11.1	6.5	*. Aspergillus niger* *Penicillium funiculosum.* *Aspergillus terreus.*	R	–0.098	–0.072	–0.085	1.98	200	Fault on phase T 13.02.2012
				S	–0.133	–0.105	–0.119	3.15	300	
				T	0.065	0.115	0.090	0.21	100	
UPL 2. L= 0.11 km 2002	43.2	6.5	*Scopulariopsis brevicaulis* *Cladosporium sp Aspergillus terreus*	R	0.051	0.081	0.066	0.31	50	
				S	–0.201	–0.103	–0.152	2.97	200	
				T	–0.243	–0.229	–0.236	5.70	300	
UPL 3. L= 0.67 km 2005	9.3	5.4	*Aspergillus niger* *Penicillium funiculosum* *Trichoderma viride*	R	–0.241	–0.265	–0.253	8.00	200	Fault on phase S 11.02.2011
				S	–0.088	–0.102	–0.095	2.00	20	
				T	–0.273	–0.301	–0.287	9.00	200	
UPL 4. L= 0.68 km 2006	21.2	5.9	*Cladosporium sp Aspergillus terreus*	R	–0.353	–0.365	–0.359	19.00	1000	
				S	–0.369	–0.379	–0.374	20.00	1000	
				T	–0.342	–0.350	–0.346	19.00	1000	
OPL 5. L=1.05 km 2006	6.1	6.1	*Scopulariopsis brevicaulis* *Trichoderma viride*	R	–0.413	–0.421	–0.417	19.00	8100	
				S	–0.550	–0.542	–0.546	21.00	9000	
				T	–0.389	–0.401	–0.395	18.00	8000	
UPL 6. L=3.01 km 1985	9.8	5.6	*Trichoderma viride* *Cladosporium sp* *Paecilomyces varioti*	R	0.011	0.025	0.018	0.20	7	Fault on phase R 04.04. 2009
				S	–0.037	–0.025	–0.031	0.50	7	
				T	–0.062	–0.052	–0.067	0.70	10	
UPL 7. L=0.86 km 2001	25.2	5.5	*Scopulariopsis brevicaulis* *Aspergillus terreus* *Paecilomyces varioti*	R	–0.141	–0.117	–0.128	0.78	39.2	Fault on phase S 07.09. 2010
				S	0.029	0.065	0.047	0.31	11.6	
				T	–0.172	–0.142	-0.157	0.85	45	
**UPL 8. L=0.59 km 2000	12.4	5.5	*Paecilomyces varioti* *Trichoderma viride*	R	–0.340	–0.350	–0.345	19	960	With cathodic protection E_c=13.5$V_{Cu/CuSO4}$
				S	–0.298	–0.310	–0.304	14	500	
				T	–0.369	–0.353	–0.361	20	1000	
**UPL 9. L=3.34 km 1984	9.9	5.5	*Cladosporium sp Aspergillus terreus*	R	0.040	0.060	0.050	0.3	13	With cathodic protection E_c=13.5$V_{Cu/CuSO4}$
				S	0.013	–0.009	0.002	0.4	14	
				T	0.070	0.110	0.090	0.2	12	

*Average value of determinations performed along UPL

**After initial determinations. the cables were equipped with corrosion protection (cathodic) according to [21 - 24];

Table 2. Annual average rates of deterioration of polymeric jacket of investigated cables.

UPL Operating time	**UPL 1.** 3 years	**UPL 2.** 6 years	**UPL 3.** 3 years	**UPL 4.** 2 years	**UPL 5.** 2 years	**UPL 6.** 23 years	**UPL 7.** 7 years	**UPL 8.** 8 years	**UPL 9.** 24 years
k [MΩ/year]	7.16	3.66	6.20	2.83	2.83	1.10	3.50	0.90	1.00

By comparing the data from the Table 1. and the Table 2. it appears that:

