# THE IMPACT OF THE ELECTROMAGNETIC POLLUTION OF THE ENVIRONMENT ON THE COMPLEX BUILD-UP MEDIA

IOSIF LINGVAY , ANDREEA VOINA, CARMEN LINGVAY, CARMEN MATEESCU

**Key words: Complex build-up media, Electromagnetic pollution, Stray currents, Corrosion.**

It were analyzed the main aspects regarding the impact of electromagnetic pollution of environment on the corrosion reactions in complex build-up media. The origin of A.C. and D.C. stray currents and their determinant factors are presented, too. From theoretical analysis of the superposed A.C. signals influence on the complex build-up media electrolytic environments resulted that the main effect of the A.C. pollutant signals consist of modification of kinetics parameters for electrochemical reactions that are developing in these – especially the increasing of the change current – that in the case of metallic structures which function in the natural electrochemical environments and/or build-up (wet concrete) carry on to the pronounced intensification of the degradation by corrosion.

## 1. INTRODUCTION

The durability and exploitation safety of constructions and installations is determinate by the degradation process, especially by corrosion.

The corrosion of metallic structures is a complex electrochemical process which is developed at the interface of metal/electrolytic media.

In case of the natural electrolytic media, the electrochemical system electrode/electrolyte (metallic structure/electrolyte – soil, ground water, wet concrete, in case of building media) is in equilibrium, being established between them an equilibrium corrosion potential $E_0$ which is determined by the system nature.

In overlapping of an electric field over the equilibrium system, through system is passing current, the system polarizes, the electrode/electrolyte potential are moving properly, the ionic atmosphere are deforming, it appears transport process and/or faraday, determining an appropriate changing in chemical composition of the electrolyte and /or surface phase of the electrode [1].

---

INCDIE ICPE–Advanced Researches, Bucharest, lingvay@icpe-ca.ro

Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **53**, *Suppl.*, p. 95–111, Bucarest, 2008

In these conditions, we can affirm that, in case of the natural electrochemical processes, as the degradations by corrosion of constructions and installations, the electromagnetic fields superposed on the reaction media can disturb the natural performing of the corrosion reactions, so they are disturbing (pollutants).

The purpose of this paper consists in theoretically analysis of the electromagnetic pollution impact of the environment on the corrosion process of metallic structures from the complex build-up media

## 2. **POLARIZATION OF ELECTROLYTIC MEDIA – STRAY CURRENTS**

Polarization currents of the metallic structures which are functioning in natural (soil, ground water, etc.) or anthropical (wet concrete) electrochemical media, caused by the electromagnetic fields superposed over the metal/electrolyte system, are called *dispersion currents* (“stray currents”), since their circulation and intensity is randomly, determined by their belonging sources.

### 2.1. ORIGIN AND INTENSITY OF STRAY CURRENTS

The source for all disturbing electrical signals of the natural electrochemical process is the chain / transport / distribution and utilization of the electrical energy system. The electrolytic environments (soil, ground water, wet concrete, etc.) are electrical conducting media of second type, having a rather low electrical conductivity that present an electric resistivity in range 0.1 Ωm and 100 Ωm. In these conditions, the current lines of a field that are applied to these media generate the changing of ionic atmosphere and of ion transport phenomenon that are described in [1]. In case that in this natural electrolytic environment (soil, ground water etc) or in industrial electrolytic environments (wet concrete), are posed metallic structures (underground metallic pipes, iron wires-concrete etc) these current lines are focus on preferential ways of high conductivity, on the shortest current way, that mean by metallic structures fixed in these environments, that have a resistivity below $10^{-6}$ Ωm. In this situation, the current lines cross (at least twice) the metal/electrolyte interface taking into account all the consequences on the mechanism and corrosion reactions kinetic.

#### 2.1.1. THE D.C. STRAY CURRENTS

The most frequent sources of the stray currents in continuous current that may cause important damages by corrosion are railways of the trams underground, as well as the industrial platform of with the equipments supplied with continuous current.

Unlike industrial platforms that produce stray currents having a relatively stabile intensity in time, the D.C. stray currents that are produced by urban electrical traction, present by their specificity (starting and stopping successively, carriages circulation), having big fluctuations in time of the intensities.

The simplified drawing of stray currents forming in c.c. from tram railways, for a single motion carriage and for a single adjacent metallic structure (metallic pipe) is shown in Fig. 1.

Certainly, in practice when the disturbed metallic structure is filiform (in case of long underground metallic pipes and of the urban utilities supply networks), this structure can be disturbed by stray currents that are produced by several trams that are simultaneously in motion. In this situation, the galvanic perturbation effects are overlapping.

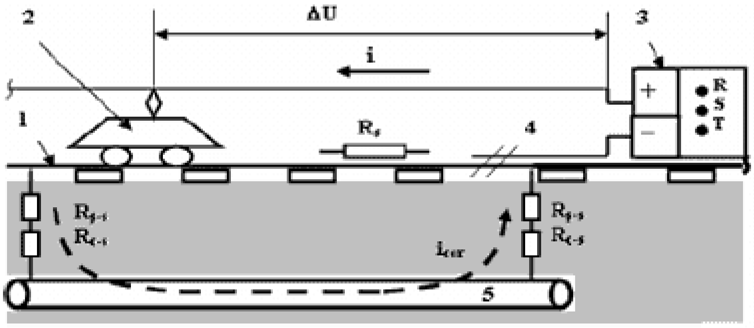



Fig. 1 – The simplified scheme of the stray currents in D.C. produced by the trams: 1 – tram railways; 2 – tram carriage; 3 – rectifying station for trams; 4 – return cable for tramline; 5 – metallic pipe; $R_{ş\text{-}s}$ – rail – soil resistance; $R_{c\text{-}s}$ – pipe/soil resistance; $R_s$ – resistance of the tram rail; $i_{cor}$ – stray current; $\Delta U$ – voltage drop on the rail; $i$ – traction current.

