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POLARIZATION PHENOMENON IN UNDERGROUND PIPELINE GENERATED BY STOCHASTIC STRAY CURRENTS FROM D.C. TRACTION

D.C. electrified traction systems are a potential source of stray currents. The important problem, technically, is to evaluate the harmful effects (electrolytic corrosion) that an electrified railway has on nearby earth–return circuits (e.g. pipelines). This phenomenon is stochastic and may aggravate electrochemical corrosion in different places depending on the position of the vehicle, the load current, soil parameters, etc. The electric circuit approach, based on the complete field method of solution of the transmission–line problem (the earth–return circuit theory), to model stray currents interference on extended structures is presented. The electrode kinetics (polarization phenomenon) is taken into account in the model developed. Random algorithm allows to explore the phenomenon of polarization for different cases, which allows for generalization of the conclusions regarding the risk of corrosion in the studied systems.

KEYWORDS: stochastic stray currents, D.C. traction, earth return circuit, earth scalar potential, simulation, polarization phenomenon

1. INTRODUCTION

Engineering practice often deals with problems connected with harmful effects (electrolytic corrosion) that direct current sources have on nearby earth–return circuits, e.g. underground metal pipelines, cables, etc. The stray currents from the D.C. rail–return circuit may flow into the earth and into the underground structure, returning to the rails or negative feeder taps in the vicinity of the substation or power plant. The general nature of the stray current problem is illustrated schematically in Fig. 1 [9, 10, 15].

Stray currents when entering or discharging metallic buried structures can cause damage in the form of structure coating disbonding in the area where the current enters and electrolytic corrosion in the area where it discharges (anodic

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zone). The extent of electrolytic damage is a function of the character of the metal and the amount of current and of time and soil conditions. Railway systems conventionally have the substation negative grounded to the rails. The system corrodes the rails remotely from the substation, whereas the foreign structures corrode near the substation, Fig. 1a.

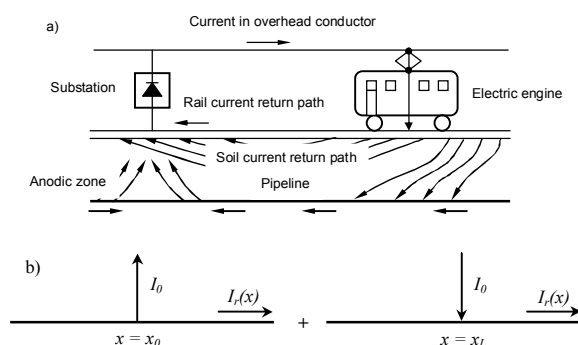


Fig. 1. Generation of stray currents: a) a railway system, b) railway system equivalents

The best approach to assessing stray currents interference is to determine the change in current density/potential on the structure subjected to the stray currents. Determining the response of the structure is not an easy task because it is a function of many factors: the location of the structure with respect to the electric flow field generated by the stray current source, the magnitude of the electric field, and the electrochemical response of the structure to the interference. In a row the outflow of stray currents into the ground depends on the properties of electric traction return circuits (the actual load of traction circuits i.e., the load of each electric locomotive, their number and position on the route, type and quality of rails and subgrade, and also the structure and conductivity of the surrounding environment, etc.). The positive potential deviation of the structure is a measurable effect which is used as electrolytic corrosion hazard criterion in standards and regulations of many countries. However, such measurements are usually post construction and thus may lead to an expensive retrofit program, in the case of undesirable results.

To predict the potential shift due to the stray current influence, calculation methods/tools can be used, especially at design stage of new traction lines or pipelines. The existing simulation models presented in the literature are mainly based on the deterministic approach, e.g. an analytical method of calculation basing on the complete field method of solution of the transmission–line problem. The analysis is applicable to any D.C. railway system in which tracks can be represented by a single earth return circuit (equivalent rail) with current (shunt) energization [9, 10, 15 – 18]. The method, similarly to the “field approach” – e.g.

the Boundary Element Method [1, 2, 12], is an alternative to the approximate method in which the equivalent rail with current energization is modeled as a large multinode electrical equivalent circuit with lumped parameters. This circuit is a chain of basic circuits, which are equivalents of homogenous sections of the rail [3, 4, 7, 8, 13, 14]. It should be pointed out, that the simulations presented by deterministic approach refer to the chosen point of time, i.e. at the time $t = \text{const}$. In reality flowing stray currents are stochastic in character, meaning that the current as well as the flow direction change at random.

