Contributions to Develop the Modern Technical Solutions for Increase of Maintenance and Reliability of Underground Power Lines.

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Abstract – **The degradation process of metallic shields of underground power lines is an important factor upon theirs maintenance, reliability and safe operation. Therefore, the paper presents theoretical aspects concerning the electric phenomena taking place in cables' insulator / dielectric, the kinetics of corrosion reactions of metallic sheaths and original technical solutions for control of corrosion and increase of insulating resistance of underground power cables operating in aggressively electrochemical media / soils (electromagnetic polluted by DC and AC stray currents, soils of high salinity and / or bacteriologic charge, deep waters etc.). Also, there are presented the application schemes of our method for single - wire cables, three - wire cables and other underground power lines using different types of cables. Some implementation examples are as well presented and the results of the method are emphasized. It clearly appears that the application of our technology lead to the mitigation / elimination of degradation risk of metallic screens, a progressive improvement of the insulation resistance of power lines and implicitly of their maintenance and reliability.**

I. INTRODUCTION

The study and fighting against corrosion of underground distribution grids of urban utility -especially of power cables- constitutes a problematical of a distinct theoretical complexity and of a great practical importance.

The theoretical complexity results from the multitudinous underground metallic grids, which are functioning, in the same electrolytic environment (soil – ionic conductor, therefore a 2nd species electro conductor) and from galvanic interactions which may occur between these. From the multitude of the acceleration corrosion factors (Electromagnetic pollution with dispersion currents as well in DC as in AC – linear and/or deformed regime [1], differential aeration, salinity, mineralization, humidity, bacteriological content, etc.) which acts, in the urban thronged soil, against materials –especially against metallic materials-.

In the precise case of underground power cables degradation, the rate of degradation process is determined by the acceleration corrosion factors (like aggressively chemical and microbiological soil, the presence of dispersion currents "stray currents" in DC generated by the urban electric transportation, etc.) which acts mainly against the metallic screen sheets. These stray currents are also generated by *the permanent presence of an electric signal in alternative current superposed to the electrochemical process* and by a high amplitude signal which substantially contributes to the acceleration of dissolution process of the metal within the screen.

The electrochemical corrosion of the metallic screen sheets afferent to cables is the determinant factor of maintenance, viability and safety of underground power lines exploitation (UPL) [3]. The effect of the corrosion of the metallic screen sheets afferent to the cables within UPL is the formation of corrosion products (metallic hydrated ions, especially $Cu^{+2}\cdot nH_2O$) which are mainly concentrated on the surface of the base insulator and generates treeing [4], substantially contributing to theirs dielectric rigidity [5]. This will finally lead to ohmic screen interruption (physical degradation), with all afferent consequences (electromagnetic environment pollution, homopolar protection systems perturbation, electric field nonuniformity distribution and cable penetration, etc.).

The purpose of this present paper consists in main theoretical aspects regarding as well the electric phenomenon within cable's dielectric, as the degradation by metallic screen sheets corrosion. This is also presented with an original technical solution [5], which, its implementation assures as well the control of metallic screen sheet corrosion, as the substantial increase in insulation's resistivity of underground power cables.

II. THEORETICAL ASPECTS

II.1 *Electric phenomena within power cables dielectric*

The insulation of the electric installations is, during exploitation, submissive to an ensemble of solicitations by electrical, thermal, mechanical, chemical, climatic and biological nature. These factors determine the degradation or even the deterioration by insulation penetration.

It is known [6], that usually the deterioration in exploitation of power cables insulation is preceded by a series of physical phenomena which occur in dielectrics under the acting of electric solicitations, like:

- **dielectric polarization** consists in the modification of the material electric state under the acting of electric fields and determines modifications of capacity and current absorbed by the insulating construction, as well as variations of absorbed electric charge, depending by insulation's composition and structure. There are two distinguished types of dielectric polarization, which are:
  - *fast/electroionic polarization*, which depends only by ion's nature presents, and which is developing in

an interval smaller than a microsecond (relaxation time of ionic atmosphere);

- *slow polarization*, which depends by insulation's composition and structure, has a duration in minutes and includes thermoionical dipoles polarization (specific for substances with polar molecules) and layer polarization (interfacial), based on electric charges accumulation (absorbed charges) upon multi-layer insulation's adjacent surfaces, or upon electroinsulative structures contained between conductive layers.

