ENERGY ISSUES AND THE IMPACT ON ADJACENT METALLIC STRUCTURES OF RUNNING ROUTES IN URBAN ELECTRIC TRANSPORT SYSTEMS

*CSUZI I.,** LINGVAY I., *SILAGHI E., **LINGVAY C.
*Regia Autonomă de Transport Local, Oradea, www.otlra.ro; E-mail: dir.gen@otlra.ro
**INCDIE ICPE-CA, Bucureşti, www.icpe-ca.ro; E-mail: lingvay@icpe-ca.ro

Abstract - In order to optimize energy consumption of urban electric transport, energy losses on the supply chain of trams were analyzed. From the results of studies we concluded that energy losses in transmission systems powered by DC can be diminished by sizing, implementation and maintenance of adequate maintenance of rectifying power stations, DC power lines, running routes and lines of contact.

Key words: urban electric transport, energy, energy loss

1. INTRODUCTION

Industrialization, urbanization, development of large urban areas required the development of organized urban public transport systems. Thus, the first organized form of urban public transport can be considered the "carriage"-type vehicle called omnibus (developed in Paris in the days of King Louis XIV). Englishman John Outram in 1775 invented the iron rail vehicle towed by horses. In 1852, through the project leaded by engineer Loubat, practically appeared the first form of tram – cars on steel rails (embedded in the pavement of the streets), pulled by horses. The system has developed rapidly; as reported in 1889 in Paris arranged routes (tracks) of about 800 km. were served by 21,000 horses, and in Budapest on routes of 41 km were used 1042 horses.

In Romania in 1869 is installed at Timişoara the first horse-tram. Subsequently, on 28 December 1872 is put into service in Bucharest the horse-tram to travel on the route Calea Griviței, Piața Sf. Gheorghe, Calea Moşilor, Obor.

Mechanization of the horse powered trams became one of the essential concerns of the 19th century innovative engineering activity. Although suffering of several attempts of utilization on traction vehicles of public transport in cities, the improvement of the steam engine did not spread because of noise and smoke (e.g. Rowan-Danemark, 28th of August 1882 – Oradea, 1906 – Bucureşti – tram with steam engine used on Gara de Nord - Bucureştii Noi route, etc.).

Urban transport significantly contributes to environment pollution (nuisance, dust, phonic, etc.). From this point of view, urban electric transportation systems present a series of advantages like: they do not pollute the urban atmosphere with noxious and produce relatively reduced phonic pollution too. Regarding these considerations, in the 19th century, one preoccupied with the development of urban transportation systems with electric traction. In this context it is notable:

- Werner SIEMENS builds the first electric locomotive 5HP, 180 V supply between the two rails being insulated one from the other and on the 16th of May 1881 at Berlin (Gross-Lichterfelde). The first line to operate public transport by electric traction is on a 2.45 km route, with an average speed of 20 km/h;
- Werner SIEMENS builds the first electric locomotive powered between the rails and one contact airline (350 V contact line) and in 1882 the first line operates in current form (Berlin – on route Charlottenburg-Spandauer Bock).
- Siemens-Halske sets up first line to operate by electric traction in Budapest city (30th of July 1889);
- 1981 electric tram is being used at Kiev;
- 9th of December 1899 the first operating line with electric traction is given in service at Bucharest city (route between Obor and Cotroceni);
- 27th of June 1899 the first operating line with electric traction is given in service at Timişoara city;
- Kandó Kálmán (1869-1931) invents and builds locomotives operating with electric traction using induction motors – in 1898, two A.C. current power lines are put in place (Lugano-Elveția, Evian le Bains-France);
- at the beginning years of the 20th century, first underground urban transport line are put in place;
- in March of 1906, at Oradea city, rail urban transport is replaced by trams using steam engines supplied from an 550V airline and 185 kW power source (Ganz "unformer") [1].

In this context, to reduce costs and to reduce urban pollution, electric traction was extended to urban transport of goods, system which operated in Oradea from 1907 to 1979 (Figure2.).

Fig. 1. First trams in Oradea city (traction with the help of two 35 kW engines)

I.S.S.N. 2067-5538 © 2010 JSE

Fig. 2. Urban transport of goods using electric traction – Oradea '70s

The urban electric transport system using electric traction is usually being supplied with D.C. – rails being used as way back for "–" traction current, causing electric interferences (galvanized) between metallic structures of adjacent running routes (tracks). As so, in only 2 years after replacement of horse powered trams with electric power ones, Los Angeles was found to encounter the water supply networks damage, really explained by the D.C. traction generated stray currents of the running routes. Therefore, one century ago, in 1910, a mobile laboratory was built for measurement of stray currents (Figure 3).

