sciendo

B&H Electrical Engineering, Volume 16, Special Issue, 2022:25-30
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0010

Original scientific paper

Submitted: September 15, 2022

Accepted: December 14, 2022

SACRIFICIAL ANODE CATHODIC PROTECTION SYSTEM MODELLING USING DIRECT BOUNDARY ELEMENT METHOD

Adnan Mujezinović[1,3], Sanja Martinez[2]

Abstract: Cathodic protection system is commonly employed approach for the protection of the metallic infrastructure placed in electrolyte against corrosion. Adequate design of the cathodic protection system requires the determination of electrical potential and current density distribution on the protected object surface that meets the defined criteria. In this paper, the application of the direct boundary element method in conjunction with Newton-Raphson method was considered for the calculation of the electric potential and current density distribution on the surface of the cathodically protected underground object. The considered method was applied on the sacrificial anode cathodic protection system of the underground pipeline. The non-linear boundary conditions of the electrode surfaces of the cathodic protection system are taken into account. The method was used to determine the current density and electric potential distribution on the external wall of the protected pipeline.

Keywords: Corrosion, Cathodic Protection System, Sacrificial Anode, Direct Boundary Element Method, Newton-Raphson Method

INTRODUCTION

Materials such as different steel types, which are used for infrastructure (such as pipelines, ship hull, etc.), placed in the electrolyte, are subject to the corrosion processes [1]. In order to protect against corrosive processes, passive protection (coatings) in combination with active electrochemical protection (cathodic protection) is most often applied to the metal infrastructure in the electrolyte [2]. The role of the cathodic protection system is slowing down or complete prevention of all corrosion forms from the metallic structure surface placed in the electrolyte [2]. The cathodic protection system can be implemented as an imposed current cathodic protection system (ICCP) or as a sacrificial anode cathodic protection system (SACP) [3,4]. In both cases, the protection of the object from corrosion is achieved by a shifting value of a protected object equilibrium potential to a more negative value [5]. Therefore, cathodic protection system design requires determination of the electric potential and protection current density distribution over the protected object surface [6]. In this way, it can be determined whether there has been a satisfactory potential shift over the protected object surface after the application of the cathodic protection system.

The electric potential and current density distribution over the protected object surface can be determined by mathematical modelling [7]. To solve this type of problem, corrosion engineers have different numerical methods at their disposal, and the choice of the numerical method primarily depends on the problem geometry and the type of boundary conditions. In this paper, the electric potential and current density distribution on the outer pipeline wall that is placed in the soil are analysed. Due to the existence of semi-infinite regions in the problem (soil) as well as the need to know the parameters only on the electrode surfaces, it is suitable to use the boundary element method (BEM) for this type of problem [8]-[11]. Since in the analysed problem exist both, Dirichlet and Neumann boundary conditions, it is suitable to use direct formulation of the boundary element method (DBEM). Electrochemical reactions on the anode and cathode surfaces cause non-linear boundary conditions [12]. This further implies that the equation system will be non-linear. Therefore, Newton-Raphson method for solution of the non-linear equation system has been used [13]-[17].

The remainder of the paper is organized as follows. In section 1 the mathematical model for the calculation of the potential distribution along with the boundary condition is described. Section 2 provides the used solution technique based on the direct boundary element method and Newton-Raphson method. Calculation example is given in section 3. Section 4 concludes the paper.

[1] *Faculty of Electrical Engineering, University of Sarajevo, Bosnia and Herzegovina*
[2] *Faculty of Chemical Engineering and Technology, University of Zagreb, Croatia*
[3] *Correspondence email: adnan.mujezinovic@etf.unsa.ba*
© 2022 Author(s). This is an open access article licensed under the Creative Commons Attribution License 4.0. (http://creativecommons.org/licenses/by/4.0/).

1. MATHEMATICAL MODEL

Scalar electric potential at any point of the homogeneous and isotropic electrolyte can be determined by solving Laplace partial differential equation [2,6,7]:

$$\nabla^2 \varphi = 0 \tag{1}$$

where φ represents electric potential and a symbol ∇ is Nabla operator.

The relationship between the current density vector and the electric potential is given by Ohm's law, as follows [2,3,11]:

$$\vec{j} = -\gamma \nabla \varphi \tag{2}$$

where $\vec{j}$ is current density vector and γ is electrolyte conductivity.