- **partial discharges** within solid dielectrics air voids – it's an appreciation criteria of insulators quality and condition.
- **insulation conductivity** which is determined by the shifting of different types of charge carriers provided by the surrounding environment (in case of the cables, from the space between the metallic screen and the insulator) and by the internal phenomena of insulation degradation.

The electric design equivalent for nonhomogenous insulation which models electric phenomena within cables dielectric is shown in Fig.1

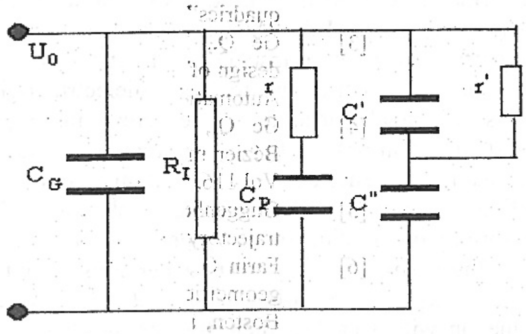

Fig. 1. The electric design equivalent to nonhomogenous insulation: U_O – applied tension voltage; C_G – insulation's geometric capacity; R_I – insulation's resistivity; r and C_P – relaxation circuit rezistivity and capacity; C', C'', r' –gas inclusion's capacity, dielectric's capacity existent within the limits of the field lines which define the inclusion, respectively the resistivity of the discharge channel.

Generally, the values for C' and C'' shown in Fig.1 are very small, so negligible compared to C_G and C_P values. In these conditions, the global insulation's capacity is (1):

$$C_I = C_G + C_P \tag{1}$$

and for a direct voltage, applied to the equivalent current shown in Fig.1. The total current delivered by the power source is (2):

$$i(t) = I_\infty + I_{ao} e^{-t/T}, \tag{2}$$

in which: - $I_\infty = U_0 / R_I$ – represents the ***conduction current***;

- $I_{ao} e^{-t/T} = i_{a(t)}$ – represents the current which corresponds to slow polarization phenomena, also named the ***absorption current***, in which care $I_{ao} = U_O / r$, and respectively $T = r \cdot C_P$ represents the slow polarization phenomena's time constant.

II.2 *Water treeing in power cables dielectric*

The water treeing phenomena, which has been made evident by experimental means during the year of 1968, is one of the main solicitation factors for power grids in cable's dielectric made by polymeric materials [4], [5], [8], [9], [10], [11],. The treeing appears and is produced as well in the interior of dielectric's mass (internal treeing), as on its surface (terminal treeing).

It has been proved, as well theoretical as experimental, that the propagation of treeing zones in dielectric's mass of polyethyilene afferent to power cables is happening due to a force field of electric nature. In this way, a series of factors have been brought up, factors that theirs combined effect directly influence the increase speed of treeing in insulators, these being:

a) polymer's type and structure
b) water's (electrolyte) quality and concentration [11] to which insulation comes in contact (content in salts and theirs concentration, water dissolved gases);
c) electric field's intensity and frequency applied to the insulator.

In Fig.2 it is shown a typical example of polyethylene insulator degradation, throughout the water treeing channels [4].

Fig.2. Degradation by water treeing under the influence of an alternative electric field of $20kV_{rms}/cm$. of a polyethylene insulator (density of $0{,}92 g/cm^3$) [4]

In real conditions, the water (humidity), to which buried cable is in contact in electrolytic environment (soil, phreatic water, etc.) contains a series of impurities –firstly ionic- as well anions as cations from the environment in which the cable is buried, as *especially cations formed by metallic screen sheets corrosion afferent to the cable.* In these conditions, under the applied electric field's influence, practically, migration of ions is taking place in the polymeric insulator's volume by "electrochemical treeing".

In the concrete exploitation conditions of UPL, cables degradation by treeing is further more accelerated, due to the fact that the insulator material *is in direct contact with ionic solution (in water)* - with a considerable concentration of metal ions originated from the screen sheet by metal *corrosion*.

II.3 *Metallic screen corrosion of underground cables*

Nonmetallic materials (usually polymeric) from which exterior protection layers are made, as well as metals from which sheets/screen afferent to underground power cables are made, are suffering from a degradation process either during burring (mechanical deterioration) or during exploitation under environment factors influence (chemical-physical, electric and biologic nature). Following degradation, water (humidity) penetrates through pores and defects of the outer polymeric lagging reaching the metallic screen and begins the degradation process by corrosion of metallic screen/sheet afferent to cables, after a typical electrochemical mechanism.