Different from the existing models, which are based on a deterministic, the papers [7, 17, 18] present a non-deterministic approach to study of effects generated on buried pipelines located in stochastic stray currents area.

When a metallic structure is electrically influenced by stray currents, the potential of the structure shifts in the positive or negative direction, where the current leaves or enters the metal surface. The key problem in the evaluation of the new foreign structure response to the stray currents interference consist in the determination of the potential shift/polarization of the structure.

The objective of the paper is to present problems of the modeling of stochastic stray currents effects generated by D.C. electrified railways. The use of the method presented permits to calculate such parameters as longitudinal rail current, rail leakage current, rail potential, a 3D primary earth potential. The special concern will be however given to the simulation of a pipeline response i.e. the pipeline potential shift (overvoltage) produced by stochastic stray currents. The calculation model is based on the deterministic model combined with the non-deterministic approach based on the Monte Carlo procedure, in which a locomotive position and a load current are independent random variables.

The analysis described in the paper may be useful in understanding effects on metal installation buried in the stochastic stray current area. The non-deterministic simulation model presented can be especially useful in the design stage of new earth return circuit (pipelines) buried in the stray current area, when frequent alterations are made as the design progresses. The efficiency of the simulation program developed is demonstrated by illustrative calculations.

2. CURRENT AND POTENTIAL EXCITED IN A RAIL BY CURRENT ENERGIZATION

The system shown in Fig. 1b may be applied directly by superposition in building up electrified railway system. In this system tracks are represented by a single conductor – equivalent to a rail continuously in contact with the earth through the track ballast. The conductor is energized with the currents I_0 and $(-I_0)$ by a feeder station and a load at points $x = x_0$ and $x = x_L$, respectively.

It should be noted that the basic model can be applied directly by superposition if there is a number of substations and loads to be considered.

The starting point for the analytical solution for current and potential along an equivalent rail located along the x – axis of the Cartesian coordinate system is, according to the multi-conductor line theory, the system of linear differential equations:

$$\begin{aligned} -\frac{dV_r(x)}{dx} &= ZI_r(x) - E_s(x) \\ -\frac{dI_r(x)}{dx} &= YV_r(x) - J_s(x) \end{aligned} \quad (1)$$

where V_r denotes the rail potential, I_r – the rail current, Z – the longitudinal impedance (resistance) per unit length (p.u.l.), Y – the p.u.l. shunt admittance (conductance), and E_s and J_s are the p.u.l. external sources (longitudinal and shunt, respectively) driving the homogeneous line. The details of the circuit with earth return parameters can be found in the literature, e.g. [9, 10, 15].

If the equivalent rail is infinite in the length and energized with the current I_0 by a substation at point $x = x_0$, the solution of the eqns (1) for the current along the rail, taking into account the boundary conditions:

$$I_r(x_0^-) = \frac{I_0}{2} \quad I_r(x_0^+) = -\frac{I_0}{2} \quad (2)$$

where $I_r(x_0^-)$ and $I_r(x_0^+)$ denote the left-hand and right-hand limits of the function $I_r(x)$ when x approaches to x_0 , is given in the form [9, 10, 15]

$$I_r(x) = -\text{sign}(x - x_0) \frac{I_0}{2} e^{-\Gamma|x-x_0|} \quad (3)$$

where

$$\text{sign}(x - x_0) = \begin{cases} -1 & \text{when } x - x_0 < 0 \\ 1 & \text{when } x - x_0 > 0 \end{cases} \quad (4)$$

and Γ is the propagation constant.

Potential along the equivalent rail can be calculate from the relationship:

$$V_r(x) = -\frac{1}{Y} \frac{dI_r(x)}{dx} \quad (5)$$

thus taking into account formulas (3) and (5)

$$V_r(x) = -Z_0 \frac{I_0}{2} e^{-\Gamma|x-x_0|} \quad (6)$$

where: Z_0 – characteristic impedance of the equivalent rail. The details of the parameters of the rails and the equivalent rail can be found in literature, e.g. [5, 6, 11].

For the case of current energization of the rail by a vehicle at the point $x = x_L$ (Fig. 1b), currents and potentials are calculated from the equations (3) and (5) with $I_0 = -I_0$ and $x_0 = x_L$, respectively.

