TECHNICAL SOLUTION AND SOLID STATE DEVICES FOR INCREASE OF DURABILITY AND RELIABILITY OF UNDERGROUND POWER LINES (UPL)

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ABSTRACT:

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 UPL. Also, there are presented the application schemes of our method and some implementation examples. are presented too and the results of the method are emphasized. The application of our technology lead to the mitigation / elimination of degradation risk of metallic screens, a progressive improvement of the insulation resistance of UPL and implicitly of their maintenance and reliability.

Key words: *corrosion, control of corrosion, power cables, treeing, underground power lines*

1. INTRODUCTION

The study and fighting against corrosion of underground distribution grids of urban utility, especially of power lines, 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 (pollution with dispersion currents as well in DC as in AC – linear and/or deformed regime [1], [2], differential aeration, salinity, mineralization, humidity, bacteriological content, etc.) which acts, in the urban thronged soil, against materials – especially against metallic materials.
In the case of underground power cables degradation, the rate of degradation process is determined by the acceleration corrosion factors (like soil chemical and microbiological aggressively, the presence of DC stray currents 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 AC, superposed to the electrochemical process* 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 durability, viability and safety of UPL exploitation [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 degradation [5]. This will finally lead to ohmic screen interruption (physical degradation).
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 [6], which, its implementation assures as well the control of metallic screen sheet corrosion, as the substantial increase in insulation’s resistance of underground power cables.

2. THEORETICAL ASPECTS

2.1. 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.

2.2. 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], [7÷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 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.1 it is shown an example of polyethylene insulator degradation, throughout the water treeing channels [5].

Fig.1. Degradation by water treeing under the influence of an alternative electric field of 20kVrms/cm of a polyethylene (density 0,92g/cm^3) insulator [5].

In real conditions, the water (humidity), to which buried cable is in contact in electrolytic environment (soil) contains a series of impurities, *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 insulator's volume by "electrochemical treeing".

In the 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.*

2.3. 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 corrosion of metallic screen/sheet, after a typical electrochemical mechanism (1):

$$Me <=> Me^{+z} + ze^{-} \quad (1)$$

in which: *Me*-the metal which is being corroded (Cu, Pb, Al, steel); *z*- number of yielded electrons (metal chemical valence); e^{-} - elementary electronic charge.

We are observing that reaction (1) is reversible, having the global speed (*v*), which results from the composition of the two partial processes' speeds: dissolution (2), which is taking place with v_1 speed, and reduction (3), which is taking place with v_2 speed.

$$Me => Me^{+z} + ze^{-} \quad (2)$$

$$Me^{+z} + ze^{-} => Me \quad (3)$$

During equilibrium, when $v_1 = v_2$, there is a potential E_{cor}, characteristic of the system, stabilizing Me/Me^{+z} (equilibrium potential – combined corrosion potential). We 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 cable's functioning voltage by "electrochemical treeing", penetrates the insulator, resulting in as well the insulation's "ageing".

Partial reaction (2) *of metal dissolution* and metallic ions formation is determined / favored by:

- metal's thermodynamic reactivity;
- environment's chemical aggressively (presence of compounds which favors the corrosion reaction - like Cl^{-}, NO^{3-} etc.);
- diffusion speed chemicals;
- imposing of a much more negative potential than the equilibrium potential in Me/Me^{+z} system (cathodic polarization – *cathodic 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 (2). In cable's case, this phenomenon can be substantially accelerated by:

- metallic screen's local anodic polarization due to DC stray currents;
- depolarizing action on equilibrium (1) (increase of v_1) as well of chemical products resulted from polymer's degradation from which the outer lagging has been realized (in case of PVC – HCl is produced), as of metabolism products of microorganisms presents in the soil – specially sulfate reductive bacteria [12];
- accelerated corrosion due to AC superposed signals to the electrochemical process, Me/Me^{+z} [13].

Considering these, we are observing that the metal, from which cables' sheets/screen are confectioned, 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 "ageing" of the insulation reaching out to it's penetration under the action of cable's functioning voltage.

The presence of metallic ions on the insulator's surface, *is impossibly* from thermodynamically point of view, if the metal's screen is cathodic polarized sufficiently negative from the environment (soil) so the partial reaction (2) to be impossible and, implicitly, the partial reaction (3) favored.