- for UPL 6. UPL 8 şi UPL 9 average rates of deterioration of jacket are minimal (cca. 1MΩ/year), although chemical aggression of soil is relatively high (approx. pH=5 and soil resistivity cca. 10Ω·m), which suggests that the molds species on the ways of these UPL have a minimal aggressiveness for jackets (*Aspergillus terreus Cladosporium sp. Trichoderma viride* and *Paecilomyces varioti*);
- for UPL1 and UPL 3. the annual average rates of jacket deterioration is maximum (k >6.2MΩ/year), which suggests that aggressiveness of identified molds on the routes of these cables (*Aspergillus niger* and *Penicillium funiculosum*) is maximum for polymers;

- on the routes of UPL2 the chemical aggressiveness of soil is minimal (low resistivity 43.2Ω·m and pH 6.5) and the annual average rate of deterioration of polymeric jacket is medium (k = 3.66 MΩ/year).

These observations suggest that for underground power cables, deterioration of polymeric jackets is determined first of all by representative molds present in the soil. Based on data from Table 1 and Table 2 can be established the hierarchical order of aggressiveness of identified molds for jacket: *Penicillium funiculosum* > *Aspergillus niger* > *Scopulariopsis brevicaulis* > *Cladosporium sp* ≈ *Aspergillus terreus* > *Paecilomyces varioti* ≈ *Trichoderma viride.* This hierarchy is in good agreement with both the data reported by N. Nowak & al. [14] for biodeterioration of polyethylene in laboratory conditions used to make underground pipelines.

The representative evolution during the monitoring of $R_{ms\text{-}s}$ (deterioration state of polymeric jacket), E_{corr} (corrosion state of metallic screen) and $R_{ms\text{-}cw}$ (ageing state of cables insulation) are shown in Figures 1-4.

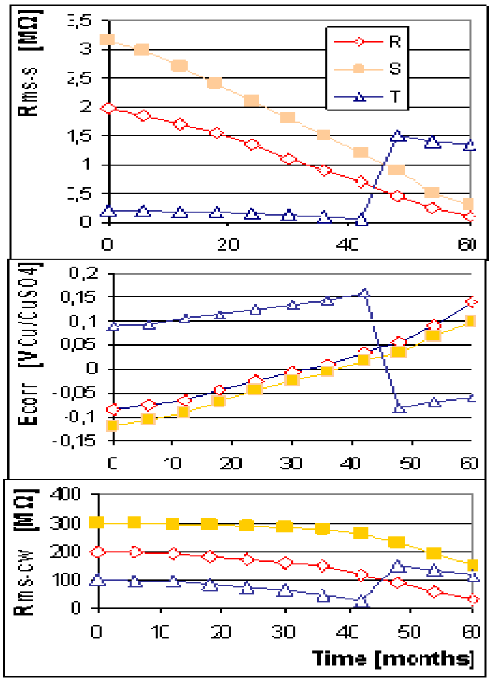

Figure 1. Evolution of $R_{ms\text{-}s}$, E_{corr} and $R_{ms\text{-}cw}$ for the cables from UPL 1. The cable from the phase T were faulted in 13.02.2012

From figure 1 and 2 it is observed that, without cathodic protection [16 – 18], $R_{ms\text{-}s}$. and $R_{ms\text{-}cw}$ of cables decreases continuously and E_{corr} continuously increased to values more electropositive. These evolutions can be explained by the polymeric jacket's deterioration ($R_{ms\text{-}cw}$ decreases), followed by water penetration to metallic screen, corrosion of metal and formation of corrosion products (usually Cu^{2+}).

With good approximation (errors of less than ±1%). descrease of values $R_{ms\text{-}s}$. and $R_{ms\text{-}cw}$ can be described by the second degree polynomial analytical relations. having the general form

$$y = ax^2 + bx + c \tag{2}$$

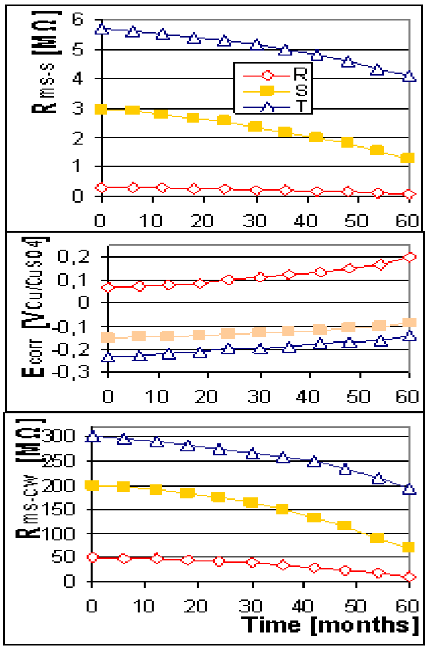

Figure 2. Evolution of $R_{ms\text{-}s}$, E_{corr} and $R_{ms\text{-}cw}$ for cables from UPL 2.