The corrosion reaction is taking place after the following relation (3)

$$Me \Leftrightarrow Me^{+z} + ze^{-}, \quad (3)$$

In which – *Me* –represents the metal which is beeing corroded (Cu, Pb, Al, steel), - *z* – the number of yielded electrons (metal chemical valence), and - e^{-} - the elementary electronic charge.

We are observing that reaction (3) is reversible, having the global speed (*v*), which results from the vectorial composition of the two partial processes' speeds: dissolution (4), which is taking place with v_1 speed, and reduction (5), which is taking place with v_2 speed.

$$Me => Me^{+z} + ze^{-}, \quad (4)$$

$$Me^{+z} + ze^{-} => Me, \quad (5)$$

During equilibrium, when $v_1 = v_2$, there is a potential, characteristic of the system, stabilizing Me / Me^{+z} (equilibrium potential – combined corrosion potential), but this DOES NOT mean that the metal (screen sheet) DOES NOT further degrades. This is because that the physical-chemical properties of *Me* resulted from reaction (5) are much more inferior to those of *Me* dissoluted by partial reaction (4). We also remark the fact that, even when $v_1 = v_2$, there are metallic ions presents at the screen/insulator interface. Ions which under the action of the electric field applied to the insulator (cable's functioning voltage) by "electrochemical treeing", penetrates the insulator, resulting in as well the insulation's degradation ("ageing"), as in the reduction of the concentration in Me^{+z} and, implicit, equilibrium shifting (3) to the right.

Partial reaction (4) *of metal dissolution* and metallic ions formation is determined / favored by:

- metal's thermodynamic reactivity;
- environment's chemical agresivity (presence of certain compounds which favors the corrosion reaction – depolarization agents of partial anodic process- like Cl^{-}, NO_3^{-} etc.);
- diffusion – partial removing of the corrosion products from the metal's surface, resulting in the loss of concentration of Me^{+z};
- imposing of a much more negative potential than the equilibrium potential in Me / Me^{+z} system (catodic polarization – *catodic protection*)

We should remark the fact that, in natural environment, the majority of the usual metals have a limited thermodynamic stability, thus it presents a natural tendency for dissolution, conforming to the corrosion reaction (4). In underground cable's case, this phenomenon can be substantially accelerated by:

- metallic screen's local anodic polarization due to dispersion currents "stray currents" in DC, provided by bearing race of urban electric transport and/or industrial platforms;
- depolarizing action on equilibrium (3) (increase of v_1) as well of chemical products resulted from natural and biological polymer's degradation from which the outer lagging has been realized (example: in case of PVC – HCl is produced), as of metabolism products of microorganisms presents in the exploitation environment (soil) – specially sulfate reductive bacteria [12];
- signal's corrosion accelerated effect in AC superposed to the electrochemical process, Me/Me^{+z}, respectively metal/electrolyte (soil, water, etc.) [13].

Considering these, we are observing that the metal, from which cables' sheets/screen are confectioned, in actual exploitation conditions (underground burring), is exposed to accelerated corrosion.

We are also observing that any metallic hydrated ions presence on the base insulator's surface favors, by "electrochemical treeing", the degradation of the insulation reaching out to it's penetration under the action of applied voltage.

The presence of metallic ions on the insulator's surface, afferent to cables *is impossibly* from thermodynamically point of view, if the metal's screen is catodic polarized sufficiently negative from the environment (soil) so the partial reaction (4) to be impossible and, implicitly, the partial reaction (5) strongly favored.

III. CORROSION CONTROL OF METALLIC SHEETS OF UNDERGROUND CABLES

From Chapter II it results that, in natural electrolytic environments (soil, phreatic water, etc.) under the influence of the acceleration corrosion factors (microbiological activity, salinity, and/or increased acidity, dispersion currents as well in DC as in AC – linear and/or deformed regime) screen corrosion and, implicitly, the degradation of the base insulator afferent to cables is taking place after a mechanism which is developing after the next successive stages:

a) humidity penetration through the outer lagging's defects (pores), (usually polymeric in modern cables), defects which exists from fabrication or occurs during cable manipulation or exploitation (microbiological degradation, accidental contact on line, etc);
b) apparition of first screen corrosion centers and inclusively of corrosion products. These products, that have a larger volume than the metal from which they are formed, create mechanical tension between the screen and the outer lagging. Due to this fact, the defects/pores opens and creates conditions for a larger quantity of water from soil to penetrate and reach out to screen's metal accelerating the corrosion process.
c) corrosion products, specially metal hydrated ions creates terminal trees on the dielectric's surface
d) terminal trees, under the influence of the electric field applied to the cable, are being propagated into the dielectric's volume (internal treeing) and are creating conductor channels with lowered electrical resistivity – until dielectric's penetration.

