

Monitoring Results of Polyethylene Insulation Degradability from Soil Buried Power Cables

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*Results from a 5-year observation of 27 cables of nine underground three-phase 20 kV power lines are presented. An analysis of the evolution in time for soil / metallic screen resistance (R_{ms}), the resistance between metallic screen and central conductor wire (R_{ms-cw}) and corrosion potential (E_{corr}^{ms}) was made. From the experimental data it was noticed that the degradation of the whole insulation for a cable is a complex process occurring in successive steps, in which the first and decisive step is the biodeterioration of external polyethylene layer. The aggressive molds were *Penicillium funiculosum* and *Aspergillus niger*, whereas *Paecilomyces varioti* and *Trichoderma viride* were the least aggressive. Both deterioration and ageing of polymeric insulation was prevented by cathodic protection against corrosion of the cable metallic screen. Moreover, an aged insulation can be rejuvenated in a limited extent using this protection.*

Keywords: power cables, polymer biodeterioration, insulation aging, molds, polyethylene

In the perspective of the sustainable development and of creating long term acceptable conditions of work and life in a clean and healthy environment the problem of providing reliable urban utilities, including electric power, is of a particular importance. The underground power network is exposed to corrosion (metal parts) and/or to deterioration (nonmetallic parts) [1-4]. The study of corrosion and deterioration of such urban utility is a complex problem with important practical, economical, ecological and social implications. The complexity of the problem results both from the constructive multiplicity and diversity of buried network as well as from the great diversity of soil characteristics. The soil from urban environments is an electrolytic medium characterised by moisture, salinity, acidity (an example is hydrochloric acid formed by decomposition of polyvinyl chloride parts), 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) [5]. It is noted that degradation of polyethylene insulation from power cable can be amplified by possible galvanic and electrical interactions between various underground networks and pipes [6,7].

The safe operation life of the power distribution system is determined primarily by ageing of electrical insulation and on long term integrity of underground power cables of medium voltage (6–100 kV) [8-10]. The buried power cables are exposed to the environment parameters (physico-chemical and microbiological aggression of soil) and those due to operation (operating voltage, currents). The simultaneous and synergistic action of these parameters leads to aging of cable insulation and even its failures in extreme situations. Obviously, estimated duration of safe operation of power cables is determined by the rate of their aging [11].

Preventing damage is possible through intelligent and preventive diagnostic studies, followed by estimation of remaining life time. 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 [12–17]; this is determined by the mechanism of cable degradation. It was shown that electrical treeing is among the main step of mechanisms responsible for electric breakdown in polymeric high voltage cables [16]. Space charge accumulation within polymeric materials has been also associated with their accelerated ageing [17].

Previously we have proposed a model of the deterioration process of power cables exposed simultaneously to operating factors and soil specific environmental factors [1,3,4]. The model shown in figure 1 was validated through several case studies and laboratory tests [1–4, 18-20].

According to our proposed mechanism of soil aggressiveness, the process starts with deterioration of external polymeric jacket leading to the decrease of isolation electrical resistance between soil and metallic shielding screen. Next, the aggressive agents (humidity, oxygen, chlorides, sulfates, etc.) from the soil migrate within pores formed in the polymer, and reaching to metallic screen the metal is corroded. Because the volume of corrosion products (hydrated metal oxides and $\text{Cu}^{2+} \cdot n\text{H}_2\text{O}$ hydrated ionic species, mainly) is higher than of metal from which are formed, mechanical stress occurs between metallic screen and the polymeric jacket and an amplification of the increase of products is recorded. Under the influence of operating voltage, especially $\text{Cu}^{2+} \cdot n\text{H}_2\text{O}$ hydrated ionic species have produced tree-like structures in the dielectric of cable which constitutes electrical tree-like circuits. These substantially reduce dielectric performances of insulation made usually from polyethylene, leading to its aging, and in extreme cases the cable breaks through short-circuit [21-24].

Biodegradability of polyethylene has been studied extensively earlier [25-42]. Polyethylene is one of the synthetic polymers of high hydrophobic level and high

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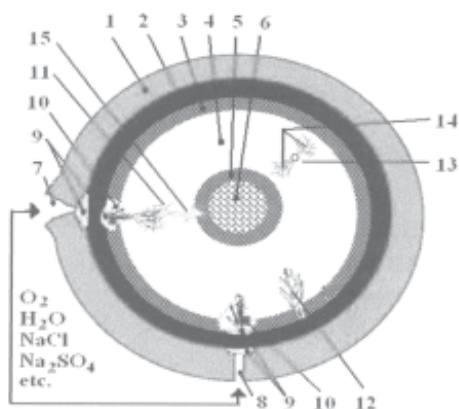