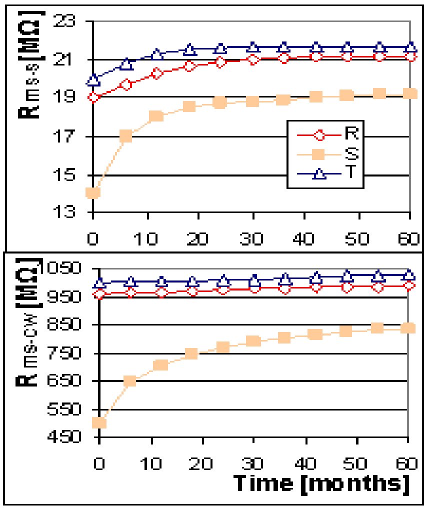

Figure 3. Evolution of $R_{ms\text{-}s}$ and $R_{ms\text{-}cw}$ for cables from UPL 8, equipped with corrosion protection system [16 – 18] (E_c=13.5$V_{Cu/CuSO4}$)

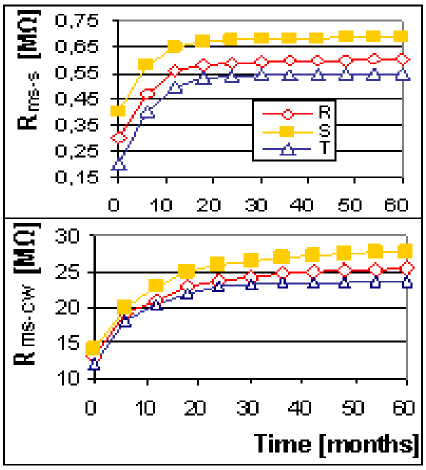

Figure 4. Evolution of $R_{ms\text{-}s}$ and $R_{ms\text{-}cw}$ for cables from UPL 9, equipped with corrosion protection system [16 – 18] (E_c=13.5$V_{Cu/CuSO4}$)

By applying (2) for functions that describe the evolution in time of $R_{\text{ms-s}} = f(t)$ and $R_{\text{ms-cw}} = f(t)$. is obtained by:

$$R_{\text{ms-s}} = a_{pj}\, t^2 + b_{pj}\, t + c_{pj} \qquad (3)$$

$$R_{\text{ms-cw}} = a_i\, t^2 + b_i\, t + c_i \qquad (4)$$

where the coefficients $\boldsymbol{a_{pj}}$ and $\boldsymbol{b_{pj}}$ characterize the evolution of polymer degradation from jacket and $\boldsymbol{c_{pj}}$ initial state (at t=0) of polymer. Similarly, coefficients $\boldsymbol{a_i}$. $\boldsymbol{b_i}$ and $\boldsymbol{c_i}$ characterize cable's insulation (aging of dielectric material).

Table 3 presents the values of analytical equations which describe the evolutions of $R_{\text{ms-s}}$. and $R_{\text{ms-cw}}$ for cables which were not damaged during the monitoring and that without cathodic protection of metallic screen. It notes that the cables with failure, evolution functions being discontinuous and these equations can be calculated separately for periods before and after the occurrence and remedy the defect.