Fig. 3. Mobile laboratory built for determining dispersion of "stray" currents

The generation of stray currents is determined, mainly, by the ohmic resistance of the running routes (of rails), and the voltage drop of the rail caused by traction current passing through it.

Voltage drops, both on rail and the entire D.C. supply system of the trams – rectifier, contacts, cables, contact lines etc. – diminish the supply voltage on the terminals of the traction engine and hence the energetically efficiency of the system.

Therefore, *the purpose of this work* is to analyze energy losses on the power supply systems elements of the D.C. urban electric transport on rails.

2. URBAN ELECTRIC TRANSPORT ON RAILS

2.1. Equivalent scheme of supply system

In terms of electricity, the main elements of urban electric transport system on rails (tram and metro) can be grouped as follows:

- Supply system (rectifying stations and its related equipment, connection, measuring and protection systems)
- „+" power lines (power cables and contact lines)
- „–" power lines (return cables and running routes)
- Cars with engine drive systems and related utilities (air compressor for braking, lighting, heating, operated doors etc.)

Simplified electrical drawing of electric urban transport system itself is presented in Figure 4.

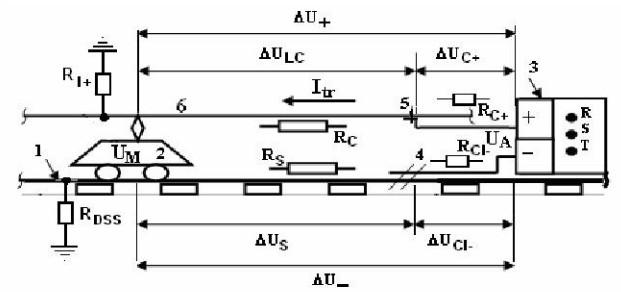

Fig. 4. Simplified sketch of the urban electric transport system on rails

The symbols used in Figure 4. are: 1 - the tread itself; 2 - engine wagon; 3 - power station; 4 - „–" return cable junction in the tread; 5 - „+" power cable junction to the contact line; 7 - power cable; I_{tr} - traction current; R_{I+} - insulation resistance of the contact line above the ground; R_{DSS} - resistance dispersion track / ground; R_S - runway resistance between 4 and engine wagon position; R_C - resistance of the contact line between 5 and the car engine position; R_{C+} - „+" power line resistance; R_{CI-} - „–" return cable resistance; ΔU_+ - voltage drop on „+" current routes; ΔU_{C+} - voltage drop on the „+" power cord; ΔU_{LC} - voltage drop on the contact line; ΔU - voltage drop on „–" current routes; ΔU_{CI-} - voltage drop on „–" return cable; ΔU_S - voltage drop on the tread (rails) between 4 and position engine wagon; U_A - power lines voltage supply; U - voltage at the terminals of the motor drive traction system .

In terms of the electrical supply neither the urban electric rail transport area (trams) and the underground (subway), does not present essential differences. What differs is the usual way of making „+" contact line, and hence its fixing insulators.

2.2. Energy efficiency - energy losses

Analyze of scheme in Figure 4. indicates that, for an engine and drive system (command) related data, in terms of energy can be defined:

- Energy efficiency of power plant (transformer MV / LV and recovery facility) – η_A, ratio between energy debit on „+" and „–" terminals and energy consumed by the input terminals and the downward voltage transformer (MV / LV – 6kV / 0,7kV)

- Energy efficiency of supply lines, witch, at a proper load (traction current) is given by:
  - ohmic voltage falls on „+" power lines (ΔU_+), given by the amount of power failure on:
    - „+" power cables (ΔU_{C+});
    - contact lines (ΔU_{LC});
    - ohmic contact between pantograph and contact line;
  - an ohmic voltage fall (ΔU_-) on „–" power lines given by the sum of power failure on:
    - „–" return cables v(ΔU_{CI-});
    - the thread (rails) (ΔU_S);
    - ohmic contact between tram rails and wheels;
  - current leakage through insulation resistance of the contact line above the ground R_{I+};