From the analysis of Fig. 1, it observes that the traction current $i$ (which actuates the tram engine) produce, on the tram rail with $R_ş$ resistance (between the connector place of the return cable "–" and tram position), a direct current voltage drop $\Delta U$.

The railway (rails/traverses system) being on the soil, by chain of resistances series (rail/soil, soil/pipe, pipe, pipe/soil and soil/rail), $\Delta U$ produces a stray current $i_{cor}$, of which intensity is determined by:

– voltage drop on the railway, $\Delta U$;
– rail/ soil dispersion resistance;
– resistivity, respectively, the electric resistance of the soil;
– dispersion resistance of the metallic pipe/soil, firstly, by anticorrosive insulation resistance of the metallic structure (organic layers applied on the pipe – when is the case).

In the large city area, where coexist the trams and subway, the disturbances by D.C. stray currents – in conformity with picture from Fig. 2 – are very complex.

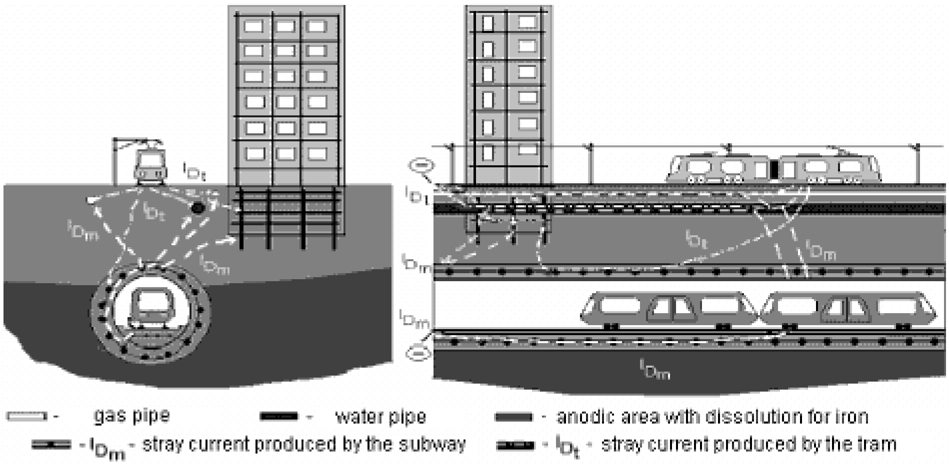



Fig. 2 – The scheme of stray currents circulation in a complex system, formed by subway, underground metallic structures, resistance structures from steel concrete and trams railway.

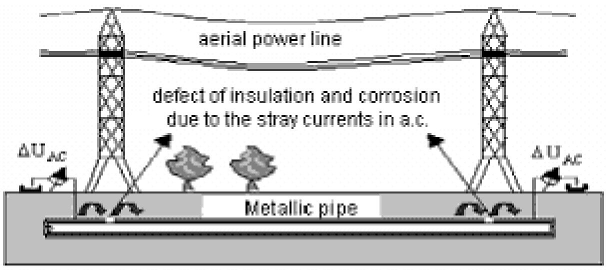
### 2.1.2. THE A.C. STRAY CURRENTS

Unlike the system generating of stray current in D.C., in A.C., the disturbing signals rise from the system of transport, distribution and utilization of the electric power by:

– induction (situations in which the underground metallic structure is in the region of aerial power lines, situation presented in Fig. 3);

– due to the disequilibrium currents which crossing between the grounding settings of the three-phase energetic system (presented in Fig. 4);

– ohmic voltage drops which appear on the rolling track of the railways with traction in A.C. and/or of the interactions among different metallic structures from the same environment (Fig. 5).



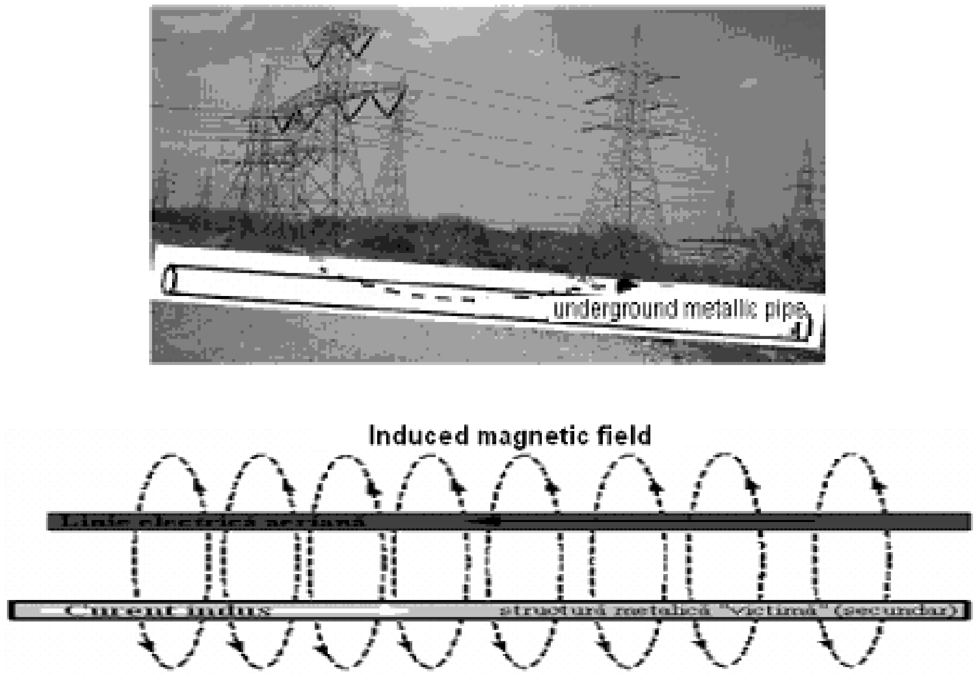



Fig. 3 – The scheme of the A.C. stray currents induction from a power line:
$\Delta U_{AC}$ – alternative voltage between metallic pipe and soil.