In these conditions, it resume that, „ageing" of insulating materials from underground power lines is a complex process, that takes place under a concerted and prolonged action of electrical, mechanical, chemical and microbiological solicitations.

By analyzing more electrical breakdown defects on medium voltage cables, it has been proposed an example of degradation mechanism (Fig.2).

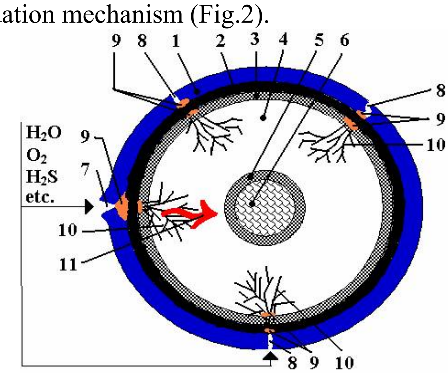

Fig. 2. Degradation process scheme of electrical cable:
1 – external polymeric layer; 2 - metallic screen; 3 - outer semiconductor layer; 4 - cable's insulation; 5 - inner semiconductor layer; 6 - conductor; 7,8 - polymeric layer's defect / pore; 9 - corrosion products; 10 - water tree channels; 11 - electrical flash – cable's electrical breakdown.

The degradation of cables (Fig. 2.) take place in steps [14]:

a) *outer polymeric protection layer's degradation (usually PVC)*– through:
   - mechanical degradation during underground cable's laying (drawing cables on hard and sharp surfaces) and / or during exploitation (touch by hard materials, landfalls etc.);
   - chemical degradation by specific reactions (forming HCl) and / or aggressive action of underground substances (oil products or other pollutant aggressive substances);
   - microbiological degradation [12];

b) *metallic screen sheet corrosion* – by outer polymeric shell defects (pores şi holes) – formed at *a)* – soil humidity and chemical agents (dissolved soil oxygen, content in salts, HCl from PVC degradation, etc) and biological [12] aggressive, penetrate the metallic screen and initiate corrosion reactions- metallic oxides formation in first stage (4):

$$2\,Me + z\,H_2O \Rightarrow Me_2O_z + 2\,z\,H^+ + 2\,z\,e^- \quad (4)$$

followed by metallic ions formation (5):

$$Me_2O_z + 2\,z\,H^+ \Rightarrow 2\,Me^{z+} + z\,H_2O \quad (5)$$

by means of global reaction(2);

c) *outer polymeric pores/defects sheet growth* – primary corrosion products formed at *b)* are bigger than original metal, which has the effect of mechanical tensions appearance between metallic screen and the outer polymeric sheet, tensions under its action the protective polymer pores and defects are opening, penetrating metallic screen and giving water and aggressive agents the chance to accelerate the process *b)*;

d) *electrochemical treeing of hydrated metallic ions in cable's insulation*– hydrated metallic ions, formed in stage *b)* from primary corrosion products and environment humidity (6):

$$Me^{z+} + nH_2O \Rightarrow Me^{z+}\cdot nH_2O \quad (6)$$

generates treeing channels in cable's insulation (Fig.1. şi Fig.2.) and, under the action of intensive electrical field made by the voltage applied between central conductor and metallic screen, are penetrating the insulator's volume, creating electrical treeing [5] sources, which has the effect of conductive channels forming- finally, decreasing substantially dielectric rigidity of insulator- until electrical breakdown occur.

In conclusion, results that underground power lines degradation mechanism (decreasing insulation electrical rigidity until breakdown occur) is a complex process, induced by the concerted action of multiples physical, chemical and biological factors. In this process, the initial stage is outer polymeric sheet degradation.

3. CORROSION CONTROL OF CABLES SHEETS

The degradation of underground cables can be prevented by special measures of corrosion control. The consecrated and safest method of metal's corrosion control consists in metal cathodic polarization (screen/sheet in case of cables) from the environment, negatively sufficient so that the corrosion reaction (2) to be thermodynamically impossible. (cathodic protection) [2], [14].

We should remark the fact that, in cables' case, following screen sheets' cathodic polarization, beside theirs corrosion control it is taking place simultaneous, the migration of metallic hydrated ions to the cathodic polarized screen, and, implicitly the according insulation's resistance increase ("*inverted electrochemical treeing*").