Consider next the case of a finite rail extending from $x = x_1$ to $x = x_2$. The rail is energized with the current I_0 at $x = x_0$ and is open circuited on both ends. The current along the rail can be now determined from the following expression:

$$I_r(x) = -\text{sign}(x - x_0) \frac{I_0}{2} e^{-\Gamma|x-x_0|} + A_1 e^{-\Gamma x} + B_1 e^{\Gamma x} \quad (7)$$

where A_1 and B_1 are constants which are to determine from the boundary conditions.

Taking into account that:

$$I_r(x_1) = I_r(x_2) = 0 \quad (8)$$

the constants A_1 and B_1 become:

$$A_1 = -\frac{I_0}{2} \frac{ch\Gamma(x_2 - x_0)}{sh\Gamma L} e^{\Gamma x_1} \quad B_1 = \frac{I_0}{2} \frac{ch\Gamma(x_0 - x_1)}{sh\Gamma L} e^{-\Gamma x_2} \quad (9)$$

where $L = x_2 - x_1$ denotes the rail length.

It is easy to show that for the case of finite length rail which is energized at the point x_L by a load current ($-I_0$), the rail current becomes

$$I_r(x) = \text{sign}(x - x_L) \frac{I_0}{2} e^{-\Gamma|x-x_L|} + A_2 e^{-\Gamma x} + B_2 e^{\Gamma x} \quad (10)$$

and

$$A_2 = \frac{I_0}{2} \frac{ch\Gamma(x_2 - x_L)}{sh\Gamma L} e^{\Gamma x_1} \quad B_2 = -\frac{I_0}{2} \frac{ch\Gamma(x_L - x_1)}{sh\Gamma L} e^{-\Gamma x_2} \quad (11)$$

It should be pointed out, that for the case of other kind of the boundary conditions, e.g. defined by impedances of finite value at rail both ends, the constants can be evaluated in similar way.

3. SCALAR POTENTIAL IN THE EARTH DUE TO CURRENT IN THE EQUIVALENT RAIL

The knowledge of the earth potential of the electric flow field in the vicinity of the tracks is required for the evaluation of stray currents effects on nearby structures. The potential (primary potential) can be obtained by the technique used in the earth return circuit theory, when the conductor with earth return carries a longitudinal current [9, 10, 15]. The basic circuit for the calculation of the earth potential is shown in Fig. 2.

The equivalent rail is placed on the earth surface and is carrying the longitudinal current $I_r(x)$ which flows in the positive direction of the x axis lying along the rail. The rail can be regarded as a set of current elements of length dx .

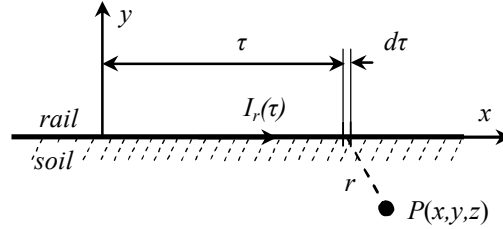


Fig. 2. Equivalent rail with longitudinal current flow on the earth surface

From each element an elementary leakage current $(-dI_r(\tau)/d\tau)$ flows into the earth with the conductivity γ , producing the elementary scalar potential. In the observation point $P(x, y, z)$ the scalar potential can be determined from the expression:

$$dV_e^0(P) = -\frac{1}{2\pi\gamma r} \frac{dI_r(\tau)}{d\tau} \quad (12)$$

where r is the distance from the current element (source point) to the observation point.

For the case of finite length equivalent rail, located in the xy plane ($y = 0$, $z = 0$), the scalar potential in the earth becomes:

$$V_e^0(x, y, z) = \frac{1}{2\pi\gamma} \int_L \frac{-dI_r(\tau)/d\tau}{\sqrt{(x-\tau)^2 + y^2 + z^2}} d\tau \quad (13)$$