Of the above shows that energy losses on E_{PLA}, power lines in time „t" are (1):

$$E_{PLA} = \left(\Delta U_- + \Delta U_+\right) \cdot \int_0^t I_{tr}(t) \cdot dt \qquad (1)$$

Where the voltage drop on ΔU_- and ΔU_+ power lines are (2) and (3):

$$\Delta U_- = \left(R_S + R_{CI-}\right) \cdot \int_0^t I_{tr}(t) \cdot dt \qquad (2)$$

$$\Delta U_+ = \left(R_C + R_{C+}\right) \cdot \int_0^t I_{tr}(t) \cdot dt \qquad (3)$$

Also that there is an energy loss, in time „t", on the insulation resistance of the contact line as long as they are under voltage U_A (even though that power section is being circulated or not), the energy loss is (4):

$$E_{PLC} = \frac{U_A^2}{R_{I+} + R_{DSS}} \cdot t \qquad (4)$$

For a given load (wagon with a related load) the integral traction current is determined by the motorman's driving methods. Under these conditions, at a given supply voltage and R_{DSS} negligible compared to the value of R_{I+}, as shown in (1) (2), (3) and (4), virtually the energy losses on feeding lines are determined by R_C, R_{C+}, R_{CI-}, R_S and R_{I+}, resistances and increase with R_C, R_{C+}, R_{CI-}, R_S increasing and R_I decreasing. For these reasons, minimize the specific energy consumption of urban rail power transmission lines can be done so:

- reducing the length of the „+" power sector, which implies a corresponding reduction of R_C;
- increasing the number of return centers, which implies a corresponding reduction of R_{CI-} and R_S;
- by optimizing geographical arrangement of the recovery stations one can minimize the length of „+" and „–" connection cables and the reduction of R_{C+} and R_{CI-};

Of course, all these measures, and the increase of current section valleys (of the rails, of the cables and the contact lines) all have economical limits, which implies technical and economical optimization both for projects/new investments and the restoration / refurbishment of present ones.

2.3. Stray currents

Analyzing Figure 4, there is a voltage fall, between the position of the wagon and the place the „–" return cable coupling to the runway, due to the R_S ohmic resistance of the runway and the total current consumed by the tram (traction current + auxiliary current consumer, compressor, lighting etc.). Sincerely that in practice the tread is posed on the ground (directly or indirectly through the foundation of reinforced concrete), it will generate I_D stray currents through the ground, currents with intensity proportional to the ΔU_S and inversely proportional to the sum of dispersion resistance of the runway R_{DSS}.

Soil is a case II electro conductive medium with a relatively high electrical resistivity, usually between 1 and 100 Ω•m. In large urban soil, specially including those with urban electric transport, there are posed a number of steel structures like: metal pipes for water related networks, sewer, gas, electric cables for low, medium and high voltage, reinforced concrete structures, foundations of buildings and civil engineering, resistance structure of art works - bridges, viaducts etc. These metallic structures having an electrical conductivity $10^7 \div 10^9$ times higher than the soils electrical conductivity, I_D current lines will preferentially flow through these metal structures with all related electrochemical reactions (corrosion), adverse consequences on the integrity and safety in mining [2], accelerated degradation of reinforced concrete structures [3], punching of underground metallic pipes, accelerated aging of underground power cables [4] etc.

There is a polarization of the interfered metal surface on the ground, a cathodic polarization in the position closest to the engine wagon and an anodic polarization in an area closest to the centre, when I_D current lines pass from soil to metal and metal to ground, situation in which the metal structure interfered dissolve anodically at the back of return centers.

In the case of DC stray currents, in anodically polarized areas, metal is dissolved at a rate proportional to the amount of electricity passing through the steel / concrete interface, and, as in Faraday's law, the m mass of the steel dissolved in time by a disturbing current having an intensity of I, is:

$$m = k\,Q = \frac{M}{n\,F}\,Q = \frac{M}{n\,F}\int I(t)\,dt \qquad (5)$$

where: - k - specific metal constant, Q - quantity of electricity passing through the electrochemical system, M - atomic mass of dissolved metal, n - metals valence, F - Farraday's constant (1F=96.500C/ equivalent gram) and expresses the amount of electricity required for the submission of a gram equivalent of any metal. From a theoretical point of view, Farraday's constant is correlated with Avogado's number N_A, as below:

$$1F = N_A \cdot e \qquad (6)$$

where: N_A is the number of ions in grams of one mole (in our case, iron), e - electron charge having the value $e=1,602 \times 10^{-19}$ coulomb.