By solving previous equations, the electric potential and current density distribution of analysed problem can be obtained. To obtain unique solution, boundary conditions on the boundary surfaces must be applied. As previously mentioned, electrochemical reactions take place on the electrode surfaces of the cathodic protection system, which results in the boundary conditions on electrode surfaces being non-linear. The boundary conditions on the electrode surfaces are set in the form of a non-linear functional relationship between the current density and the electric potential. These functional relationships are called electrodes polarization characteristics. These functional relationships depends on the type and number of partial electrochemical reactions that take place on the electrode surface [6]. Metal dissolution, oxygen reduction and hydrogen separation simultaneously occur on the cathode surface. Therefore, for the cathode surface, the following functional relationship between current density and electric potential can be used as a boundary condition [3,11,12]:

$$j_C = j_{0,Fe} \cdot 10^{\frac{\varphi-\varphi_{Fe}}{\beta_{Fe}}} - j_{lim,O_2} \cdot \left(1+10^{\frac{\varphi-\varphi_{O_2}}{\beta_{O_2}}}\right)^{-1} - j_{0,H_2} \cdot 10^{\frac{-\left(\varphi-\varphi_{H_2}\right)}{\beta_{H_2}}} \tag{3}$$

where j_C is the total current density of the cathode surface, $j_{0,Fe}$ represents current density associated with the metal dissolution electrochemical reaction, j_{lim,O_2} is limiting current density of the electrochemical reaction of oxygen reduction, j_{0,H_2} is current density associated with the electrochemical reaction of hydrogen separation, φ_{Fe}, φ_{O_2}, φ_{H_2} are the corrosion potentials for corresponding reactions β_{Fe}, β_{O_2}, β_{H_2} represent Tafel's slopes and φ represent the potential difference of interface cathode/electrolyte.

On the sacrificial anode surface the partial electrochemical reaction of anode metal dissolution and oxygen reduction take place simultaneously. Therefore, functional relationship between current density and electric potential for anode surface is defined as follows [3,6]:

$$j_A = j_{O_2} \cdot \left(10^{\frac{\varphi-\varphi_A}{\beta_A}} - 1\right) \tag{4}$$

where j_A is the total current density of the anode surface, φ_A represents the corrosion potential of the sacrificial anode, and β_A represents Tafel's slope of the sacrificial anode.

By applying an adequate Green's function, it is not necessary to discretize the soil-air boundary surface, nor is it necessary to set specific boundary conditions to this boundary. Therefore, in this paper the following Green's function was used in this paper [2]:

$$G(p,q) = \frac{1}{4\pi}\left(\frac{1}{|p-q|} + \frac{1}{|p'-q|}\right) \tag{5}$$

where q is observation point, p is field source point, $|p - q|$ is the shortest distance between source point p and observation point q and $|p' - q|$ is the shortest distance between observation point q and image of the source point p'. According to the image theory, the field source point p and the image of the field source point p' are equidistant from the soil-air boundary [2,3].

In the model, it is necessary to ensure that the current flow in the cathodic protection system is conservative [3,11]. From a mathematical point of view, this means that the Gaussian condition defined by the following equation must be satisfied [10]:

$$\int_\Gamma j(p)\, d\Gamma = 0 \tag{6}$$

where Γ is boundary surface of the domain of interest.

By introducing the Gauss condition, it was ensured that there is no current leakage on the infinite boundary.

2. SOLUTION TECHNIQUE

According to the direct boundary element method, the electric potential and current density can be calculated by solving the integral field equation. The integral field equation for analyzed problem is obtained by applying Green's symmetric identity to Laplace equation (1). Furthermore, the integral field equation needs to satisfy Gauss condition (6), and therefore, the constant potential at infinite boundary is added on the right side of the integral field equation [2,3,6-9]. Hence, the integral field equation for the analyzed problem take the following form:

B&H Electrical Engineering, Volume 16, Special Issue, 2022:25-30
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0010

$$c(q)\varphi(q)+\int_{\Gamma}\varphi(p)\cdot\left(\vec{n}\cdot\nabla G(p,q)\right)d\Gamma=-\frac{1}{\gamma}\int_{\Gamma}G(p,q)\cdot j(p)\,d\Gamma+\varphi_{\infty} \quad (7)$$

where $c(q)$ is a constant, $\varphi(q)$ is the electric potential of the observation point q, $\varphi(p)$ is the electric potential of the field source point p, φ_{∞} is electric potential at the infinite boundary and $\vec{n}$ is normal unit vector.