Table 3: Analytical equations for insulation resistances ($R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$) evolutions of cables without cathodic protection and which have not been failed during the monitoring period

UPL	Phase	$y = a_{pj}\, x^2 + b_{pj}\, x + c_{pj}$ $y = R_{\text{ms-s}}$ [MΩ] ; x = time [months]	$y = a_i\, x^2 + b_i x + c_i$ $y = R_{ms\text{-}cw}$ [MΩ] ; x = time [months]
UPL 1	R	$y = -0.0001x^2 - 0.0269x + 1.98$	$y = -0.0513x^2 + 0.2869x + 200$
	S	$y = -0.0001x^2 - 0.0436x + 3.15$	$y = -0.0658x^2 + 1.7467x + 300$
UPL 2	R	$y = -0.00002x^2 - 0.0021x + 0.30$	$y = -0.0095x^2 - 0.0709x + 50$
	S	$y = -0.0002x^2 - 0.0133x + 2.97$	$y = -0.0327x^2 - 0.1956x + 200$
	T	$y = -0.0003x^2 - 0.0092x + 5.70$	$y = -0.0239x^2 - 0.2422x + 300$
UPL 3	R	$y = -0.0004x^2 - 0.0538x + 8.00$	$y = -0.008x^2 - 1.3789x + 200$
	T	$y = -0.0008x^2 - 0.0377x + 9.00$	$y = -0.012x^2 - 0.6808x + 200$
UPL 4	R	$y = -0.0007x^2 - 0.0056x + 19.00$	$y = -0.0116x^2 - 1.3353x + 1000$
	S	$y = -0.0006x^2 - 0.0212x + 20.00$	$y = -0.0112x^2 - 0.7253x + 1000$
	T	$y = -0.0004x^2 - 0.0304x + 19.00$	$y = -0.0118x^2 - 1.7561x + 1000$
UPL 5	R	$y = -0.0001x^2 - 0.0035x + 19.00$	$y = -0.0285x^2 + 0.2332x + 8100$
	S	$y = -0.0002x^2 + 0.0045x + 21.00$	$y = -0.0115x^2 - 0.5366x + 9000$
	T	$y = -0.000x^2 - 0.0011x + 18.00$	$y = -0.0188x^2 - 0.482x + 8000$
UPL 6	S	$y = -0.00008x^2 - 0.0026x + 0.50$	$y = -0.0007x^2 - 0.0295x + 10$
	T	$y = -0.00008x^2 - 0.0013x + 0.70$	$y = -0.0009x^2 - 0.0101x + 10$
UPL 7	R	$y = -0.00008x^2 - 0.0059x + 0.78$	$y = -0.0022x^2 - 0.0221x + 39.2$
	T	$y = -0.0001x^2 - 0.0043x + 0.86$	$y = -0.0028x^2 - 0.0716x + 45.0$

From figure 1 it is observed that excessive aging of cables insulation, respectively $R_{\text{ms-cw}}$ decrease at approx. 5MΩ, which leads to the failure of the cable by breakdown. Similar situations have been recorded on phase S – UPL3, R – UPL6 and S – UPL7. From these experimental dates it is estimated that the limit value of $R_{\text{ms-cw}}$ at which the 20 kV cables are safer in operation is 10 MΩ, below this value the risk of cable failure is high. It is also noted at all recorded defects the value of $R_{\text{ms-s}}$ was relatively small values (between 0.1and 0.5MΩ).

For all faulty cables, after defect correction, $R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$ increased substantially and E_{corr} decreased to values more electronegative. These observations suggest that defects (pores) from polymeric jackets and the treeing from the insulation are not uniformly distributed along the cable – the fatal defects are concentrated in a short distance, where the cable is damaged. Under these conditions, it is noted that in preventive diagnostic studies and the remained life time evaluation relative values (measured values $R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$ related to the length of cable) are not relevant. Absolute (measured) values of $R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$ are relevant (which characterize the most deteriorated / aged portion of cable).

Based on our experimental data it is recommended that in calculations of remained life time estimation, as functional parameter that determine safe operation of cable to be provided $R_{\text{ms-s}} \geq 0.5$MΩ and $R_{\text{ms-cw}} \geq 10$MΩ.

Considering these observations and the mechanism of degradation/aging of cable (figure 5), it is considered that the coefficients $\boldsymbol{a_{pj}}$ and $\boldsymbol{b_{pj}}$ are determined primarily by species of microorganisms from the soil, and $\boldsymbol{a_i}$ and $\boldsymbol{b_i}$ are given by chemical and microbiological aggressiveness of soil that corrode metallic screen, contribute to the formation of $Me^{z+} \cdot n\ H_2O$, which generates electrochemical and electrical trees (conductive channels in dielectric material).