We should remark the fact that in the case of gas holes presence in dielectric (local defects), its degradation and penetration is much more rapidly achieved, because every gas hole represents an ideal concentration and multiplication center of treeing.

Considering these, it results that the degradation of cables afferent to underground power lines can be prevented by special measures of corrosion control. The consecrated and safest method of metal's corrosion control which are functioning in electrolytic environment consists in metal cathodic polarization (screen/sheet in case of cables) from the environment, negatively sufficient so that the partial reaction (4) to be thermodynamically impossible. (cathodic protection) [14].

Cathodic polarization, by cathodic current injection, from the electrolytic environment (soil, phreatic water) in which the cable is buried, is possible only if the screen is not galvanic connected to ground (like usually encountered because of electrosecurity and electromagnetic compatibility reasons). In such conditions, regarding the insurance of active anticorrosion –cathodic- protection of metallic screens, theirs galvanic separation from the electrosecurity ground plates is imposed. The galvanic separation may be realized by the implementation of certain specialized galvanic separation devices, electroprotection and electric decoupling, between the screen and ground plates.

We should remark the fact that, in cables' case, following screen sheets' cathodic polarization, beside theirs corrosion control (with all the afferent implications like: screen ohmic interruption and protection system perturbation, corrosion products treeing and insulator degradation) it is taking place simultaneous, the migration of metallic hydrated ions (already in by treeing in cable's base insulation) to the cathodic polarized screen, and, implicitly the according insulation's resistivity increase ("inverted electrochemical treeing").

The electroprotection compatibility with anticorrosion –cathodic- protection of metallic structures is traditional realized by polarization cells [15] implementation, which theirs utilization presents a series of major disadvantages [16]. In the case of power cables, with the purpose of eliminating these disadvantages, in Germany, there have been conceived, from discrete rectifier diodes, polarized systems connected as shown in Fig 3 [17]. This mounting that, by his U/I specific characteristic, given by the resultant of voltage drops in forward polarization, assures simultaneous as well the galvanic screen separation from the soil, as its electroprotection and polarized drainage to ground plates of dispersion currents in DC.

The technical solution presented in Fig.3 presents the following disadvantages:

- high costs and large size, because it involves the utilization of at least four rectifier diodes of high power;
- relative high voltage drop in forward polarization (V_F about 1V, characteristic to usual rectifier diodes), which implies polarized drainage of signals only bigger than 1V;
- increased dynamic resistivity at the input of an assembly of three back-to-back diodes in voltage stabilizer regime and stabilized, relatively small (about 3V), voltage in inverted polarization (the sum of voltage drop of the three back-to-back and antiparalel diodes). This voltage, while it is sufficient for the insurance of galvanic separation for the cathodic protection, it is insufficient if we are after the extraction of the hydrated metallic ions (already in the cable's base insulation by treeing) from the base insulation volume, respectively of defects / dislocations occurred due to theirs "electrochemical treeing".

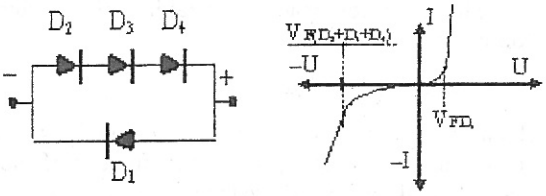

Fig.3 The mounting diagram of galvanic separation and diodes grouping electroprotection, and the u/i afferent characteristic

For eliminating these disadvantages and for insuring supplemental facilities, there have been recently, in Romania at S.C. ICPE – Cercetări Avansate S.A. (Advanced Research Institute for Electrical Engineering) Bucharest, with technical assistance from S.C. Băneasa S.A. Bucharest in the base of an original technical solution [5], developed, experimented and introduced in fabrication electroprotection and electric decoupling devices "solid body", specialized for electroprotection compatibility with cables' active (cathodic) anticorrosion protection, devices from DPC [17], [18], [19] and [20] series.

The DPC [20] device's U/I characteristic is shown in Fig.4, and in Fig.5 we are presented with theirs sketch.