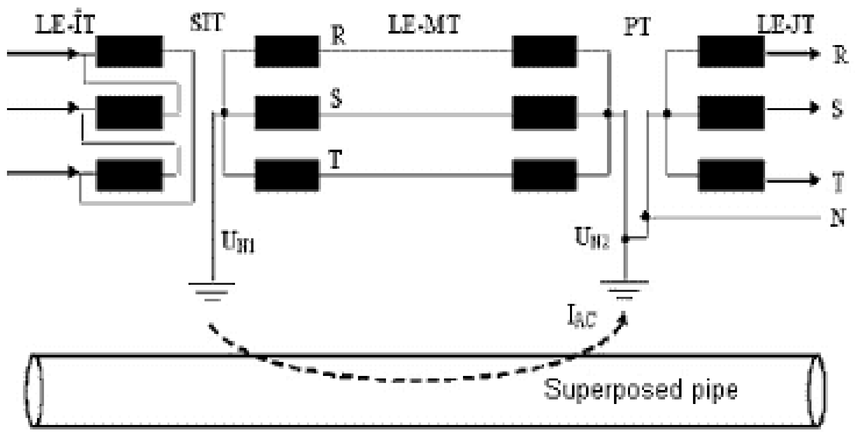



Fig. 4 – The scheme of the A.C. stray currents due to the disequilibrium's from the three phase energetic system; $I_{AC}$ – disequilibrium current that passes between grounding settings for of high/medium voltage station and of transformer plant of medium/high voltage; $U_{N1, N2}$ – disequilibrium voltages; LE – power line; IT – high voltage; MT – medium voltage; JT – low voltage; SIT – high/medium voltage station; PT – transformer plant.

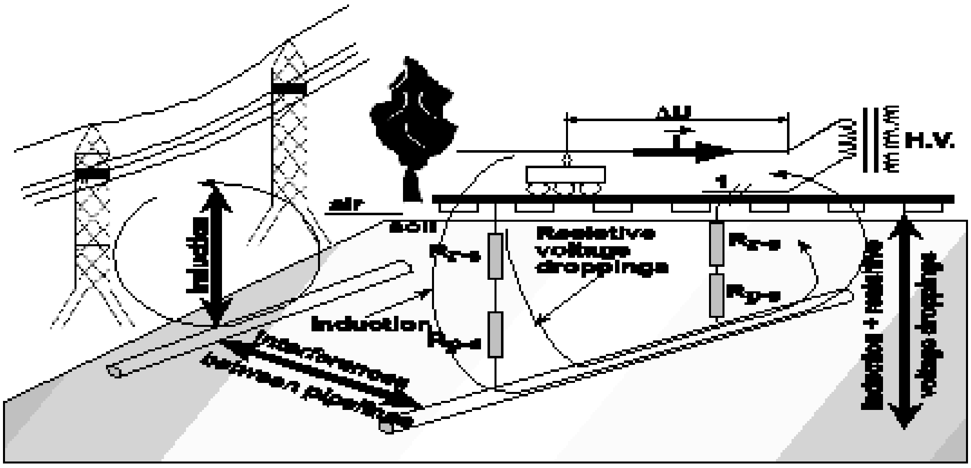



Fig. 5 – Stray currents interferences scheme in AC within a power line, electrified railroad and pipelines: $R_{r\text{-}s}$ – rail/soil resistance; $R_{p\text{-}s}$ pipelines/soil resistance; H.V. high voltage station; *1* – cables/rail contact.

### 2.1.3. COMPOSED STRAY CURRENTS

In practice, in the conglomerate urban environments, the natural electrochemical processes are disturbed by the stray currents, which have the origin in various sources. Thus, over the signal component of 50 Hz from the transport/distribution/utilization chain of the electric energy – from the three-phase energetic system (Fig. 3, Fig. 4 and Fig. 5) are superposed:

– harmonics (especially those odd) of the 50 Hz basic due to the system non-linearity;

– transients produced by the commutations from the system and electric drive with controlled rectifier diodes;

– components with high frequency produced by the industrial generators and supply sources in commutation;

– radio-frequency signals in 100 kHz ÷ 15 GHz spectrum produced by the broadcast, TV emitters, radio-communications systems, GSM telephony etc;

– the components of D.C. and these variations, produced by the urban electric traction (Fig. 1 and Fig. 2);

– the components in D.C., relative constants in time, rise from the industrial equipment supplied in D.C. (especially electrolysers).

It turns out that, in these conditions the disturbance current which polarizes the natural electrochemical systems is a composed current, and the shape of the disturbance signal is very complex.

## 2.2. THE IMPACT OF THE STRAY CURRENTS ON THE KINETICS OF NATURAL ELECTROCHEMICAL PROCESSES

Generally, an oxidation process (1) or reduction process (2) that is developing by charge transfer (electrochemical) can be written as:

$$\mathrm{R} \rightarrow \mathrm{O}^{z+} + \mathrm{ze}; \tag{1}$$

$$\mathrm{O}^{z+} + \mathrm{ze} \rightarrow \mathrm{R}, \tag{2}$$

where R is the reduced specie, $O^{z+}$ is oxidized specie, and $ze^{-}$ represents the number of exchanged elementary charges (electrons).