Fig. 1. Schematic representation [16] of the structure of a buried monowire power cable: 1- external protective polymeric jacket; 2- metallic shield usually made from copper foil or wire texture (screen); 3- external semiconducting layer; 4- cable insulator usually made from polyethylene; 5- internal semiconducting layer; 6- conductor wire; 7,8- defects/pores in polymeric jacket formed during manufacturing, handling or operation as channels for penetration of chemical species (some examples were shown); 9- corrosion products; 10- electrochemical tree-like structure; 11- electrical treeing formed on electrochemical tree; 12- arborescent electrical tree inside semiconductor layer; 13- a gas bubble inside; 14- arborescent electrical structure formed near gas bubble; 15- cable short-circuit

molecular weight which is widely used. With such a large amount of polyethylene accumulated in the environment, generating plastic waste ecological problems, are needed thousands of years to an efficient degradation [38]. However, some conditions in soil make the material hydrophilic and therefore, microorganisms can easily access, attack and deteriorate the external part of buried cables. Thus, the polyethylene can undergo physical, chemical or biological degradation, or combination of all these [32]. Physical and chemical degradations facilitate microbial degradation and the complete mineralisation of the polymer happens due to biodegradation, which is generally the final step. It seems that even hydrophobic nature of polyethylene resulted from carbon-only backbone is not a hindrance during biodegradation, since fungi, due to their ability to form hydrophobic proteins, can easily attack the polymer surface [43]. The polymer is a carbon and energy source for soil microorganisms such as fungi, bacteria and actinomycetes (Gram-positive bacteria). Fungi survive environments with low nutrient availability, low pH and low moisture as well [44,45].

During the laboratory experiments filamentous fungi as *Aspergillus niger*, *Aspergillus terreus*, *Aureobasidium pullulans*, *Paecilomyces varioti*, *Penicillium funiculosum*, *Penicillium ochrochloron*, *Scopulariopsis brevicaulis*, *Trichoderma viride* and their mixtures were employed for the biodegradation [43]. As results, significant changes in the basic chemical structure of the polymer such as cross-linking, chain scission and formation of functional groups (e.g., unsaturation, hydroxyl, carbonyl and hydroperoxides) were observed. These chemical reactions may be due to biological organisms which produce corrosive chemical substance.

The action of water is another source of degradation and ageing; Massey et al. [9] proposed a mechanism of degradation of polyethylene that suggest that there is no chain scission during hydrolytic degradation of the material. Using XPS technique, the evidence that an oxidation occurs was demonstrated for all low density polyethylene samples by formation of C-O and C=O groups. On the whole, the degradation process of polyethylene insulation has two decisive steps: (i) deterioration of outer polymeric jacket, after which it becomes possible the penetration to metallic screen of humidity and aggressive agents from the soil; (ii) corrosion of metallic screen and formation of corrosion products, which accelerate the deterioration of polymeric jacket or dielectric insulation. Obviously, by preventing the formation of corrosion products, insulation aging can be prevented. To control corrosion of metallic screens of underground power cables an original method for cathodic protection has been employed, which leads to the thermodynamical impossibility of corrosion [46-48].

The present paper identifies a host of possible situations in which a buried three-phase power line may be subject to external degradation and ageing. These situations are discussed in detail, with establishing the correlations between the aggressiveness of soil and the deterioration rate of polymeric jacket, as well as ageing of the dielectric insulation used for 20 kV buried power cables. Suggestions are given on how to identify underground damages without excavating large sections of cable, to mitigate existing conditions of degradation of polyethylene insulations for soil/metallic screen and for metallic screen/conductor wire interfaces, and to ensure a safe operation of cables.

Experimental part

In order to establish correlations between environmental factors and the state of deterioration of cables on routes of nine 20 kV underground power lines (UPLs) both electrical resistivity and acidity (pH) of soil in 0.6-0.7 m depth were determined. Also, soil sampling from the ends of each UPL was done to identify representative species of microorganisms which were present in soil. The samples were collected in sterile vials and were incubated in conditions applied in microbiology [49]; then they were periodically observed, analyzed, separated and isolated to identify species. Filamentous fungi *Aspergillus niger*, *Aspergillus terreus*, *Paecilomyces varioti*, *Penicillium funiculosum*, *Scopulariopsis brevicaulis*, *Trichoderma viride* and *Cladosporium sp.* were identified as microorganisms involved in biodegradation.

Soil resistivity was measured with a MI 2086 EUROTTEST 61557 (METREL) equipment. In order to measure the soil pH a sample of about 50 g was collected in a glass beaker and mixed with 100 mL water; after 5 min. of sedimentation, a pH indicator paper (Merck) was immersed. The resistivity and acidity of soil were measured both at the ends of the cable and at every 50-100 m along the route of UPL.

The investigated UPL cables were monitored for 5 years using periodic measurements of soil / metallic screen resistance, denoted R_{ms-s}^{ms-s} (this characterizes the deterioration stage of outer polymeric jacket). In the same manner, the electrical resistance between metallic screen and central conductor wire, R_{ms-cw}^{ms-cw} (which characterizes the aging of dielectric insulation) as well as the corrosion potential, E_{corr}^{corr} (which characterizes corrosion state of metallic screen) were determined periodically.

Measurements of R_{ms-s}^{ms-s} , R_{ms-cw}^{ms-cw} and E_{corr}^{corr} were carried out of about 6 in 6 months for cables out of service and screens disconnected from grounded plugs [50,51]. R_{ms-s}^{ms-s} and R_{ms-cw}^{ms-cw} measurements were made in DC voltage at 5 kV with a FLUKE 1550B megaohmmeter. E_{corr}^{corr} measurements were made with Cu/CuSO₄ specialized reference electrode using a digital multimeter type HC 81.