If a finite rail extending from $x = x_1$ to $x = x_2$, is energized with the current I_0 at $x = x_0$ and open circuited on both ends, the current along the rail is described by eqn. (7). Thus the scalar potential can be determined from the following expression:

$$\begin{aligned} V_e^0(P) = & \frac{I_0\Gamma}{4\pi\gamma} \left[-e^{-\Gamma x_0} \int_{x_1}^{x_0} \frac{e^{\Gamma\tau}}{\sqrt{(x-\tau)^2 + y^2 + z^2}} d\tau - e^{\Gamma x_0} \int_{x_0}^{x_2} \frac{e^{-\Gamma\tau}}{\sqrt{(x-\tau)^2 + y^2 + z^2}} d\tau + \right. \\ & - \frac{ch\Gamma(x_2 - x_0)}{sh\Gamma L} e^{\Gamma x_1} \int_{x_1}^{x_2} \frac{e^{-\Gamma\tau}}{\sqrt{(x-\tau)^2 + y^2 + z^2}} d\tau + \\ & \left. - \frac{ch\Gamma(x_0 - x_1)}{sh\Gamma L} e^{-\Gamma x_2} \int_{x_1}^{x_2} \frac{e^{\Gamma\tau}}{\sqrt{(x-\tau)^2 + y^2 + z^2}} d\tau \right] \quad (14) \end{aligned}$$

For the case of current energization of the finite length rail by a vehicle at the point $x = x_L$ the scalar potential is calculated from the eqn. (15) with $I_0 = -I_0$ and $x_0 = x_L$, respectively.

The total earth potential in the observation point P results from the superposition and can be numerically solved.

4. CURRENT AND POTENTIAL ALONG A PIPELINE BURIED IN THE D.C. STRAY CURRENTS AREA

Current and potential along a pipeline (infinitely long earth return circuit) located in an electric flow field ($E(x) = -dV_e/dx$) due to stray currents can be calculated according to the system of equations (1). If the pipeline is placed along the x – axis of the co-ordinate system, the current along the pipeline can be obtained from the relation

$$I(x) = \frac{Y_p}{2} \left[e^{-\Gamma_p x} \int_{-\infty}^x V_e(v) e^{\Gamma_p v} dv - e^{\Gamma_p x} \int_x^{\infty} V_e(v) e^{-\Gamma_p v} dv \right] \quad (15)$$

and pipeline potential takes the form

$$V(x) = \frac{\Gamma_p}{2} \left[e^{-\Gamma_p x} \int_{-\infty}^x V_e(v) e^{\Gamma_p v} dv + e^{\Gamma_p x} \int_x^{\infty} V_e(v) e^{-\Gamma_p v} dv \right] \quad (16)$$

on the assumption that the potential V_e is finite when x approaches infinity.

On the other hand, the pipeline, similarly as the rail, can be modeled as a circuit with lumped parameters. Assuming a segment of the pipeline to be homogeneous, it is possible to model the segment by a π – two port. If the pipeline is subjected to the electric field with the potential V_e , the passive model has to be completed by the voltage sources acting in shunt branches of the π – two port. The pipeline model – a chain of such basic two-ports with the D.C. stray currents effects taking into account, is well suited for computer – aided circuit analysis.

5. INCORPORATING ELECTRODE KINETICS

After the stray currents have been entered or discharged the potential of the underground metal structure becomes more negative/positive than the steady state potential V_s , the difference consisting of the polarization potential η , the ohm drop of potential in soil and the defects in insulation V_{IR} , hence

$$V = V_s + \eta + V_{IR} \quad (17)$$

The literature on the problem of calculating stray currents effects on metal underground structures mainly does not deal with the polarization, treating that phenomenon as insignificant when compared with the ohm drop of potential. In practical calculations, based on determining the ohm drop of potential, it is usually assumed that the ohm drop of potential should have a certain definite value [19]. Similarly, the criteria for cathodic protection are based on the change

of the potential difference between the metal and the nearby soil [20]. However, neglecting the electrochemical polarization in calculation of currents and potentials in metal underground structures influenced by stray currents can lead in some cases to results with essential errors.

To model properly effects of stray currents on a pipeline it is necessary to introduce the electrochemical behavior of the pipeline into the model described in previous section. Electrochemical reactions that can occur e.g. on bare steel are: corrosion (oxidation) of the metal, reduction of dissolved oxygen and evolution of hydrogen. The electrochemical behavior manifests itself as a non-linear relationship between the potential and current density at the metal-to electrolyte interface. The functional relationship, known as the polarization curve, is dependent upon the type of metal, ionic species in the electrolyte, temperature, velocity, etc. The total polarization η (overvoltage) of an electrode is the sum of the contributions of activation polarization and concentration polarization [19, 21]:

$$\eta = \pm\beta \log \frac{J}{J_0} + 2.3 \frac{RT}{nF} \log \left(1 - \frac{J}{J_L} \right) \quad (18)$$

where: which J is a total current density, β is a constant termed Tafel constant and is represented by the expression:

$$\beta = 2.3 \frac{RT}{\alpha nF} \quad (19)$$

and R is the gas constant, T is absolute temperature, n is the number of electrons transferred, F is the Faraday constant, α is the symmetry coefficient which describes the shape of the rate-controlling energy barrier, J_0 is the exchange-current density representing the exchange-reaction rate, and J_L is the limiting diffusion current density representing the maximum rate of reduction possible for a given system.