To highlight the dangerous forms of corrosion, one proposed a calculation exercise: considered dispersion current with the intensity of just 1A, acting on a metal structure of carbon steel for one year, and require the amount of dissolved steel. If in (5), we considered the intensity of current being constant, $I(t)$ = constant = 1A, we calculate the mass of iron dissolved in one year. We obtain a mass loss of $\Delta m \approx 9,15$ kg / year, the equivalent of:

- approximately *1161 cm*^{3} carbon steel which represents almost *14,8m reinforcement bar having de 10mm diameter, or cca 3,7m reinforcement bar having de 20mm diameter,* dissolved in one year; or
- approximately 1100 holes with *1cm*^{2} surface in only one year (average of 3 per day), in a gas pipeline with 10 mm wall thickness; or
- approximately *9,15 kg/year steel metal screen or* approximately *10,5 kg/year cooper metal screen dissolved on underground power cables* and with their implications on the dielectric rigidity of their insulation.

Considering V being the speed of the anodic dissolution of metal, (including carbon steel associated to metal structures adjacent to running channels of urban electric transport system on rails), with the mass of metal Δm dissolved in time t, one can determine the intensity of dispersion current and the intensity of anodic current that polarize the metal surface, the current passing through the electrolyte system as so:

$$V = \frac{\Delta m}{t} = \frac{M}{z \cdot F} \cdot I \qquad (7)$$

As neither, the dispersion resistances R_{DSS}, and the currents consumed by motor wagon are not constants, results that in practice the intensity and I_D current routes are random hence the name dispersion or „stray" currents.

If it is considered that the metal structure disturbed by stray currents generated by the trams in a steel pipe, for analysis one propose the electrical equivalent diagram from Figure 5:

The significance of notations from Figure 5 are: *SR* - Rectifying station for D.C., R_{C+} - resistance of the „+" contact line cable, I_{tr} - traction current intensity, R_C - electrical resistance of the contact line, R_M and L_M - resistance and inductance of the traction motor, R_{sv} - electrical resistance of consumers of various services (lighting, compressor, heating etc.), $R_Ş$ - electrical resistance of the rail line, R_{DSS} - dispersion resistance of rail/ground; R_{sol} - electrical resistance of the soil between the rail and pipeline, R_{Csol} - resistance between the metal disturbed structure and the ground, R_{strmet} - electrical resistance of the disturbed metal structure, R_{CI-} - electrical resistance of the returning „–" cable, "; I_{Dcor} – intensity of the dispersion current that cause accelerated corrosion of the metallic structure disturbed by anodic dissolution of the metal, I_{trs} - traction current flowing through the rail, A - cable connection, B - wagon position.

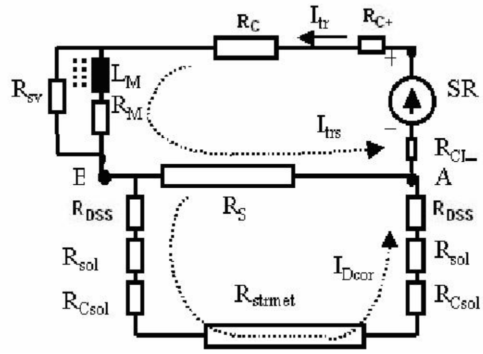

Fig. 5. The electrical equivalent diagram of D.C. stray currents

The sketch showing the stray currents in metal structures adjacent to the running tracks of the trams is shown in Figure 6 (for a metal pipe), and in Figure 7 (for a reinforced concrete structure):