Table 1
SOIL CHARACTERISTICS (RESISTIVITY, ACIDITY, MOULDS PRESENCE) AND ELECTRICAL PARAMETERS OF THREE-PHASE POWER LINES MEASURED AT INITIAL TIME OF INVESTIGATION. REMARKS REGARDING FAILURE AND TOTAL PERIOD OF OPERATION ARE PRESENTED IN THE LAST COLUMN

UPL No. and length of cable	Electrical resistivity of soil* [$\Omega\cdot m$]	pH*	Representative moulds species in soil	Time elapsed from cable burial to initial measurement	Phase inside the UPL cable	Initial E_{corr} value [$mV_{Cu/CuSO_4}$]			R_{ms-s} [$M\Omega$]	R_{ms-cw} [$M\Omega$]	Remarks about failure of cable
						End A	End B	Average			
UPL 1 0.4 km	11.1	6.5	<i>Aspergillus niger</i> , <i>Penicillium funiculosus</i> , <i>Aspergillus terreus</i>	3 years	R	-98	-72	-85	1.98	200	Short-circuit on phase T after 6 years of operation
					S	-133	-105	-119	3.15	300	
					T	+65	+115	+90	0.21	100	
UPL 2 0.11 km	43.2	6.5	<i>Scopulariopsis brevicaulis</i> , <i>Cladosporium</i> sp., <i>Aspergillus terreus</i>	6 years	R	+51	+81	+66	0.31	50	
					S	-201	-103	-152	2.97	200	
					T	-243	-229	-236	5.70	300	
UPL 3 0.67 km	9.3	5.4	<i>Aspergillus niger</i> , <i>Penicillium funiculosus</i> , <i>Trichoderma viride</i>	3 years	R	-241	-265	-253	8.00	200	Short-circuit on phase S after 5 years of operation
					S	-88	-102	-95	2.00	20	
					T	-273	-301	-287	9.00	200	
UPL 4 0.68 km	21.2	5.9	<i>Cladosporium</i> sp., <i>Aspergillus terreus</i>	2 years	R	-353	-365	-359	19.00	1000	
					S	-369	-379	-374	20.00	1000	
					T	-342	-350	-346	19.00	1000	
UPL 5 1.05 km	6.1	6.1	<i>Scopulariopsis brevicaulis</i> , <i>Trichoderma viride</i>	2 years	R	-413	-421	-417	19.00	8100	
					S	-550	-542	-546	21.00	9000	
					T	-389	-401	-395	18.00	8000	
UPL 6 3.01 km	9.8	5.6	<i>Trichoderma viride</i> , <i>Cladosporium</i> sp., <i>Paecilomyces varioti</i>	23 years	R	+11	+25	+18	0.20	7	Short-circuit on phase R after 24 years
					S	-37	-25	-31	0.50	7	
					T	-62	-52	-57	0.70	10	
UPL 7 0.86 km	25.2	5.5	<i>Scopulariopsis brevicaulis</i> , <i>Aspergillus terreus</i> , <i>Paecilomyces varioti</i>	7 years	R	-141	-117	-129	0.78	39.2	Short-circuit on phase S after 9 years
					S	+29	+65	+47	0.31	11.6	
					T	-172	-142	-157	0.85	45	
UPL 8 0.59 km **	12.4	5.5	<i>Paecilomyces varioti</i> , <i>Trichoderma viride</i>	8 years	R	-340	-350	-345	19	960	Very good behavior in 12 years due to cathodic protection in the last 4 years
					S	-298	-310	-304	14	500	
					T	-369	-353	-361	20	1000	
UPL 9 3.34 km **	9.9	5.5	<i>Cladosporium</i> sp., <i>Aspergillus terreus</i>	24 years	R	+40	+60	+50	0.3	13	Very good behavior in 28 years due to cathodic protection in the last 4 years
					S	+13	-9	+2	0.4	14	
					T	+70	+110	+90	0.2	12	

*Average values at determinations performed in soil along each UPL line.

**After initial determination, the cables were equipped for 5 years with a corrosion protection system ($E_c=13.5 V_{Cu/CuSO_4}$ cathodic polarization) according to ref. [46,47].

Results and discussions

Durability and long term integrity are of great importance for power lines network, and the main purpose of this work has been to increase the knowledge of factors controlling the endurance of the external jacket and dielectric insulation, both made usually from polyethylene. In order to evaluate lifetime of underground power cables, respectively establishing the kinetics of degradation and electrical tree initiation due to insulation aging, there were monitored evolutions in time for insulation resistance between soil and metallic screen, and between screen and central copper conductor, for 27 cables (related from 9 UPLs). In the following we present the results concerning

the modifications of structural and dielectric properties of polyethylene insulation of medium voltage cables (20 kV) subject to ageing and deterioration, according to the aggressivity of soil and on the trail laying.