In the case in which the process speed (1) is equally with the process speed (2), the system is in equilibrium (3), to whom it correspond an equilibrium potential $E_0$.

$$\mathrm{R} \leftrightarrow \mathrm{O}^{z+} + \mathrm{ze}. \tag{3}$$

Polarization in D.C. of the electrochemical system that is in equilibrium (3), has as effect the motion of the electrochemical potential of the system to values more negative than $E_0$ in the case of cathodic polarization $E_k$ (4), respectively to values more positive in case of anodic polarization $E_A$ (5)

$$E_k = E_0 - \eta_k; \tag{4}$$

$$E_A = E_0 - \eta_A, \tag{5}$$

where, $\eta_k$ represents the cathodic overvoltage (6), and $\eta_A$ the anodic overvoltage (7):

$$\eta_k = a_k - b_k \cdot \ln j_k; \tag{6}$$

$$\eta_A = a_A - b_A \cdot \ln j_A, \tag{7}$$

where, $a_k$ and $a_A$ are the Taffel constants, $b_k$ and $b_A$ are the Taffel slopes – specific for the electrochemical systems, and $j_k$ and $j_\mathrm{A}$ represents the densities of the cathodic, respective anodic polarization current.

Like it determines from the relations (1÷7), the evolution of electrode potential in an electrochemical system in function of the polarization D.C. current can be illustrated by plotting (Fig. 6) of the polarization curves $E = f(j)$.

From the Fig. 6 analysis was determined that off the equilibrium potential $E_0$, the partial anodic current (the measure of the process speed (1)) is equally with, the partial cathodic current (the measure of the process speed (2)), namely $|i_a| = |i_k| = i_0$ – change current (the intensity of the charge exchanges to equilibrium).

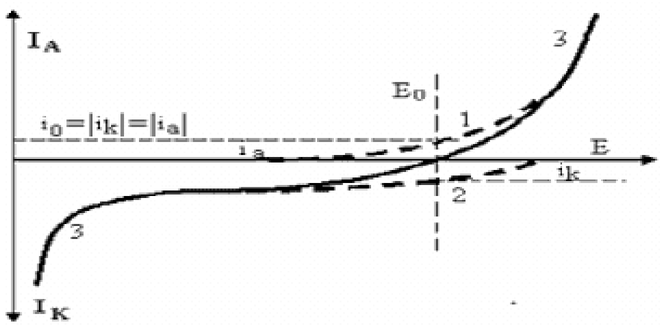



Fig. 6 – Polarization curves which characterize the electrode/electrolyte systems: 1 – polarization curve specific to partial anodic process; 2 – polarization curve specific to partial process; 3 – global polarization curve; $i_a$ – partial anodic current; $i_k$ – partial cathodic current; $i_0$ – the change current specific to the system; $I_A$ – global anodic current; $I_K$ – global cathodic current; $E_0$ – equilibrium potential; $E$ – potential of the electrode/electrolyte system.

The size of the change current $i_0$ is determined by the nature of electrolytic system and is:

$$i_0 = zFk_1C_{Me}\exp\left[-\frac{U_a^0 - \alpha zF\varepsilon_e}{RT}\right] = zFk_2C_{Me^{z+}}\exp\left[-\frac{U_k^0 + (1-\alpha)zF\varepsilon_e}{RT}\right] \quad (8)$$

where, $k_1$ and $k_2$ represent the equilibrium constants of the anodic partial reaction, respectively cathodic, $C_{Me}$ – concentration of the reduced specie, and $C_{Me^{z+}}$ – concentration of the oxidized specie, $U_a^0$ – activation energy of the partial anodic reaction, $U_k^0$ – activation energy of the partial cathodic reaction, $\alpha$ – transfer coefficient, $\varepsilon_e$ – equilibrium potential $E_0$, $R$ – gases universal constant, $T$ – absolute temperature.

Considering the electrochemical corrosion process, the reduced specie $R$ is metal Me that corrode itself, and oxidized specie $O^{z+}$ is the formed corrosion product, the metallic ion $Me^{z+}$ having valence Z, because the re-deposed metal in partial cathodic reaction (2) can not present the physical-chemical properties similar with those of dissolved metal in the partial anodic process (1), we notice that measure of metal corrosion natural rate $v_{cor}$ is just the change current specific to the mentioned electrochemical current, respectively $i_0 = i_{cor}$.

Also analyzing Fig. 6, we observe that, by anodic polarization of the metal in electrolyte (for example by D.C. stray currents) the metal corrosion is strengthening and the dissolving rate V (9) will be determined by anodic current intensity $I$, by Faraday relation (10), respectively (11)

$$V = \frac{D_m}{t}; \tag{9}$$

$$D_m = I \cdot t \cdot \frac{M}{zF}; \tag{10}$$

$$V = \frac{D_m}{t} = \frac{M}{z \cdot F} \cdot I. \tag{11}$$

It also noticed that at cathodic polarization of the metal with a current having higher intensity than $i_k$ (respectively than $i_0$), the corrosion of the metal is thermo-dynamic impossible (in compliance with principle of anticorrosive active-cathode protection).

The first theoretical studies regarding the A.C. signals impact overlapping on electrode/electrolyte systems was carried out by T. Erdey – Gruz and Devay [2]. Their studies was focused only on sinusoidal and linear signals superposed on equilibrium processes, analyzing the change current evolution and of equilibrium potential function of the electrochemical system nature, the A.C. signals applied to equilibrium systems can generate significant increase of the change currents and consequently of the corrosion rate. Recently, many studies and case analysis have emphasized the very high corrosion accelerator effect of the A.C. stray currents, both the underground metallic pipes [3, 4] (even to those cathodic protected against corrosion) and also to, steel concrete structures [5] that are burial [6] and/or apparent [7].