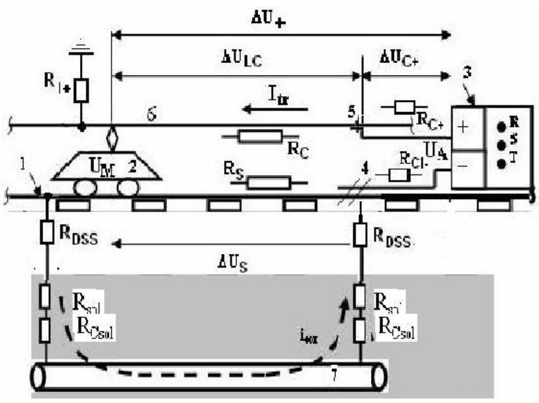

Fig.6. D.C. stray currents running through an underground metal pipeline

where; 1 - tram running route, 2 - tram wagon, 3 - power station (rectifier), 4 - returning „–" cable connected to the trams running route, 5 - „+"cable connected to the contact line, 6 - contact line, 7 - disturbed metallic pipeline, I_{tr} - traction current, R_{I+} - insulation resistance of the contact line above the ground, R_{DSS} - dispersion resistance of rail/ground; R_S - runway resistance between contact line 4 and engine wagon position 2; R_C - resistance of the contact line between 5 and the car engine position; R_{C+} - „+" power line resistance, R_{CI-} - „–" return cable resistance; ΔU_+ - voltage drop on „+" current routes; ΔU_{C+} - voltage drop on the „+" power line; ΔU_{LC} - voltage drop on the contact line; ΔU - voltage drop on current routes; ΔU_S - voltage drop on the tread (rails) between 4 and position engine wagon; U_A - power lines voltage supply, U_M - voltage at the terminals of the traction engines drive system, R_{sol} - electrical resistance of the soil between the rail and pipeline, R_{Csol} - resistance between the metal disturbed structure (7) and the ground.

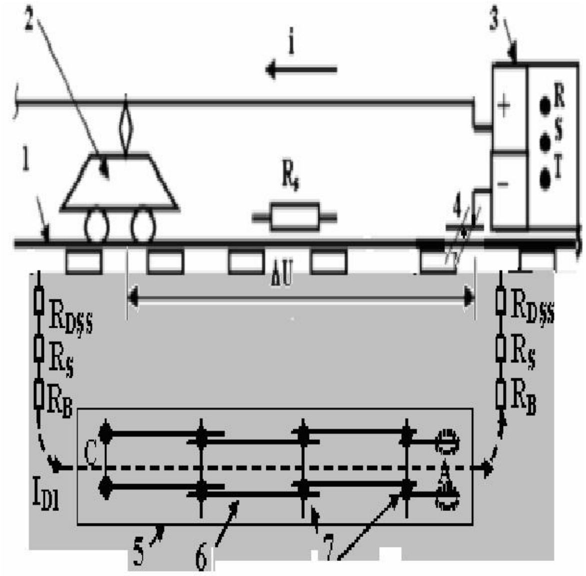

Fig. 7. Generated D.C. stray currents running through reinforced concrete structures

where, 1- tram running route, 2 - tram wagon, 3 - power station (rectifier), 4 - returning „–”cable connected to the trams running route, 5 - reinforced concrete foundation, 6 - reinforcement bars, 7 - joints between the reinforcing bars, i - traction current, $R_Ş$ - electrical resistance of the rail line, ΔU - voltage drop on rails, R_{DSS} - dispersion resistance of rail/ground, R_S - resistance of the ground, R_B - electrical resistance of concrete, I_{D1} - dispersion current through reinforced concrete structures, A - anodically polarized area (anodic dissolution), C - cathodically polarized area.

The degradation of concrete structures is a complex process, in which the accelerating effect of stray currents is substantial. The stray currents accelerate not only the deterioration of concrete structures but the reinforcement corrosions too. Thus in areas with excessive cathodic polarization oxide constituents of concrete reduce their degree of oxidation, followed by the diminution of their volume, which produces concrete cracking. Anodic dissolution occurs in certain areas of concrete structure what reduce the growth of porosity and a sharp decrease of resistivity of concrete. Also, in anodic areas concrete reinforcement is being dissolved.

For large urban areas operating in metro and trams, metallic and reinforced concrete structures interferences adjacent to running channels, are more complex. The simplified sketch of the movement and the formation of stray currents illustrating complex interferences are presented in Figure 8:

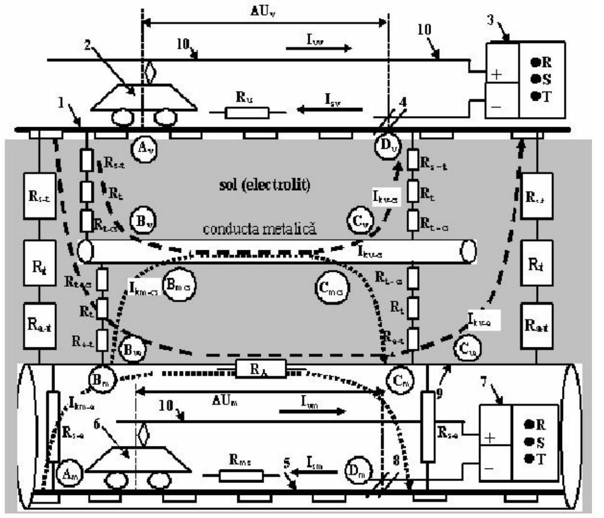

Fig. 8. Simplified sketch of C.C. disturbances, characteristic for large urban areas.