Table 1 shows the characteristics of all three-phase power lines (UPLs) and the electrochemical / electrical results for each phase (denoted as R, S or T) of power line at the time when it began monitoring. During monitoring, we noticed that the decrease of R_{ms-s} ohmic resistance characterizes the deterioration state of the external polymeric (polyethylene) jacket, while the decrease of R_{ms-cw} resistance is related to the aging of polyethylene dielectric insulation. Also, the evolution in time of corrosion

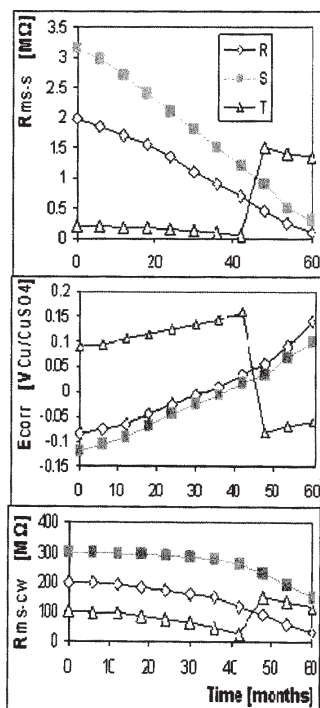


Fig. 2. The evolution of R_{ms-s} , E_{corr} and R_{ms-cw} parameters for cables from UPL 1. The phase T was short-circuited after 6 years of operation

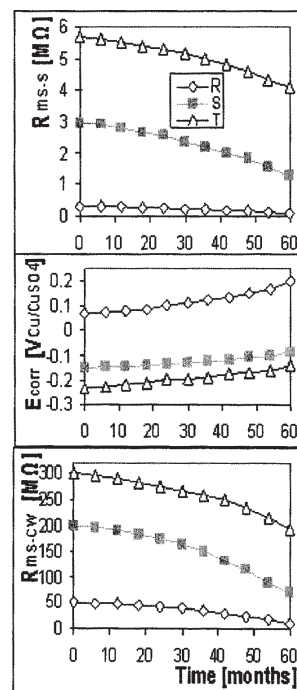


Fig. 3. The evolution in time of R_{ms-s} , E_{corr} and R_{ms-cw} parameters of cables from UPL 2

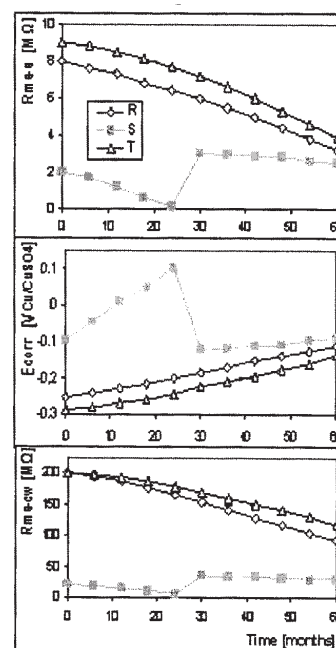


Fig. 4. The evolution in time of R_{ms-s} , E_{corr} and R_{ms-cw} parameters of cables from UPL 3. The phase S was short-circuited after 5 years of operation

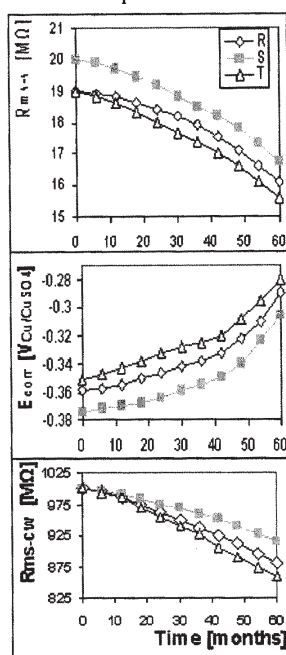


Fig. 5. The evolution in time of R_{ms-s} , E_{corr} and R_{ms-cw} parameters of cables from UPL 4

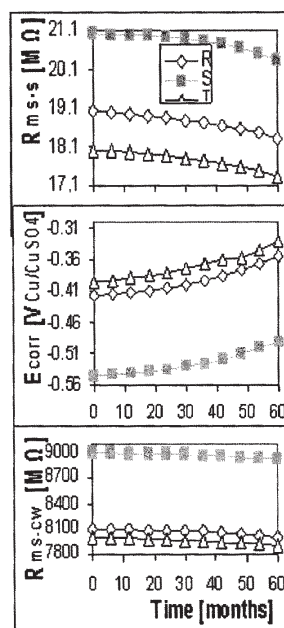


Fig. 6. The evolution in time of R_{ms-s} , E_{corr} and R_{ms-cw} parameters of cables from UPL 5

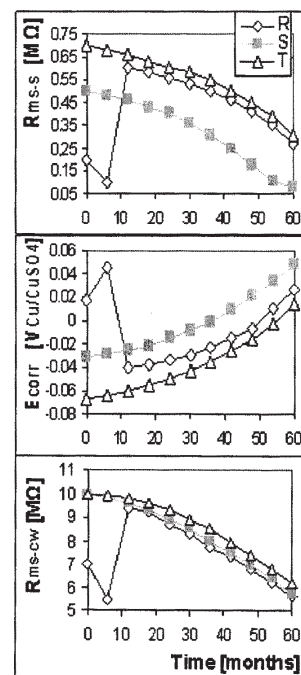


Fig. 7. The evolution in time of R_{ms-s} , E_{corr} and R_{ms-cw} parameters of cables from UPL 6. The phase R was short-circuited after 24 years

potential, E_{corr} , towards more positive values characterizes the enhancement of corrosion of metallic screen.