Among these studies, we can underline the observation of E. Binni [4] from 1997 that affirm followings: *Until now, some tenth of cases of heavily interfered pipelines have been reported în Europe.As a result, more than 700 corrosions have been reported, with a total of 4 gas leaks. Most probably, many other AC corrosion cases will be discovered as soon as the operators will focus their attention on this relatively new phenomenon*.

From Binni [4] observation we can conclude that the operators and the specialists of the underground metallic structure administrators (transport and supply networks for urban utilities, natural gases or liquid hydrocarbons transport pipes etc) do not know yet or are not familiarized with the specific aspects of the accelerated corrosion due to the A.C. stray currents this thing can be explained as this energy form is relative new being more frequent in the last two or three decimals, when as consequence of industrializing and technological development, the production and demand for electric energy have increased considerably, especially in the west Europe countries.

Also in this time, due to a technological development, using of magnetic amplifiers in electrical operating was completely surrendered, being replaced by the acting systems realized with electronic montages based on "solid state" devices (especially controlled rectifier diodes – "thiristors").

Typical to these electrical drive systems, besides all the technical-economical advantages, is the fact that they are strong transient generators so the non linear component content of the supplied electric energy increase significantly and, as a consequence increase the level of disturbing nonlinear A.C. stray currents.

It was demonstrated by experimental testing that the corrosion accelerator effect of the A.C. disturbing signals in disturbing conditions is considerably higher than for signals in nonlinear system [5].

The influence of disturbing A.C. signals superposed on the electrode process can be represented by applying a sinusoidal signal in the equilibrium potential of the system (Fig. 7) – or in case of prepolarized systems in D.C., in anodic (Fig. 8) or cathodic (Figs. 9, 10) dynamic potential.

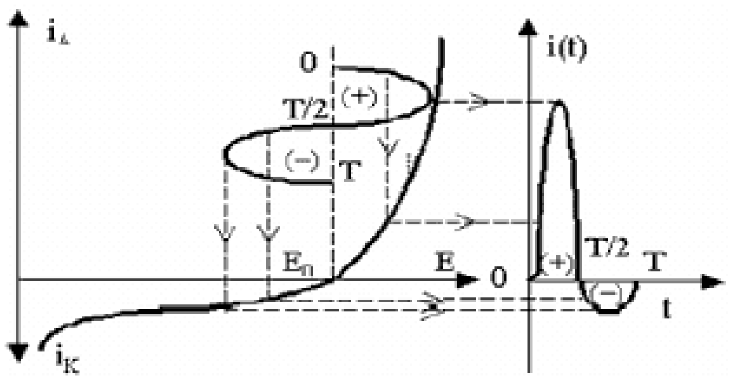



Fig. 7 – The influence of superposed A.C. signals on electrode/electrolyte interface in equilibrium ($E_0$) and the response of the electrochemical system.

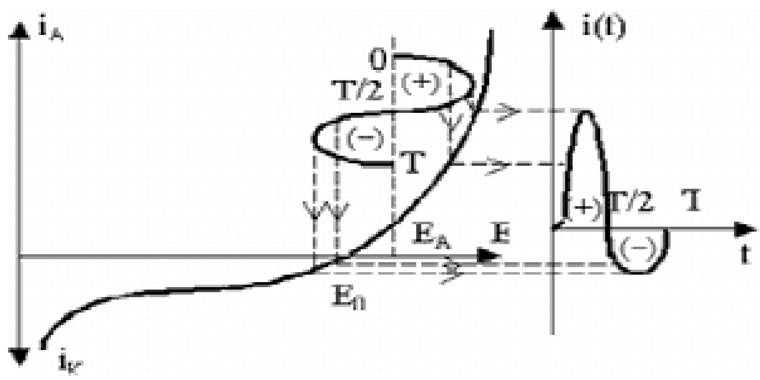



Fig. 8 – The influence of a superposed A.C. signal on an anodic prepolarised ($E_A$) electrode/electrolyte interface and the response of the electrochemical system.

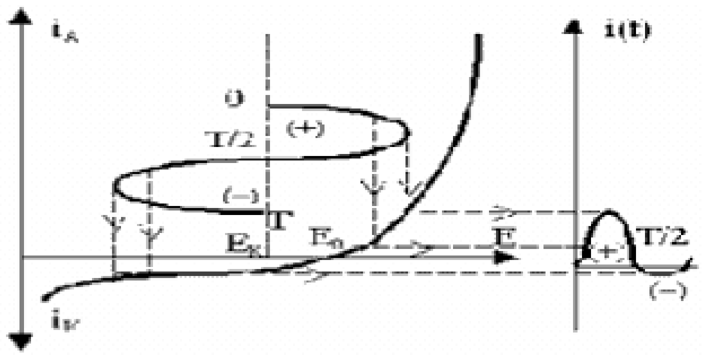



Fig. 9 – The influence of a superposed A.C. signal with relatively high amplitude on an cathodic prepolarised ($E_K$) electrode/electrolyte interface and the response of the electrochemical system.

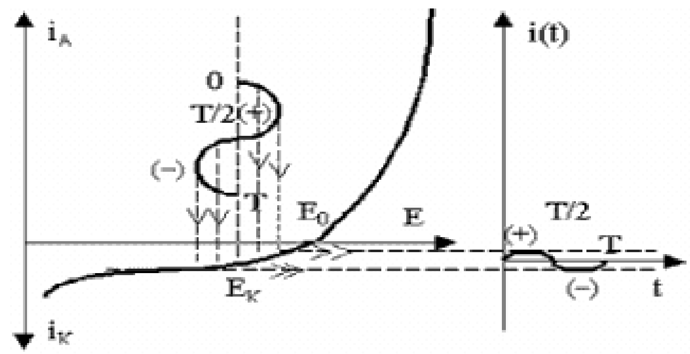



Fig. 10 – The influence of a relatively low amplitude (under 0.5 $V_{pp}$) A.C. signal superposed on an cathodic protected ($E_K$) electrode/electrolyte interface and the response of the electrochemical system.