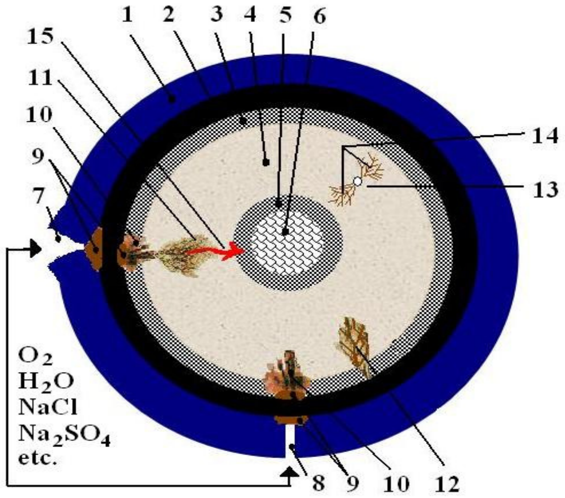

Figure 5. Schematic representation of the structure of monowire underground power cables and the mechanism of their degradation [2]

Notes from the figure 5: 1 – external protective polymeric jacket; 2 – metallic shield usually from copper foil and/or wire; 3 – external semiconducting layer; 4 – cable insulator usually from polyethylene; 5 – internal semiconducting layer; 6 – cable conductor wire; 7 - fault/pore in polymeric jacket formed during operation; 8 – fault/pore in jacket formed during manufacturing or handling; 9 – corrosion products; 10 – electrochemical treeing; 11 – electrical treeing formed on electrochemical trees; 12 – electrical treeing formed on semiconducting layer; 13 – gas bubble in insulation; 14 – electrical treeing formed on gas bubble; 15 – cables fault.

According to the mechanism shown in Figure 5, the main steps of the deterioration process to the failure of the power cables are:

a) - deterioration of external polymeric jacket (which results in decreased isolation resistance between soil and metallic shielding screen) – during burial (scratches, punctures etc.) and/or by the action of soil specific stress factors (chemical and microbiological aggression, trepidations etc.)

b) - through the pores formed in the polymer penetrate aggressive agents (humidity, oxygen, chlorides, sulfates, etc.) from the soil to the metallic screen, and metal *Me* corrode. In the first stage, when pores in the polymer are few and small, and the quantity of water penetrated is limited, metal oxides are formed:

$$2\,Me + z\,H_2O \Rightarrow Me_2O_z + 2\,z\,H^+ + 2\,z\,e^- \tag{5}$$

$$2\,z\,H^+ + 2\,z\,e^- + \tfrac{1}{2}\,z\,O_2 \Rightarrow z\,H_2O \tag{6}$$

Me_2O_z volume is higher than that of *Me* from which the insulation is formed, mechanical tensions are formed between metallic screen and the polymeric jacket. Under the action of the created mechanical tensions the pores/ faults in polymer are opened, humidity access to the metallic screen it is not limited – in the presence of humidity the primary corrosion product converts to hydrated metal ions:

$$Me_2O_z + 2\,z\,H^+ \Rightarrow 2\,Me^{z+} + z\,H_2O \tag{7}$$

$$Me^{z+} + n\,H_2O \Rightarrow Me^{z+}\cdot n\,H_2O \tag{8}$$

c) - hydrated metal ions, especially $Cu^{2+}\cdot nH_2O$, under the influence of operating voltage, form electrochemical trees in dielectric of cable;

d) - the electrochemical trees produce internal mechanical tensions in the dielectric of cable, under the action of mechanical tensions and operating voltage, on electrochemical treeing appears electrical treeing;

e) - the conductive channels of electrical and electrochemical treeing substantially reduce dielectric, of insulation, insulation aging, and in extreme cases due to operating voltage cable break through discharge [1 - 3].