Under the condition $|\eta| \geq 50$ mV the overvoltage of an electrode can be calculated from the equation [21]:

$$\eta = \pm\beta \log \frac{J}{J_0} \quad (20)$$

with the value of β for electrochemical reactions ranging between 0.05 and 0.15 volts. However, η can be measured in the laboratory or from field data and accurately approximated as a series of data points with intermediate values being evaluated by interpolation.

Except of the voltage source η the remaining elements of the basic circuit are linear. The equivalent circuit with η in the shunt branch, allows the calculation of all electric quantities appearing in the circuit. The polarization behavior is now incorporated into the simulation model with lumped parameters using the iterative process. Convergence of the iterative process is usually rapid.

6. EXAMPLES OF CALCULATION

An electrified D.C. railway system (producer of stray currents) and a nearby underground pipeline (victim of stray current interference) create a conductively coupled system of earth return circuits. Almost all parameters of the system present random characteristics. The outflow of stray currents into the ground depends on the properties of electric traction return circuits: the actual load of traction circuits i.e., the load of each electric locomotive, their number and position on the route, type and quality of rails and subgrade, and also the structure and conductivity of the surrounding environment, etc. Similarly, such parameters as conductance of pipeline insulation, soil structure and conductivity (seasonal changed), groundings along the pipeline route, insulating flanges, etc. influence electrical parameters (mutual conductance, series and shunt resistances, propagation coefficients) of the coupled earth return circuits. It is assumed in the paper as in [7, 17, 18], that two stochastic quantities: locomotive position and a load current are most useful, as independent random variables characterized by suitable probability distribution, for the estimation of stochastic stray currents effects on affected pipelines.

The method proposed is intended as a tool for estimation of location of anodic/cathodic zones along a pipeline buried in stochastic stray current area. The calculation model is based on the deterministic block of models described in sections 2, 3 and 4 combined with the non-deterministic approach based on the Monte Carlo procedure, in which the independent random variables are treated as input parameters for calculation of random characteristics of pipeline responses (output parameters of deterministic block) e.g. potential shift along an affected pipeline. The values of the pipeline responses compose statistical distributions and each of them can be suitably processed, thus obtaining significant parameters like maximum, minimum, median and mean values. Hence the pipeline regions more exposed to corrosion risk can be estimated. The application of the method presented shall be illustrated in the sequel.

The usefulness and efficiency of the computation algorithm developed shall be demonstrated by an example of the calculation of overvoltage value in the vicinity of the D.C. single track traction. The equivalent rail is treated as an earth return circuit with unit-length parameters $R = 0.02 \Omega/\text{km}$ and $G = 0.76 \text{ S/km}$ and is energized at point $x_0 = 0 \text{ km}$. Two vehicles energize the rail at random points along the rail with random currents in the range of 100 – 1000 A for each of them. The rail length $L = 5 \text{ km}$ and the route is straight. The earth potential due to stray currents of the D.C. electrified railway system has been calculated at the depth 1.0 m in the soil with the conductivity $\gamma = 0.01 \text{ S/km}$. Metal pipeline with the length 1 km is buried parallel under the rail at distance 100 m from the station and at depth –1 m. The electrical parameters of the pipeline with the

diameter 355,6 mm are: $R_p = 0.02 \Omega/\text{km}$, $G_p = 11 \text{ S}/\text{km}$. To calculate polarization effect it was assumed $\beta = \pm 0.1 \text{ V}$, and $J_o = 0.004 \text{ A}/\text{m}^2$. In order to determine the distribution of overpotential values 1000 test was carried out. The results of calculations are shown in the form of histograms and mean value of overpotential along the pipeline (Fig. 3 – 4).