Analyzing Figs. 7÷10 we notice that, excepting the cases where the electrochemical system is cathodic pre-polarized and the disturbing signal has low amplitude (values up to RT/zF, that means up to 0.05 $V_{RMS}$ – Fig. 10), the response of the electrolytic system to the A.C. disturbing signals is a deformed A.C. for which the positive (anodic) semiperiod contribution is higher than negative semi-period, so the system is preponderantly anodic polarized.

This effect is very accentuated for anodic prepolarized systems (Fig 8). In this situation, for metallic structures that operate in electrolytic environments (soil, ground water, wet concrete), the risk for damage by corrosion is extremely high.

It has also been observed that even in case of metallic structures protected against corrosion by cathodic protection (cathodic pre-polarization that are disturbed by pollutant A.C. signals at relatively high amplitude (above 0.05 $V_{RMS}$)

it arise the risk for corrosion degradation that is higher in case signals above $0.5V_{VV}$ [8].

## 3. THE IMPACT OF ELECTROMAGNETIC POLLUTION ON CORROSION FROM THE COMPLEX BUILD-UP MEDIA

World has firstly been confronted with depreciation by accelerated corrosion due to D.C. stray currents at the beginning of XX Century, when following the technical revolution, at the trams in Los Angeles, hypo traction was replaced by D.C. electric traction (1906). In two years only it has appeared significant damages in drinkable water supplying network, and in 1910 it was just reported the existence of the first mobile auto-laboratory, specialized in investigation and establishing of D.C. stray currents (Fig. 11).

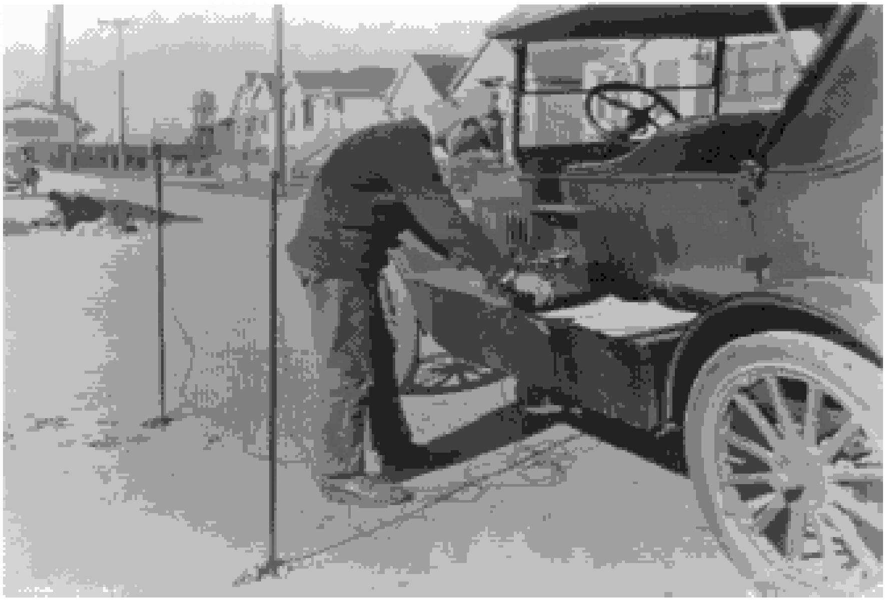


Fig. 11 – Mobile auto-laboratory designed for stray currents monitoring (Los Angeles 1910). In Background (left) it can be observed digging for an underground pipe perforated by stray currents.

In the absence of implementing a proper protective technical solutions and/or of conception and un properly make of a build-up complex systems, the intensity of the D.C. stray currents is high (for example, at under underground train in Bucharest it have been determined stray currents, up to 800 A [6] and consequently their afferent damages are considerably (Figs. 12–15).

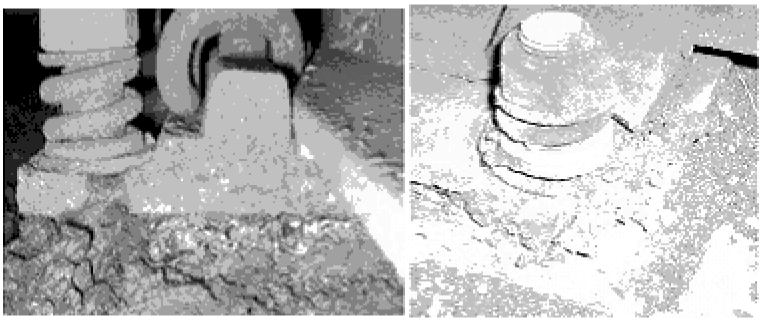


Fig. 12 – Advanced damages fixing element at underground train in Budapest (formed in about 2 years) due to D.C. stray currents.

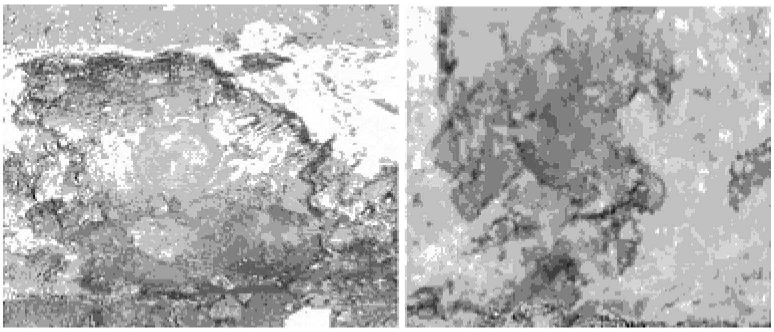


Fig. 13 – Localised corrosion on some gas pipes due to D.C. stray currents of trams and underground train in Bucharest.