The evolution during the 5-year monitoring of R_{ms-s} , E_{corr} and R_{ms-cw} values are shown in figures 2-10. Note that only dependences in time of R_{ms-s} and R_{ms-cw} resistances were recorded for UPLs No. 8 and No. 9 (figs. 9 and 10), because these two UPLs were protected against corrosion.

Figures 2-8 show that cables without cathodic protection have R_{ms-s} and R_{ms-cw} electrical resistances which are decreased continuously in time, while E_{corr} corrosion potential is shifted continuously towards more positive values. These evolutions can be explained by the

deterioration of both external polymeric jacket and polyethylene insulation, with consequent decrease of R_{ms-cw} resistance, especially.

With a very good approximation (errors of less than $\pm 1\%$) the decrease in time (t) of R_{ms-s} and R_{ms-cw} values can be described by the polynomial equations of second degree, having the general forms:

$$R_{ms-s} = a_{pj} t^2 + b_{pj} t + c_{pj} \quad (1)$$

$$R_{ms-cw} = a_i t^2 + b_i t + c_i \quad (2)$$

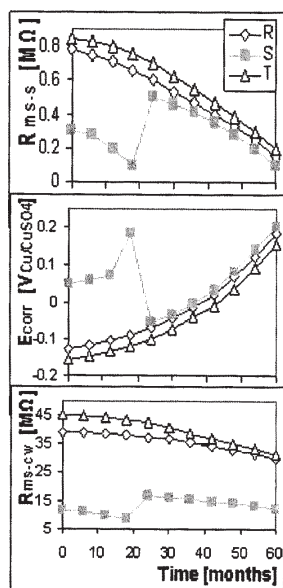


Fig. 8. The evolution in time of R_{ms-s} , E_{corr} and R_{ms-cw} parameters of cables from UPL 7. The phase S was short-circuited after 9 years

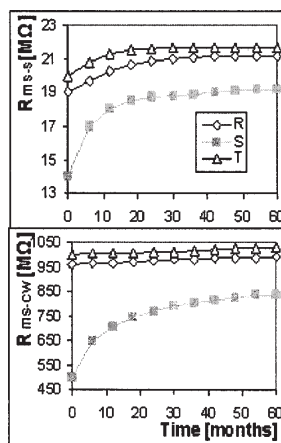


Fig. 9. The evolution in time of R_{ms-s} and R_{ms-cw} parameters of cables from UPL 8, equipped with corrosion protection system (cathodic voltage $E_c = 13.5$ V_{Cu/CuSO4}) in the last 4 years

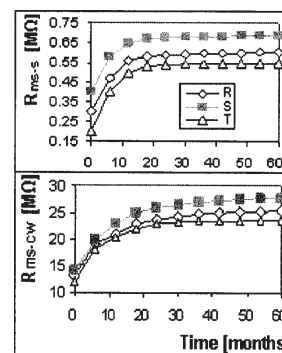


Fig. 10. The evolution in time of R_{ms-s} and R_{ms-cw} parameters of cables from UPL 9, equipped with corrosion protection system (cathodic voltage $E_c = 13.5$ V_{Cu/CuSO4}) in the last 4 years

The a_{pi} and b_{pi} coefficients characterize the evolution in time for degradation of polymer jacket (external polymer layer), and c_{pi} coefficient represents the electrical resistivity in the initial state of this external polymer layer. Similarly, all coefficients a_i , b_i and c_i characterize the behavior in time of polyethylene insulation, in an evolution which illustrate the aging of dielectric material.

Table 2 presents the particular expressions of polynomial equations of R_{ms-s} and R_{ms-cw} dependences in time for non-protected cables, i.e., without cathodic protection of metallic screen. It is worth to note that for the cables reaching the short-circuit failure, the evolution functions are discontinuous and two different equations can be expressed separately for time periods before and after the occurrence and remedy the defect.

From figures 2, 4, 7 and 8, an excessive aging of cable insulation is observed, respectively the value of R_{ms-cw} resistance decreases at approx. 5 MΩ, value which leads to the failure of the cable by perforation. It was estimated that the limit value of R_{ms-cw} resistance at which the 20 kV cables are safer in operation is 10 MΩ; the risk of cable failure is very high below this value. At all recorded defects, the R_{ms-s} electrical resistance of external polymeric layer was relatively small, with values between 0.1 MΩ and 0.5 MΩ, depending on the burial period of cable and on soil characteristics.

We have noticed that after correction of defects, the R_{ms-s} and R_{ms-cw} resistances of cables have increased substantially, and E_{corr} potential was shifted to more negative values. These observations suggest that the defects (pores) from polymeric jackets and the tree-like structure of defects from polyethylene insulation are not uniformly distributed along the cable. Usually, the fatal defects are concentrated in a short distance, where the cable is damaged.