From the analysis of the steps of cable damage process, results that aging process of insulation has two decisive steps:

I - deterioration of polymeric jacket, after which it becomes possible for penetration to metallic screen of humidity and of aggressive agents from the soil;

II - corrosion of metallic screen and formation of corrosion products, which on the one hand accelerates the deterioration of polymeric jacket, and on the other hand initiates electrical treeing and electrochemical treeing and the formation of conductive channels in the cable dielectric (aging of insulation). It is found that, by preventing the formation of corrosion products, insulation aging can be prevented.

To corrosion control of metallic screens from buried power cables an original method for cathodic protection has been deployed, which leads to the thermo dynamical impossibility of the process (5) and (6) [16 – 18]. This method was implemented to cables from UPL 8 and UPL 9 during the initial investigations (September 2008).

$R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$ evolutions of cables with cathodic protection are shown in figure 3 and 4. It is noted that at a cathode potential E_c = 13.5V$_{\text{CU/CuSO4}}$ the values $R_{ms\text{-}s}$ *and* $R_{ms\text{-}cw}$ increase in the first two years, after which tend asymptotically to a limit value. In these conditions in a range of approx. ±3% evolution $R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$ can be described by polynomial functions of the form

$$\boldsymbol{y = ax^4 + bx^3 + cx^2 + dx + e} \tag{9}$$

respectively

$$R_{\text{ms-s}} = a_{pj\_cp}t^4 + b_{pj\_cp}t^3 + c_{pj\_cp}t^2 + d_{pj\_cp}t + e_{pj} \tag{10}$$

$$R_{\text{ms-cw}} = a_{i\_cp}t^4 + b_{i\_cp}t^3 + c_{i\_cp}t^2 + d_{i\_cp}t + e_j \tag{11}$$

where coefficients $a_{\text{pj\_cp}}$. $b_{\text{pj\_cp}}$. $c_{\text{pj\_cp}}$ and $d_{\text{pj\_cp}}$ characterize the evolution of insulation from polymeric jacket and e_{pj} initially state (at $t = 0$ – date of carrying in operation of cathodic protection system) of polymeric jacket. Similarly, the coefficients $a_{\text{i\_cp}}$, $b_{\text{i\_cp}}$ $c_{\text{i\_cp}}$ and $d_{\text{pi\_cp}}$ characterize the evolution of protected cable insulation ("rejuvenating" the dielectric material) and e_{j} the initial state (at t=0) of insulation. Analytical equations that describe evolutions $R_{ms\text{-}s}$ *and* $R_{ms\text{-}cw}$ of cathodically protected cables are shown in Table 4.

Table 4.: **Analytical equations for insulation resistances ($R_{\text{ms-s}}$ and $R_{\text{ms-cw}}$) evolutions of cables with cathidic protection**

UPL	Phase	$\boldsymbol{y = a_{pj\_cp}\,x^4 + b_{pj\_cp}\,x^3 + c_{pj\_cp}\,x^2 + d_{pj\_cp}\,x + e_{pj}}$ $y = \boldsymbol{R}_{\textbf{ms-s}}$ [MΩ] ; x = time [months]	$\boldsymbol{y = a_{i\_cp}\,x^4 + b_{i\_cp}\,x^3 + c_{i\_cp}\,x^2 + d_{i\_cp}\,x + e_i}$ $y = \boldsymbol{R_{ms\text{-}cw}}$ [MΩ] ; x = time [months]
UPL 8	R	$y = -9\cdot10^{-8}x^4 + 3\cdot10^{-5}x^3 - 3.4\cdot10^{-3}x^2 + 0.1432x + 19$	$y = 8\cdot10^{-6}x^4 - 1.1\cdot10^{-3}x^3 + 0.046x^2 + 0.051x + 960$
	S	$y = -3\cdot10^{-6}x^4 + 5\cdot10^{-4}x^3 - 2.55\cdot10^{-2}x^2 + 0.572x + 14$	$y = -1\cdot10^{-4}x^4 + 1.92\cdot10^{-2}x^3 - 1.0539x^2 + 27.132x + 500$
	T	$y = -6\cdot10^{-7}x^4 + 1\cdot10^{-4}x^3 - 6.4\cdot10^{-3}x^2 + 0.1686x + 20$	$y = -6\cdot10^{-6}x^4 + 7\cdot10^{-4}x^3 - 1.75\cdot10^{-2}x^2 + 0.4217x + 1000$
UPL 9	R	$y = -2\cdot10^{-7}x^4 + 3\cdot10^{-5}x^3 - 1.6\cdot10^{-3}x^2 + 3.58\cdot10^{-2}x + 0.30$	$y = -5\cdot10^{-6}x^4 + 7\cdot10^{-4}x^3 - 4.13\cdot10^{-2}x^2 + 1.0827x + 13$
	S	$y = -2\cdot10^{-7}x^4 + 3\cdot10^{-5}x^3 - 1.6\cdot10^{-3}x^2 + 3.58\cdot10^{-2}x + 0.40$	$y = -4\cdot10^{-6}x^4 + 7\cdot10^{-4}x^3 - 4.25\cdot10^{-2}x^2 + 1.1683x + 14$
	T	$y = -2\cdot10^{-7}x^4 + 3\cdot10^{-5}x^3 - 1.8\cdot10^{-3}x^2 + 4.2\cdot10^{-2}\mathrm{x} + 0.20$	$y = -5\cdot10^{-6}x^4 + 8\cdot10^{-4}x^3 - 4.43\cdot10^{-2}x^2 + 1.1403x + 12$