Fig. 14 – Advanced corrosion of a medium voltage cable in Cluj, due to stray currents caused by trams [9].

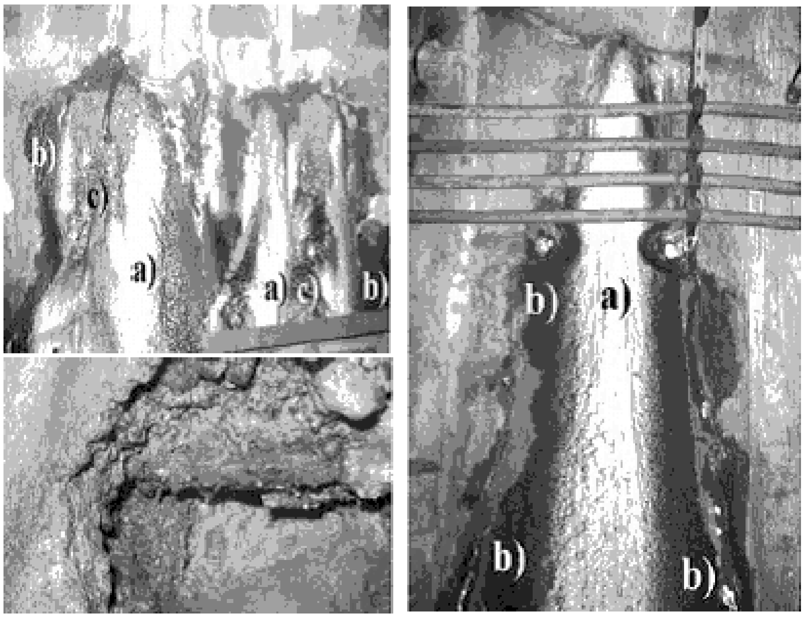



Fig. 15 – Underground tubes damages in Bucharest due to D.C. stray currents [6]:
a) calcium levigation; b) mycromicetes colony; c) iron dissolving.

Considering damages by accelerated corrosion of some metallic structures exposed to A.C. or in composed stray currents actions, these are illustrated by photos in Figs. 16 and 17.

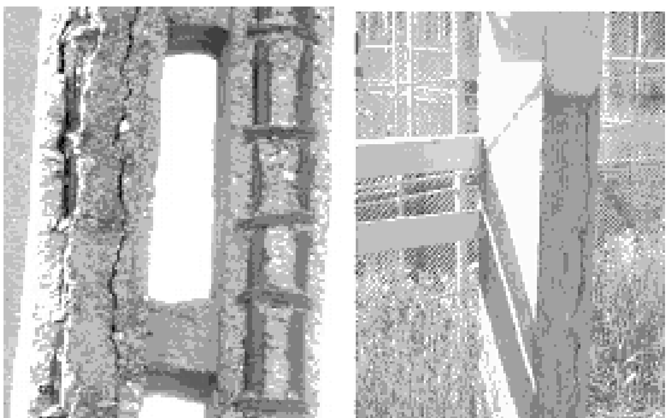


Fig. 16 – Steel concrete support elements degradation that are operating in high electromagnetic field.

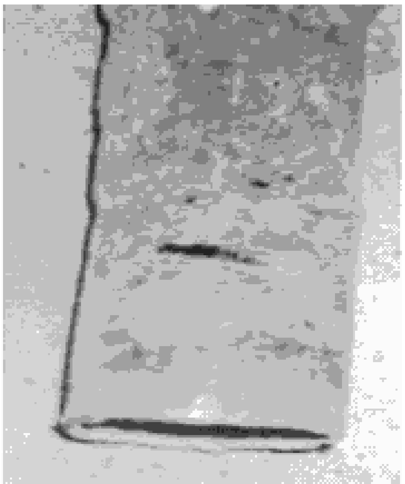


Fig. 17 – Generalized corrosion caused by composed (D.C.+ A.C.) stray currents.

For prediction of degradations and localization of the areas with high risk of degradation due to the electromagnetic pollution of environment, recently were elaborated computation models, which allow impact evaluation of some transport installations, distribution or utilization of the electric energy on a representative metallic structures, respectively the computation of the currents and voltages induced in the disturbed metallic structures [10]. By applying of these computation models, for resistance structure from steel concrete of a crossing bridge for more electrified railways it determined a good concordance (Fig. 18) among the places with maximum values of the induced currents and physical degradations of the bridge structure [11].

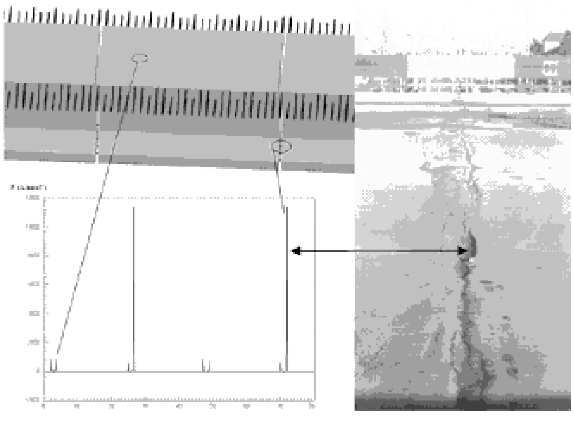


Fig. 18 – The visual degradations of the bridge are in good accordance with the maximum computation values of the induced current densities.