The repair of the defects is done by removing the portion containing the main defect, thus increasing the values of R_{ms-s} and R_{ms-cw} resistances. Under these conditions, it is noted that in preventive diagnostic studies as well as in the evaluation of the remained life time, the specific values (that is, measured values R_{ms-s} and R_{ms-cw} related to the length unit of cable) are not relevant; only the absolute values (measured values) of R_{ms-s} and R_{ms-cw} resistances are relevant, because they correctly characterize the most

deteriorated/aged portion of cable. Based on the experimental data, values of $R_{ms-s} \geq 0.5$ MΩ and $R_{ms-cw} \geq 10$ MΩ are recommended in calculations of remained life time, as functional parameters that determine safe operation of the cable.

For the evaluation of the annual average rate of degradation (k) of the polymeric jacket from the commissioning of cable and date of first evaluation, it is considered a new cable the insulation resistance R_{0ms-s} between screen and soil which, depending on type of cable, should have a value in the range: $23 \text{ M}\Omega \leq R_{0ms-s} \leq 27 \text{ M}\Omega$ [24,51]. With average value $R_{0ms-s} = 25 \text{ M}\Omega$, and data from table 1 (the years of commissioning and R_{ms-s} values the date of first investigation) is calculated k expressed in MΩ/year:

$$k = \frac{R_{0ms-s} - R_{ms-s}}{n} \quad (3)$$

where n is the time duration of the use of cable, respectively $n = t - t_0$; t – the year of first investigation and t_0 – the year of cable burial. For investigated cables, shown in table 1, the average calculated values of k are presented in table 3.

The most intense changes were found on the surface of polymeric jackets, that when are made with non-degraded material is smooth, without cracks and holes. Visual changes were a first indication of any microbial attack in almost all tests. Hyphae and conidiophores grow directly onto the polymer surface. As a result of fungal degradation, surface irregularities as peeling, exfoliation and cracking in texture of polymer were visible and the surface was covered with spores. The occurrence of small holes suggests that the fungi penetrate into the sample matrix during degradation.

The following observations can be made by comparing data from tables 1 and 3:

- on the routes of UPL 1 and UPL 3, the annual average rates of deterioration of polymeric jacket are maxima ($k > 6.2$ MΩ/year), which suggests that aggressiveness for polymers of identified molds on the routes of these cables (*Penicillium funiculosum* and *Aspergillus niger*) is maximum. The destructive process of biodegradation was very prominent.

- on the route of UPL 2, where the chemical aggressiveness of soil is minimal (low salinity, pH=6.5 and electrical resistivity 43.2 Ω·m) a medium annual average rate of deterioration for polymeric jacket was recorded ($k = 3.66$ MΩ/year).

- for UPL 6, UPL 8 and UPL 9 the average rates of deterioration for external polymeric jacket are minimal (k values around 1 MΩ/year), although the chemical aggressiveness of soil is relatively high (approx. pH=5 and 10 Ω·m for soil pH and electrical resistivity, respectively), which suggests that the identified representative molds species on the routes of these cables (*Cladosporium sp*, *Aspergillus terreus*, *Paecilomyces varioti* and *Trichoderma viride*) present a minimal aggressiveness for polymer material.

These findings suggest that the deterioration of polymeric jackets is determined first of all by representative molds present in the soil. Based on data from tables 1 and 3, for investigated cable routes it can be established the hierarchical order of aggressiveness of identified molds for polymeric jacket:

Penicillium funiculosum > *Aspergillus niger* > *Scopulariopsis brevicaulis* > *Cladosporium sp H* > *Aspergillus terreus* > *Paecilomyces varioti H* > *Trichoderma viride*.

This hierarchy is in good agreement with the data previously reported [32,39,43,45] for biodeterioration of polyethylene in laboratory conditions. The changes induced by the action of these microorganisms are deep and distinct, and confirm that *Penicillium funiculosum* and other mixed fungi population excrete enzymes able to cleave macromolecules of polyethylene. *Penicillium funiculosum* expanded its colonies over the entire surface of neat polyethylene jacket. *Aspergillus niger*, *Scopulariopsis brevicaulis*, *Aspergillus terreus*, *Trichoderma viride* and mixed fungal population grew less rapidly and primarily on the edges, proving that growth of fungi cannot be considered only as a result of the surface moistness.

According to these observations and the mechanism of degradation/aging of cable (fig. 1), it is considered that the coefficients a_{pj} and b_{pj} are determined primarily by species of microorganisms from the soil, and a_i and b_i are given by chemical and microbiological aggressiveness of soil that corrodes metallic screen, contributing to the formation of Me^{2+} ions, which generates electrochemical and

electrical trees (conductive channels in dielectric insulation).