In the process of numerically solving the integral field equation (7) using the direct boundary element method, a discretization of the calculation domain boundary into an appropriate number of boundary elements is required After the discretization of the domain of interest into M boundary elements, the integral field equation is solved over each boundary element. Then for each boundary element takes the following form:

$$c(q_i)\varphi(q_i)+\sum_{k=1}^{M}\int_{\Gamma^k}\varphi_k(p)\cdot\left(\vec{n}\cdot\nabla G(p,q_i)\right)d\Gamma^k =-\frac{1}{\gamma}\cdot\sum_{k=1}^{M}\int_{\Gamma^k}G(p,q_i)\cdot j(p)\,d\Gamma^k+\varphi_{\infty} \quad (8)$$

where Γ^k is boundary surface of the k-th boundary element.

The idea of the boundary element method is to transform the integral field equation into a system of algebraic equations. After applying the collocation method at a point and Gauss-Legendre quadrature formulas, the problem can be represented by a set of algebraic equations. A set of algebraic equations in matrix form is given below:

$$\begin{bmatrix}H_{cc} & H_{ca} & -1\\ H_{ac} & H_{aa} & -1\\ 0 & 0 & 0\end{bmatrix}\cdot\begin{Bmatrix}\varphi_{S,c}\\ \varphi_{S,a}\\ \varphi_{\infty}\end{Bmatrix}=\begin{bmatrix}G_{cc} & G_{ca}\\ G_{ac} & G_{aa}\\ A_c & A_a\end{bmatrix}\cdot\begin{Bmatrix}j_{S,c}\\ j_{S,a}\end{Bmatrix} \quad (9)$$

where $[H]$ and $[G]$ are coefficient matrices, $\{\varphi_c,\ \varphi_a,\ \varphi_{\infty}\}^{\mathrm{T}}$ vector of unknown electric potentials and $\{j_c, j_a\}^{\mathrm{T}}$ vector of unknown current densities. In the previous matrices, the indices a and c denote the anodic and cathodic surfaces, respectively. Therefore, the elements (submatrices) with indices aa and cc indicate that both the collocation point and the field source point are on the same surface (anode or cathode), while the index ac indicates that the collocation point is on the anode surface while the field source point is on the cathode surface and vice versa for the case when the index is ca.

The elements of the coefficient matrices can be calculated by using following equations [2]:

$$H_{i,j}=\sum_{j_1=1}^{NG}\sum_{j_2=1}^{NG}\sum_{m=1}^{Nt}N_m\left(\xi_{j,j_1},\eta_{j,j_2}\right)\cdot\left(\vec{n}\cdot\nabla G_k\left(\xi_{j,j_1},\eta_{j,j_2},q_i\right)\right)\cdot\det\left[J\left(\xi_{j,j_1},\eta_{j,j_2}\right)\right]\omega_{j_1}\omega_{j_2} \quad (10)$$

$$G_{i,j}=-\frac{1}{\gamma}\sum_{j_1=1}^{NG}\sum_{j_2=1}^{NG}\sum_{m=1}^{Nt}N_m\left(\xi_{j,j_1},\eta_{j,j_2}\right)\cdot G_k\left(\xi_{j,j_1},\eta_{j,j_2},q_i\right)\cdot\det\left[J\left(\xi_{j,j_1},\eta_{j,j_2}\right)\right]\omega_{j_1}\omega_{j_2} \quad (11)$$

$$A_j=\sum_{j_1=1}^{NG}\sum_{j_2=1}^{NG}\sum_{m=1}^{Nt}N_m\left(\xi_{j,j_1},\eta_{j,j_2}\right)\cdot\det\left[J\left(\xi_{j,j_1},\eta_{j,j_2}\right)\right]\omega_{j_1}\omega_{j_2} \quad (12)$$

where N_G denotes the number of applied Gauss-Legendre quadratures, N_t denotes the number of nodes per boundary element, ξ,η are Gauss points, $N_m(\xi,\eta)$ is shape function, $det[\mathrm{J}(\xi,\eta)]$ is determinant of Jacobean matrix, ω_{j1} and ω_{j2} are weights coefficients for Gauss points ξ and η, respectively.