It is interesting to note that for UPL 9, the deterioration of polymeric jacket was very advanced (0.2 < Rms-s > 0.4MΩ), practically below the safe operating limit of the cables. Yet by cathodic protection of metallic screens, $R_{\text{ms-s}}$ increase significantly (in 2 years over 0.55 MΩ – in the area of safe operation of the cable). This observation suggests that following cathodic protection a significant part of pores/defects of polymer were hermetically sealed with a dielectric material, which can be explained by the formation of alkaline earth carbonates ($CaCO_3$, $MgCO_3$)

insoluble and dielectrics with relative permittivity less than 10. In these conditions the rejuvenation of insulation is limited and determined by coefficients $\boldsymbol{a}_{i\_cp}$, $\boldsymbol{b}_{i\_cp}$, $\boldsymbol{c}_{i\_cp}$ and $\boldsymbol{d}_{i\_cp}$ which depend on the state of aging of the cable at the date of application of cathodic protection (size of electrochemical trees and the carbonation degree of electrochemical and electrical trees due to partial discharges [16. 18]).

4. CONCLUSION

After processing and interpretation of acquired experimental data on soil characteristics (resistivity, pH and representative molds) on the route of nine UPL and monitoring for five years of evolutions in the state of deterioration of cables insulation (in total 9 x 3 = 27 cables) it was found that:

- aging of cable insulation is a complex process which is due to several stress factors. which influence each other and act synergistically;
- insulation aging mechanism is carried out through several successive stages, the determining step being microbiological deterioration of polymeric jacket's;
- the aggressiveness of representative mold species identified in the soil from UPL routes is: *Penicillium funiculosum* > *Aspergillus niger* > *Scopulariopsis brevicaulis* > *Cladosporium sp* ≈ *Aspergillus terreus* > *Paecilomyces varioti* ≈ *Trichoderma viride*;
- corrosion of metallic screen's takes place only after deterioration of polymeric jacket's, corrosion products formed lead as to accelerate the process of deterioration of polymeric jacket's, as well as the formation of electrochemical trees - followed by growth of electrical trees, which makes the insulation resistance of the cables to fall (insulation is aging);
- electro insulating block of pores/defects from polymeric jackets and metallic screen's corrosion prevent can be achieved by cathodic protection of metallic screen's;
- by cathodic protection of metallic screen's degree of aging of the insulation decreases (increase the insulation between metallic screen and conductor wire of cables, increase being significant in the first two years of protection when tend asymptotically to a maximum value given by the state of the insulation from the date of service of the cathodic protection system) - insulation "rejuvenates";

The analysis of cable failure conditions without cathodic protection establish that the safe operation of the cables can be provided only at $R_{\text{ms-s}} \geq 0.5\text{M}\Omega$ and $R_{\text{ms-cw}} \geq 10\text{M}\Omega$ - values characterizing the end of the life of the cable.

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