R_{ms-s} and R_{ms-cw} evolutions in time of cables having cathodic protection implemented during the initial investigations are shown in figures 9 and 10. It is noted that at an imposed cathodic potential $E_c = 13.5 \text{ V}_{\text{Cu/CuSO}_4}$ the values of R_{ms-s} and R_{ms-cw} increase in the first two years, after which they tend asymptotically to a limit value. In these conditions, in an error range of approx. $\pm 3\%$, the evolution in time (t) of R_{ms-s} and R_{ms-cw} can be described by polynomial functions of the four order:

$$R_{ms-s} = a_{pj_cp} t^4 + b_{pj_cp} t^3 + c_{pj_cp} t^2 + d_{pj_cp} t + e_{pj} \quad (4)$$

$$R_{ms-cw} = a_{i_cp} t^4 + b_{i_cp} t^3 + c_{i_cp} t^2 + d_{i_cp} t + e_i \quad (5)$$

where coefficients a_{pj_cp} , b_{pj_cp} , c_{pj_cp} and d_{pj_cp} characterize the evolution of electrical resistance of external polymeric jacket and e_{pj} characterizes initial state (at time $t = 0$ – date of putting in operation of cathodic protection system) of polymeric jacket from the cathodic protected metallic screen. Similarly, the coefficients a_{i_cp} , b_{i_cp} , c_{i_cp} and d_{i_cp} characterize evolution of insulation from protected cable with the “rejuvenated” dielectric material, and coefficient e_i describes the initial state (at $t=0$) of insulation. The analytical equations that describe time evolutions of R_{ms-s} and R_{ms-cw} for cathodically protected cables are shown in table 4.

It is interesting to note that for UPL No. 9, the deterioration of polymeric jacket was very advanced, illustrated by R_{ms-s} values between 0.2 MΩ and 0.4 MΩ, practically below the safe operating limit of the cables. By applying cathodic protection of metallic screen, R_{ms-s} increases significantly, for instance reaching a value over 0.55 MΩ after two years, this being in the range 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 new dielectric material. The phenomenon is supported by the formation of alkaline earth carbonates (CaCO_3 , MgCO_3) which are insoluble and dielectrics, having relative permittivity (dielectric constant) with a value of approx. 10 [52]. The pure chemical process of forming of CaCO_3 (and similar MgCO_3) can be described

UPL cable	Phase	$y = a_{pj} x^2 + b_{pj} x + c_{pj}$ $y = R_{ms-s} [\text{M}\Omega]; x = \text{time} [\text{months}]$	$y = a_i x^2 + b_i x + c_i$ $y = R_{ms-cw} [\text{M}\Omega]; x = \text{time} [\text{months}]$
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	$y = -0.0002x^2 + 0.0045x + 21.00$	$y = -0.0115x^2 - 0.5366x + 9000$
UPL 6	T	$y = -0.000x^2 - 0.0011x + 18.00$	$y = -0.0188x^2 - 0.482x + 8000$
	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	$y = -0.0001x^2 - 0.0043x + 0.86$	$y = -0.0028x^2 - 0.0716x + 45.0$

Table 2
ANALYTICAL EQUATIONS FOR EVOLUTION IN TIME OF INSULATION RESISTANCES (R_{ms-s} AND R_{ms-cw}) FOR CABLES WITHOUT CATHODIC PROTECTION

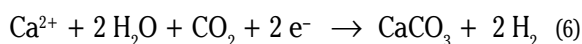
Annual deterioration rate	UPL and operating time								
	UPL 1	UPL 2	UPL 3	UPL 4	UPL 5	UPL 6	UPL 7	UPL 8	UPL 9
	3 years	6 years	3 years	2 years	2 years	23 years	7 years	8 years	24 years
k [MΩ/year]	7.16	3.66	6.20	2.83	2.83	1.10	3.50	0.90	1.00

Table 3
ANNUAL AVERAGE RATES OF DETERIORATION FOR POLYMERIC JACKET OF CABLES

Table 4
ANALYTICAL EQUATIONS FOR INSULATION RESISTANCES (R_{ms-s} AND R_{ms-cw}) EVOLUTION OF CABLES WITH CATHODIC PROTECTION