Beside the effect accelerator of corrosion for the environment electromagnetic pollution, is important the fact that the A.C. voltages induced in the metallic structures "victim" (industrial or civil installations, like pipes for transport and distribution of the natural gases) from the lines of transport and distribution of the electric energy, in some cases, can have dangerous values, that – in the absence of some technical solutions of adequate protection – can damage the operators security/integrity and/or of consumers (Fig. 19).

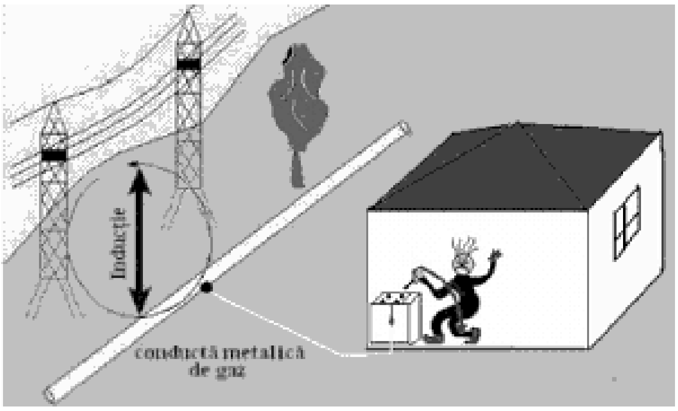



Fig. 19 – The induced voltages in the "victim" metallic structures of the environment electromagnetic pollution can achieve dangerous values for the servicing personal of the installations and/or of the natural gases consumers

## 4. **CONCLUSIONS**

It were analyzed the main aspects regarding the impact of electromagnetic pollution of environment on the corrosion reactions in complex build-up media.

From theoretical analysis of the superposed A.C. signals influence on the complex build-up media electrolytic environments resulted that the main effect of the A.C. pollutant signals consist of modification of kinetics parameters for electrochemical reactions that are developing in these – especially the increasing of the change current – that in the case of metallic structures which function in the natural electrochemical environments and/or build-up (wet concrete) carry on to the pronounced intensification of the degradation by corrosion.

Also, were analyzed the provenience sources of the electromagnetic pollution of the natural and complex build-up medium and it concluded that the source of all disturbing signals, of the D.C. and A.C. stray currents – both linear and/or nonlinear regime – is the system of transport/ distribution/utilization of the electric energy.

Of course without electric energy, modern life on the Earth can not be conceived – so the humanity must be aware of fact that the electric energy utilization has negative effects on the environment – both on the biological environments, and on complex build-up medium. In these conditions it imposes the intensification of the studies and researches which must regards on the one hand optimization/diminishing of the electric energy consumption, and on the other hand the diminishing of the electromagnetic pollution impact of environment on both of bio-electrochemical processes from nature, and on the corrosion reactions from the complex build-up media.

ACKNOWLEDGMENTS. The authors thank medc for the sustained financing of the research, especially of the ceex program, by which was realized this paper (the director project).

*Received on 15 September, 2007*

## REFERENCES

1. Iosif Lingvay, Carmen Mateescu, Carmen Lingvay, Andreea Voina, *The Impact of the Anthropic Electromagnetic Fields on the Electrochemical Reactions from the Biosphere*, The 4$^{th}$ International Workshop of Electromagnetic Compatibility, CEM 2007, September 18–19, 2007, Baia Mare, Romania, pp. 45–53.
2. T. Erdey-Gruz, J.Dévay, Acta Chimica Acad. Sci. Hung., **37**, (1963), p. 405.
3. W. Vesper, *Wechselstromkorrosion,* 4-th International Conference CEOCOR '97, 3–5 September, Viena, secteur A, pp. 45–67.
4. E. Binni, L. Di Biase, *Assessment of External Corrosion Protection of Buried Pipelines*, 4-th International Conference CEOCOR'97, 3–5 September, Viena, secteur A, pp. 18–36.
5. Cristina Rata Lingvay, F. Stoian, *Study of Reinforced Steel Concrete Corrosion in the Presence of Stray Currents* (*D.C. and A.C.–Linear and Non-Linear Regime*) – EUROCORR '97, Trondheim, Norway, 22–25 Sept. 1997, Vol. I, pp. 445–451.
6. I Lingvay, M. Gabor, Carmen Lingvay, *Degradarea prin coroziune a structurilor din beton armat. 1. Studii privind coroziunea structurilor din beton armat, aferente metroului din Bucureşti*, Rev. Chimie (Bucureşti), **57**, *2*, 2006, pp. 180–183.
7. I. Lingvay, Carmen Lingvay, C. Homan, O. Ciogescu, *Degradarea prin coroziune a structurilor din beton armat. 5. Contribuţii la studiul coroziunii elementelor de susţinere din beton armat din instalaţiile de transport şi distribuţie a energiei electrice*, Rev. Chimie (Bucureşti), **57**, *12*, 2006, pp. 1279–1282.
8. I. Lingvay, *Coroziunea datorată curenţilor de dispersie "vagabonzi"*, Edit. Electra, Bucureşti, 2005, p. 168.
9. I. Lingvay, Carmen Lingvay, O. Ciogescu, C. Homan, *Contribuţii la studiul şi controlul degradărilor prin coroziune ale cablurilor electrice subterane. 1. Studiul stării de coroziune a unor linii electrice subterane*, Rev. de Chimie (Bucureşti), **58**, *1*, 2007, pp. 44–47.
10. D. D. Micu, I. Lingvay, E. Simion, *Modelarea şi predicţia fenomenelor de interferenţă în regim electrocinetic*, Edit. Electra, Bucureşti, 2006 .
11. L. Man, D. D. Micu *et.al.*, *Numerical modeling of perturbations produced by A.C. electrical traction system,* URB-CORR 2007, Cluj, Romania, 20–23 June 2007, pp. 35–41.