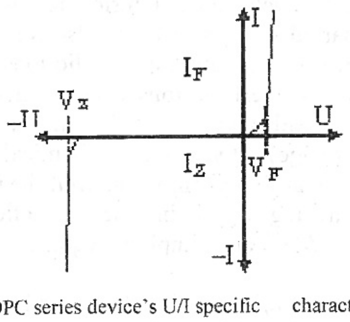

Fig. 4. DPC series device's U/I specific characteristic.

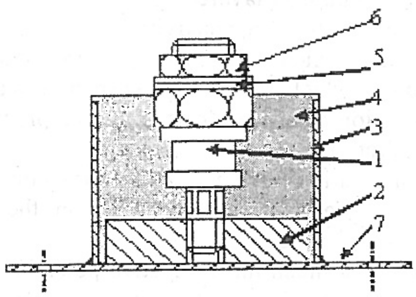

Fig.5 DPC device's sketch, developed for electroprotection compatibility with cable's anticorrosion protection: 1 – high power zener diode; 2 – internal radiator; 3 – metallic case; 4 – type A+B resin; 5 - circlers; 6 – M18 screw nut; 7 – device's bottom plate.

In Table 1 we are presented with the electric performances of DPC100 series devices according to Technical Specification NR. 6/2002 from Institute for Advanced Research in Electrical Engineering - Bucharest.

TABLE 1 Electric performances of DPC100 series devices

Parameter	Type A	Type B
Forward voltage V_F [V] at I_F = 100 A	**<0,85**	**<0,75**
Reverse voltage V_Z [V] at I_Z = 1 A	35 ± 5V	15 ± 5V
Rated current in forward polarization I_F [A]	110	120
Rated current in reverse polarization I_Z [A]	3	6,5
Current integral in forward polarization [A^2s]	200 000	200 000
Current integral in reverse polarization [A^2s]	40 000	80 000

IV. CORROSION CONTROL OF MONOPOLAR POWER CABLES

The underground power lines realized with monopolar cables (most encountered in practices), from protection's possibility point of view, represents a particular case, for which has been conceived and experimented an original method [5] of active anticorrosive protection and, implicitly, an increase in maintenance, reliability and exploitation safety.

Limited rectifying of divided voltage U bases the developed technical solution [5]. This voltage appears on the cable's screen (due to capacity divider formed by cable's linear capacity C_I-active conductor/insulator/shield – and screen's linear capacity from soil –screen/outer polymeric lagging/soil-) when it is powered by a nominal voltage Un ~, in accordance to the sketch shown in Fig.6.

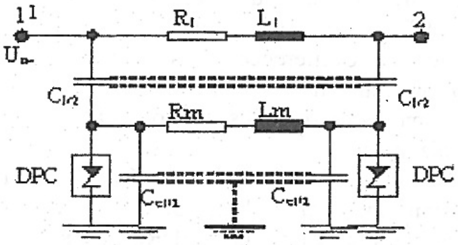

Fig. 6. Electric diagram equivalent to a single-phase cable with active anticorrosive protection: Rl, Ll – active conductor's resistance, inductance; Rm, Lm – screen's resistance, inductance; C_l – cable's linear capacity (active conductor/screen); Ce – screen /soil capacity; 1, 2 – electric cable's ends; DPC – "solid state" device.

By analyzing Fig.6 it result that the divided voltage U, which appears on cable's screen (at the DPC's connection) - calculable by (6) – is limited rectified by U/I zener type characteristic of DPC device [5] and so the cable's screen is being cathodic polarized from the soil through the ground plates afferent to the terminal electric cells:

$$U = k \cdot U_n = \left(\frac{C_i}{C_i + C_e} \right) \cdot U_n \qquad (6)$$

In these conditions, we are observing that, at the monopolar power cables afferent to UPL, by the presented sketch in Fig.6, it is actually insured a total –cathodic-active anticorrosive protection "intrinsical" (without independent cathodic current source), by limited rectifying of currents of linear capacity loss given by the construction of the cable.

The level of cathodic polarization of the screen is given by the limited voltage through DPC's invert characteristic, his zener voltage (V_Z) respectively. In case when DPC with V_Z is implemented in 10 ÷ 30V domain, it insures the screen with a sufficiently negative potential which assures as well the thermodynamic impossibility of metallic ions build-up by reaction (4), as the extraction and neutralization by reaction (5) of already in ions by treeing (anterior to the DPC devices implementation) from the cable's base insulator. In these conditions, it is obtained a drop of currents afferent to cable's partial discharges and, implicitly, a substantial raise of insulation resistivity.