where: 1 - tram running route; 2 - tram position; 3 - tram power supply source; 4 - returning „–”cable connected to the trams running route; 5 - metro running route, 6 - metro wagon; 7 - metro wagon power supply source; 8 - returning „–”cable connected to the metros running route; 9 - metro tunnels metallic structure; 10 - „+” contact lines; R_{s-t} - dispersion resistance between tram running route and ground; R_t - the equivalent resistance of the ground; R_{t-cs} - dispersion resistance between the adjacent disturbed metallic structure (underground pipeline) and ground; R_{a-t} – dispersion resistance between the metallic structure of the tunnel and ground; R_{s-a} - dispersion resistance between the metro running route and the metallic structure of the tunnel; R_{vs} - line resistance of the tram running route; R_{ms} - line resistance of the metro running route; R_A - line resistance of the metal structures associated with the resistance of the metro tunnels and galleries reinforced concrete structure; I_{sv} - current passing through tram running route; I_{vv} - tram traction current; I_{kv-cs} - dispersion current produced by trams between interfered metallic structures; ΔU_v - voltage drop on tram running route; ΔU_m - voltage drop on a single metro running route; I_{sm} - current passing through metro running route; I_{vm} - metro traction current (contains wagon consumers current, compressors, lighting, etc.); I_{km-cs} - stray current produced by metro through the interfered metallic structures; I_{km-a} - stray current produced by metro through the metro tunnels metallic structure; R, S, T - rectifiers three-phased power supply; A_v - stray currents polarize and dissolve anodically the trams running route; B_v - tram produced stray currents pass through disturbed metallic structure and polarize them cathodically; C_v - tram produced stray currents exit disturbed metallic structure and polarize them anodically; B_{va} - tram produced stray currents enter the metallic structures of the metro tunnel; C_{va} - tram produced stray currents exiting the metallic structures of the metro tunnel and polarize them anodically; A_m - metro produced stray currents exit the running route and anodically dissolve not only the track shoe but the metal elements used for mounting the rail on sleepers; B_m - metro produced stray current enter the tunnels reinforcement; C_m - metro produced stray current exit the tunnels reinforcement; D_m - stray currents return to the running route; B_{mcs} - metro produced stray currents enter the tunnels adjacent disturbed metallic structure, polarizing cathodically the pipeline; C_{mcs} - metro produced dispersion current exit the tunnels adjacent disturbed metallic structure and anodically disturb the electrochemical equilibrium steel pipe / soil.

From the analysis of Figure 8, results highly complex interactions such as metro running rout systems/ metro tunnel associated metal structures/ underground metallic structures/ tram running routs. So, the stray currents generated by the metro running rout - A_m - polarize anodically and galvanically disolve metal elements for mounting the rail in places where insulation track / foundation is weak (Figure 9).

Fig. 9. Deterioration of the running routes rail fixings caused by stray currents

Current lines are closed by steel reinforcement of the tunnel and on the right side of the return center - C_m - and anodically polarize the reinforcement. Also nearby A_m, ,I_{km-cs} exit the tunnels reinforcement, pass through the adjacent metallic structure of the tunnel, and from there exits nearby the return center and anodically dissolves it s metal - $C_{mcs.}$. Similarly, tram produced stray currents pass through metallic underground pipeline I_{kv-cs}, and through metro tunnels reinforcement producing their anodic dissolution.

Representative images of the destructions caused by stray currents of underground reinforced concrete structures are shown in Figure 10.