UPL No.	Phase	$y = a_{pj_cp} x^4 + b_{pj_cp} x^3 + c_{pj_cp} x^2 + d_{pj_cp} x + e_{pj}$ $y = R_{ms-s} [M\Omega] ; x = \text{time [months]}$	$y = a_{i_cp} x^4 + b_{i_cp} x^3 + c_{i_cp} x^2 + d_{i_cp} x + e_i$ $y = R_{ms-cw} [M\Omega] ; x = \text{time [months]}$
UPL 8	R	$y = -9 \cdot 10^{-8} x^4 + 3 \cdot 10^{-5} x^3 - 3.4 \cdot 10^{-3} x^2 + 0.1432x + 19$	$y = 8 \cdot 10^{-6} x^4 - 1.1 \cdot 10^{-3} x^3 + 0.046x^2 + 0.051x + 960$
	S	$y = -3 \cdot 10^{-6} x^4 + 5 \cdot 10^{-4} x^3 - 2.55 \cdot 10^{-2} x^2 + 0.572x + 14$	$y = -1 \cdot 10^{-4} x^4 + 1.92 \cdot 10^{-2} x^3 - 1.0539x^2 + 27,132x + 500$
	T	$y = -6 \cdot 10^{-7} x^4 + 1 \cdot 10^{-4} x^3 - 6.4 \cdot 10^{-3} x^2 + 0.1686x + 20$	$y = -6 \cdot 10^{-6} x^4 + 7 \cdot 10^{-4} x^3 - 1.75 \cdot 10^{-2} x^2 + 0.4217x + 1000$
UPL 9	R	$y = -2 \cdot 10^{-7} x^4 + 3 \cdot 10^{-5} x^3 - 1.6 \cdot 10^{-3} x^2 + 3.58 \cdot 10^{-2} x + 0.30$	$y = -5 \cdot 10^{-6} x^4 + 7 \cdot 10^{-4} x^3 - 4.13 \cdot 10^{-2} x^2 + 1.0827x + 13$
	S	$y = -2 \cdot 10^{-7} x^4 + 3 \cdot 10^{-5} x^3 - 1.6 \cdot 10^{-3} x^2 + 3.58 \cdot 10^{-2} x + 0.40$	$y = -4 \cdot 10^{-6} x^4 + 7 \cdot 10^{-4} x^3 - 4.25 \cdot 10^{-2} x^2 + 1.1683x + 14$
	T	$y = -2 \cdot 10^{-7} x^4 + 3 \cdot 10^{-5} x^3 - 1.8 \cdot 10^{-3} x^2 + 4.2 \cdot 10^{-2} x + 0.20$	$y = -5 \cdot 10^{-6} x^4 + 8 \cdot 10^{-4} x^3 - 4.43 \cdot 10^{-2} x^2 + 1.1403x + 12$

by the alkalization of soil near the cathode, which leads to the formation of calcium (or magnesium) hydroxide; in contact with the carbon dioxide from aerated soil the hydroxide converts into carbonate. It should be noted that if an excessive cathodic polarization is applied (voltage higher than $13.5 V_{Cu/CuSO_4}$), a parallel electrochemical process may take place as:



In these conditions, increase of R_{ms-s} resistance is limited by pores/defects size from the polymeric jacket, by the content of alkaline earth metal ions of soil and by CO_2 concentration/quantity available on the polymeric jacket's surface. Thus, the coefficients a_{pj_cp} , b_{pj_cp} , c_{pj_cp} and d_{pj_cp} are determined by the degree of deterioration of polymeric jacket and by soil characteristics, i.e. the content of Ca^{2+} and Mg^{2+} ions, and also by CO_2 content / penetration of CO_2 .

Increased R_{ms-cw} values after cathodic protection can be explained by the fact that at $E_c = 13.5 V_{Cu/CuSO_4}$ the corrosion is thermodynamically impossible and metal ions existing in electrochemical trees migrate to metallic screen, where are reduced to metal:



making the conductivity of the channels of electrochemical trees to decrease substantially. In these conditions the rejuvenation of insulation is limited and determined by coefficients a_{i_cp} , b_{i_cp} , c_{i_cp} and d_{i_cp} which depend on the state of aging of the cable at the date of application of cathodic protection. This means a strong influence of the size of electrochemical trees and degree of carbonization inside electrochemical and electrical trees after partial electrical discharges [22,51].

Conclusions

After processing and interpretation of acquired experimental data on soil characteristics (resistivity, pH and representative molds) along the route of nine UPL cables and monitoring the evolution for five years regarding the state of deterioration of cable insulation (for $9 \times 3 = 27$ cables) it was found that the aging of cable insulation is a complex process which is due to several stress factors, which influence each other and act synergistically. The insulation aging mechanism is carried out through several successive stages, the determining step being microbiological deterioration of polymeric jacket. The aggressiveness of representative mold species identified in the soil along UPL routes increases in the series:

Penicillium funiculosus > *Aspergillus niger* > *Scopulariopsis brevicaulis* > *Cladosporium sp H* > *Aspergillus terreus* > *Paecilomyces varioti H* > *Trichoderma viride*.

Corrosion of metallic screen of cables begins only after deterioration of outer polymeric jacket. The corrosion products accelerate the process of deterioration of polymeric jacket, as well as the formation of electrochemical tree branches, followed by growth of these electrical trees; this makes the insulation resistance of the cables to fall (insulation is aging). The blocking of pores/defects from polymeric jacket and prevention of metallic screen corrosion can be achieved by cathodic protection. Thus, the degree of aging of the insulation decreases with an increase of electrical insulation between metallic screen and conductor wire of cables. This increase is significant in the first two years of protection when the insulation tends asymptotically to a maximum value, therefore the insulation "rejuvenates".

The analysis of failure conditions for cables without cathodic protection has shown that the safe operation of the power cables can be provided only by reaching $R_{ms-s} \geq 0.5 M\Omega$ and $R_{ms-cw} \geq 10 M\Omega$, both values characterizing the end of the life of the cable. Also, the cable monitoring for 5 years leads to establish some analytical equations that describe R_{ms-s} and R_{ms-cw} variation in time. Experimental results suggest that ageing of insulation exposed to chemical and electrical stress is due to the formation and growth (propagation) of electrochemical trees. All these data and correlations are useful to substantiate preventive and reparatory diagnostic studies and are essential in assessing the remaining life time of the power cables.

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