The method and afferent specialized devices [5] has been implemented and experimented on 4 medium voltage UPL in Bucharest and in Cluj, realized with A2YSY or similar type of cables. In Fig.7 we are presented with a representative picture from Cluj, and in Fig.8 and 9 with one from Bucharest. Before the implementation there has been measured the insulation resistivity on each cable – measurement, which has been, took again after approx. 6 and 12 months from the implementation.

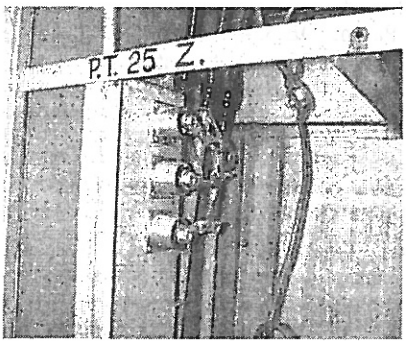

Fig. 7. DPC devices mounted in a M.T. cell, from Cluj.

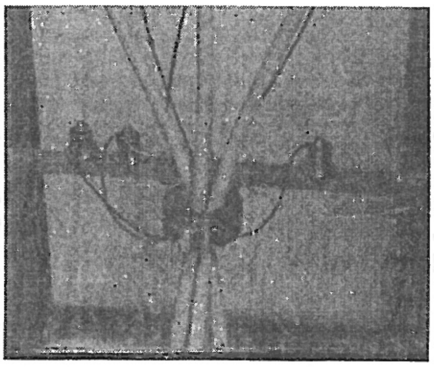

Fig. 8. DPC devices mounted in a M.T. cell with homopolar protection, from Bucharest

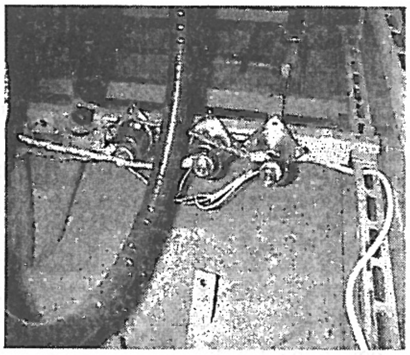

Fig. 9. DPC devices mounted in a M.T. cell, from Bucharest

Before the implementation of protection method [6], on each phase (cable) of UPL there has been measured the insulation resistivity (inductor at 5kV). From the comparative analysis of initial values with the ones periodic measured (six month interval), it result that, due to the functioning of active anticorrosion protection system which has been realized in accordance with [5], the insulation conductor resistance active/screen *have been substantially increased* - 10 ÷ 7500 times (on R phase of UPL T3483/T204 from Bucharest the insulation resistivity increased from 4MΩ to 30GΩ). This increase of insulation resistances during the functioning of the implemented system is explained by the fact that, following metallic screen's cathodic polarization, there has been a decrease in dislocations ("treeing") formed in cable's insulator before the implementation, respectively the metallic ions migrated towards the screen (cathodic polarized), where they have reduced in accordance with reaction (5).

From Fig.7, Fig.8 and 9 we remark that DPC devices can be implemented with relatively low material and payments expenses in any type of cell of medium voltage.

V. CONCLUSIONS

There have been analyzed the theoretical aspects regarding as well the electric phenomenon within power cables, as the ones which regards the degradation by corrosion of screen sheets afferent to cables, analysis which revealed the fact that the main causes for the degradation of the insulation resistivity of power cables ("ageing") is the corrosion of the screen and formation of corrosion products (hydrated metallic ions), products which, by electrochemical treeing are reaching into dielectric's cable an are forming electro conductor channels.

An original technical solution was conceived, realized and experimented and which, by its implementation assures total corrosion control over the metallic screens afferent to cables and stops the formation of metallic ions, therefore cable's degradation. By implementation of this method on already existent in exploitation cables, and which into theirs dielectric have already formed treeing of hydrated metallic ions, by cathodic screen polarization, the metallic ions in dielectric migrates towards the screen ("inverted treeing"), where they are reduced. In such conditions, the cable's insulation resistivity is substantially increased (the cable's youth is recovered), and, implicitly, the maintenance and UPL viability is increased.

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