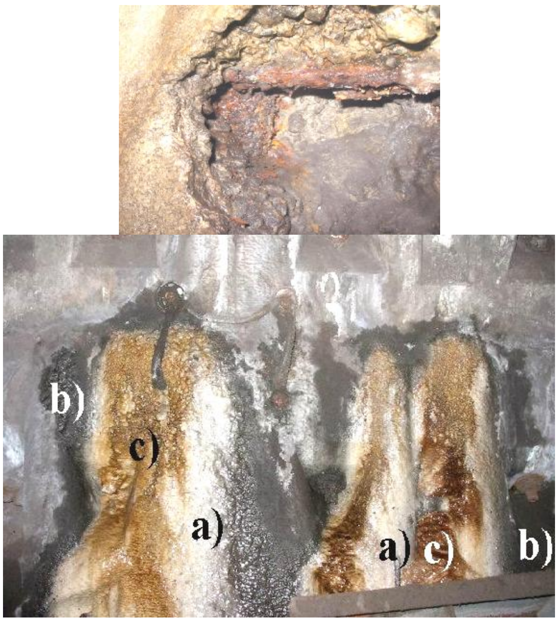

Fig. 10. Deterioration of concrete structure for the underground tunnel caused by stray currents and groundwater: a) leaching calcium; b) micromicete colonies; c) irons armor dissolution

Representative images showing of underground metal pipes perforation is shown in Figure 11. Figure 12 illustrates damage to underground cables caused by stray currents.

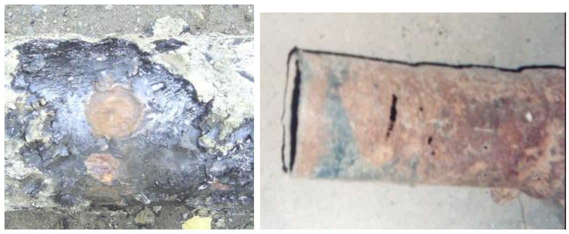

Fig. 11. Deterioration of underground metallic pipelines caused by stray currents

Fig. 12. Deterioration of underground power cables caused by stray currents

From the analysis of Figures 6, 7 and 8, we see that in case of large urban agglomerations using D.C. electrical traction systems, tram and metro produced stray currents act on the adjacent metallic structures of their running routs. In this case, in lack of appropriate technical measures such as fighting the destructive effect of D.C. stray currents or diminish the intensity of stray currents, the risk of destruction of metal structures by stray current is particularly significant. One can also tell that the stray currents value is determined by the rails resistance, by the rails running routs, but also by the dispersion resistance between rail and group and the dispersion resistance between the disturbed metallic structure and ground. Under these circumstances, solutions to reduce the destruction by D.C. currents, coming from the running routes of vehicles driven in D.C. are:

- ensure minimum line resistance of the running route, which could be achieved by increasing the rail section to an optimal value, ensures the ohmic continuity of the running route (remedy cracks and breaks in rails, permanent control of the rail switches and other technological disruptions of the rails);
- the correct sizing, execution and maintenance of centers and return cable;
- ensure a proper electric insulation between the rails, sleepers and ground.

Of course, organizational measures and technical solutions of the said have technical and economic limits. Therefore, to avoid damage caused by accelerated corrosion, due to D.C. stray currents, to ensure increased operational safety for construction related steel structures and areas passed by tram produced stray currents, it is required implementing specific active methods against corrosion.

Of note is that the maximum value of D.C. stray currents produced by urban electric traction is theoretically regulated by technical normatives (in Romania, STAS 833-72 [6], in Europe, prEN 50162-2000 [7], EN 50122-2/2000 [8] etc.). Unfortunately, designers and operators of urban electric transport neglect the provisions of these normatives, and so they report the accelerated degradation of the municipal distribution utilities underground metal pipes and reinforced concrete structures. Under these circumstances, many representative constructions encounter extensive degradation of the structures of resistance [2, 3, 9÷11], with all their implications, like: costly repairs, social and environmental effects etc.

3. CONCLUSIONS

One analyzed energy issues and the impact on the adjacent metallic structure related to the running routes of urban electric rail transport. Main conclusions of the investigations undertaken are:

- the specific energy consumption of electric traction related to electric urban transport is mainly determined by design, implementation and maintenance of D.C. supply system, particularly current path sections (power bars, connection cables, contact wires, rails etc.), contacts, electrical continuity of running routes (the rails and joints of these);
- ohmic voltage drops on running routes, which significantly increase the specific energy consumption, generates dispersion „stray” currents which cause the degradation of steel structures (underground metal pipelines, underground cables,) and degradation of running routes adjacent reinforced concrete structures (building foundations, reinforced concrete elements related to running routes, reinforced concrete bridges etc.).

Given the above, to prevent damage due to dispersion currents, National and European technical regulations require proper design, implementation and operation of the running routes and implementation of appropriate protection systems.