In the base of an original technical solution [6], was developed and tested a new "solid state" device, specialized for assure the electro safety and the active (cathodic) corrosion protection of cable's screen - devices DPC [15], [16] series. The DPC [16] device's U/I characteristic is shown in Fig.3.

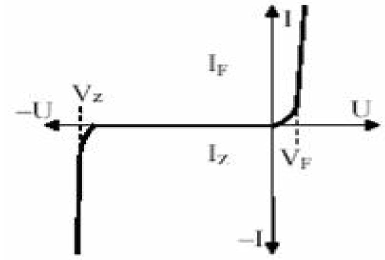

Fig. 3. DPC series device's U/I specific characteristic.

4. POWER CABLES PROTECTIONS

The cables protection by original technical solution [6] is based on the rectifying, by DPC devices, of divided voltage U, which appear on the cable's screen (due to capacity divider formed by cable's linear capacity C_l – 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 Fig.4.

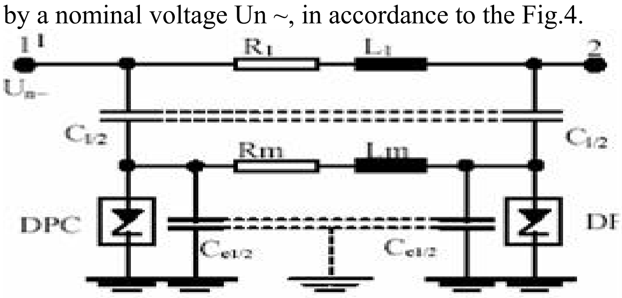

Fig. 4. Electric diagram of protected cable [6]: *Rl, Ll - active conductor's resistance, inductance; Rm, Lm - screen's resistance, inductance; Cl - cable's linear capacity (active conductor/screen); Ce - screen/soil capacity; 1, 2 - cable's ends; DPC - "solid state" device.*

By analyzing Fig.4 it result that the divided voltage U, which appears on cable's screen (at the DPC's connection) - calculable by (7) - is limited rectified by U/I zener type characteristic of DPC device [6] and so the cable's screen is being cathodic polarized from the soil through the ground plates from the terminal electric cells:

$$U = k \cdot Un = \left(\frac{Ci}{Ci + Ce}\right) \cdot Un \quad (7)$$

In these conditions, we are observing that, at the power cables afferent to UPL, by the presented sketch in Fig.4, it is actually insured a total –cathodic- active corrosion 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 reverse 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 (2), as the extraction and neutralization by (3) of already in ions by treeing (anterior to the DPC devices implementation) from the cable's insulator. In these conditions, it is obtained a drop of currents afferent to cable's partial discharges and, implicitly, a substantial raise of insulation resistance.

The method and afferent specialized devices [6] has been experimented on 30 medium voltages (10 and 20kV) UPL, realized with A2YSY or similar type of cables. In Fig. 5 we are presented a DPC mounting scheme and examples.

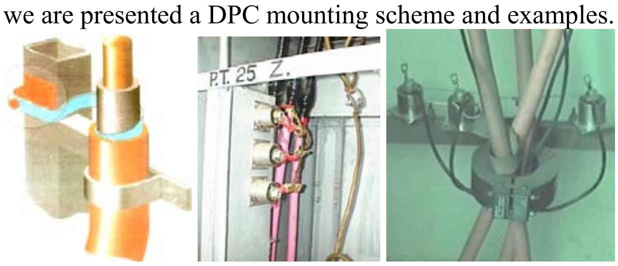

Fig. 5. The implementation of DPC devices.

Before the implementation of protection method [6], on each phase (cable) of UPL there has been measured the insulation resistance (at 5kV), which has been, took again after 6 and 12 months. From the comparative analysis of initial values with the ones periodic measured (six month interval), it result that, due to the functioning of corrosion protection [6], the insulation resistance *have been substantially increased* - 10 ÷ 7500 times (on R phase of UPL T3483/T204, Bucharest, the insulation resistance increased from 4MΩ to 30GΩ). This increase of insulation resistances is explained by 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 (3).

5. CONCLUSIONS

There has 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 resistance 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 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 from dielectric migrates towards the screen ("inverted treeing"), where they are reduced. In such conditions, the cable's insulation resistance is substantially increased.

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