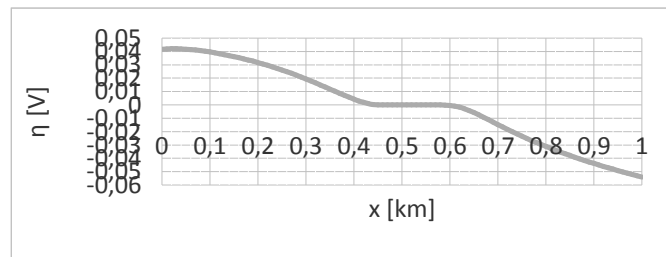


Fig. 3. The average value of overvoltage along the tested pipeline

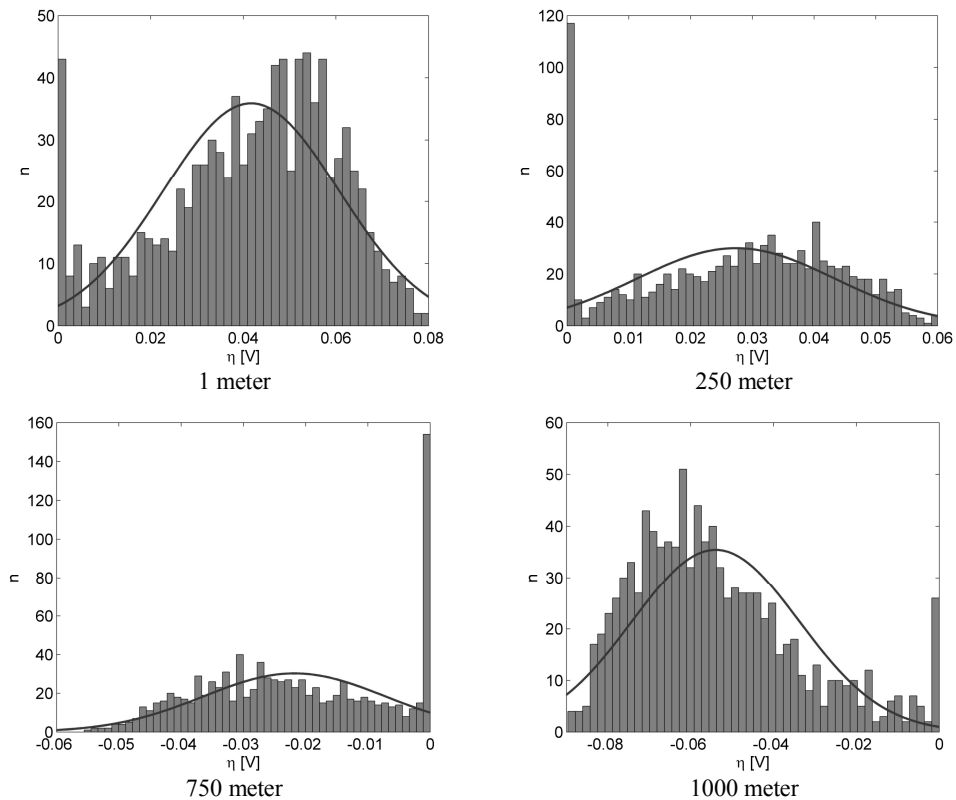


Fig. 4. Histograms showing the distribution of overvoltage at various points of the test pipeline

7. FINAL REMARKS

The paper presents method of the calculating the polarization effect (overvoltage value – electrochemical phenomena on the interface metal–soil electrolyte) in underground pipeline. In the method the equivalent rail is considered as an earth return circuit. It is assumed in the paper that the system considered is linear, that the earth is isotropic, homogeneous medium of finite conductivity and that the effects of currents in nearby underground metal installations on the potential generated in the earth by track currents (primary earth potential) can be disregarded.

The stochastic nature of the phenomenon of stray currents is taken into account and determination of the overpotential distribution for different cases (load current, the location of vehicles) is calculated. Selected calculation example allows to interpret the results correctly. Near the station mean value of the overpotential its positive and amounts for used example about 50 mV. This is where there is the largest phenomenon of electrochemical corrosion. At the end of the pipe farthest away from the station remains the negative overpotential, so risk of corrosion is very small.

The analysis described in the paper may be useful in understanding effects on metal installation buried in the stray current area. The simulation models presented can be especially useful in the design stage of new earth return circuit buried in the stochastic stray current area, when frequent alterations are made as the design progresses.

Moreover the method developed can be used as a tool to verify other simulation models of D.C. traction systems, e.g. the lumped parameters model.

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