REFERENCES

[1] I. CSUZI, I NAGY, Villamosközlekedés Nagyváradon - Trams in Oradea, Proceedings of the Conference X ENELKO, Târgu Mureş, october 8-11, 2009. pp. 16-20.

[2] J. LINGVAY, Z. PUKLUS, Carmen LINGVAY, L. HODOSSY, The impact of electric traction over the environment. 1. The Origin of Stray Currents and Its Inflicted Degradation by Corrosion, Proceedings of the Conference IV ENELKO, Cluj, october 8-10, 2004, pp. 104-109.

[3] I. LINGVAY, M. GABOR, Carmen LINGVAY, Degradation by corrosion of steel rebars from reinforced concrete structures. 1 Studies regarding the corrosion of the Bucharest metro’s structures of concrete steel, Rev. Chim. (Bucureşti) 57, nr. 2, 2006. pp. 180-183.

[4] I. LINGVAY, Carmen LINGVAY, O. CIOGESCU, C. HOMAN, Contributions to study and control of the degradations by corrosion of the underground power cables. 1. Study of corrosion state for some underground power lines. Rev. Chim. (Bucureşti) 58, nr.1, 2007. pp. 44-47.

[5] I. LINGVAY, Carmen LINGVAY, Degradarea prin coroziune a liniilor electrice, Editura PRINTECH, Bucureşti, 2008. pp. 127-154.

[6] *** STAS 833-72, Tracțiunea electrică urbană. Prescripții pentru reducerea curenților vagabonzi.

[7] *** prEN, 50162 – 2000, Protection Against Corrosion by Stray Current from DC Systems.

[8] *** EN 50122-2/2000, Railway applications – Fixed Installations. Part 2: Protective Provisions Against the Effects of Stray Currents Caused by D.C. Traction Systems.

[9] Z. PUKLUS, I. LINGVAY, L. HODOSSY, A kóboráramok és hatásainak vizsgálata a millenniumi földalatti vasút környe-zetében, Korróziós figyelő, 45, 2, 2005, pp. 43-48.

[10] C. HOMAN, I. LINGVAY, D. ISOC, Carmen LINGVAY, O. CIOGESCU, Contributions to the Study of Corrosion of Concrete Steel Sustaining Elements from the Energy Transportation and Distribution Plants, 4th International Conference "Study and Control of Corrosion in the Perspective of Sustainable Development of Urban Distribution Grids" – URB-CORR 2005, June 9-11, 2005, Sibiu, Romania, pp. 220-222.

[11] I. LINGVAY, Andreea VOINA, Carmen LINGVAY, Carmen MATEESCU, The impact of the electromagnetic pollution of the environment on the complex build-up media, Revue Roumaine des Sciences Techniques série Électrotechnique et Énergétique, Tome 53,2008, N° 2bis, Avril-Juin, pp 95-112.

[12] *** EN 12696, Cathodic Protection of Steel in Concrete.

[13] Carmen LINGVAY, Coroziunea structurilor din beton armat, Editura Printech, Bucureşti, 2008. pp. 27-68.

[14] I. LINGVAY, M. GABOR, C.D. VOINIȚCHI, Carmen LINGVAY, Degradarea prin coroziune a structurilor din beton armat. 3. Contribuții la studiul degradării fizice a betonului armat datorată curenților de dispersie - Degradation by corrosion of steel rebars from reinforced concrete structures. 3. Contributions to Study of Physico-Mechanical Degradation of Reinforced Concrete due to Stray Currents, Rev. Chim. (Bucureşti) 57, nr. 4, 2006, pp. 378-382.

[15] I. LINGVAY, S. GOMBOS, Carmen LINGVAY, Júlia KOVÁCS, C.D. VOINIȚCHI, Degradarea prin coroziune a structurilor din beton armat. 4. Modificările de pH şi de compoziție chimică ale betonului expus acțiunii curenților de dispersie - Degradation by corrosion of steel rebars from reinforced concrete structures. 4. The pH and chemical composition modifications of concrete caused by stray currents, Rev. Chim. (Bucureşti) 57, nr. 5, 2006, pp. 498-500.

[16] A. LEGAT, Monitoring of steel corrosion in concrete by electrode arrays and electrical resistance probes, Electrochimica Acta 52 (2007) 7590–7598.

[17] I. LINGVAY, Carmen LINGVAY, Degradarea prin coroziune a liniilor electrice, Editura Printech, Bucureşti, 2008. pp. 129-134