The equations (10) and (11) are valid only for the calculation of the elements outside the main diagonal of the matrices $[H]$ and $[G]$, i.e. for $i \neq j$. The reason for this is that there are singular terms on the main diagonal of the considered matrices, i.e. collocation point and field source point are the same points. The terms on the main diagonal of the matrix $[G]$ are calculated using the Gauss singular quadrature formulas together with the Gauss–Legendre quadrature formulas [10]. The elements on the main diagonal of matrix $[H]$ are calculated using Gibbs' theorem, by summing all off-diagonal elements of the row whose diagonal element is calculated [3,11], as in:

$$H_{i,i}=1-\sum_{\substack{j=1\\(j\neq i)}}^{n_{ak}+n_{ck}}H_{i,j} \quad (13)$$

where n_{ak} and n_{ck} represent the number of collocation points on the anode and cathode surfaces, respectively.

As already mentioned, by solving the matrix equation (9), the solutions of the desired parameters are obtained at the collocation points of all boundary elements. This matrix equation system is nonlinear since the elements of the vector $\{j\}$ are given as non-linear functional relationships between the current density and the electric potential on the electrode surface [6]. To solve the nonlinear system of matrix equations, the Newton-Raphson method was applied. In accordance with the Newton-Raphson method, the current density vector can be developed into a Taylor series [18]. Therefore, current density vector can be determined from following equation [6]:

$$\{j\}_k=\{j\}_{k-1}+\left[\frac{\partial j}{\partial\varphi}\right]_{k-1}\{\Delta\varphi\}_k \quad (14)$$

where k denotes the current iteration, $[\partial j/\partial\varphi]$ is Jacobian's matrix and $\{\Delta\varphi\}$ is vector of electric potential increments between the two adjacent iterations and is given by following equation [6, 16]:

$$\{\Delta\varphi\}_k=\{\varphi\}_k-\{\varphi\}_{k-1}=\begin{Bmatrix}\Delta\varphi_a\\ \Delta\varphi_c\\ \Delta\varphi_{\infty}\end{Bmatrix} \quad (15)$$

By inserting matrix equations (14) and (15) into matrix equation (9), the following matrix equation can be written:

$$[H]\cdot\left(\{\varphi\}_{k-1}+\{\Delta\varphi\}_k\right)=[G]\cdot\left(\{j\}_{k-1}+\left[\frac{\partial j}{\partial\varphi}\right]_{k-1}\{\Delta\varphi\}_k\right) \quad (16)$$

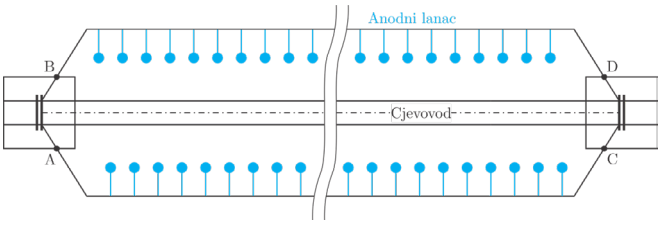
Finally, the following matrix equation can be written:

$$\left([H]-[G]\cdot\left[\frac{\partial j}{\partial\varphi}\right]_{k-1}\right)\cdot\{\Delta\varphi\}_k=[G]\cdot\{j\}_{k-1}-[H]\{\varphi\}_{k-1} \quad (17)$$

The previously given procedure represents an iterative procedure for the calculation of the electric potential and current density on the electrode surfaces. To start the iterative procedure, it is necessary to set initial values. When modeling the cathodic protection system with sacrificial anodes, it can be assumed that the value of the electric potential on the anode surface is known while the current density is recalculated [19]. Neither the electrical potential nor the protective current density is known on the cathode surface. In order to start the iterative procedure, the current density is set on the cathode surface, and the electric potential and current density of the cathode surface are calculated iteratively.

3. CASE STUDY

The previously described mathematical model is employed to calculate the electric potential and protection current density distribution of the pipeline protected by the sacrificial anode cathodic protection system. The length of the analysed pipeline section is 580 (m). The protected pipeline is laid down 3.75 (m) below the ground surface. The external diameter of the analysed pipeline was 4 (m). The geometry of the analysed object is given in Figure 1 [20,21].



Analysed sacrificial anode cathodic protection system of the pipeline [20,21]

The cathodic protection system was realized by installing deep sacrificial anode (SA) strings, an alloy mostly containing zinc. As shown in Figure 1, the SA-s are placed both sides of pipeline. The longitudinal distances between two adjacent SA-s on the same side of the pipeline is 12 (m), whilst a distance between SA-s and axis of the pipeline is 5.5 (m). There is a longitudinal displacement of 6 (m) between SA-s on opposite sides of the pipeline. The SA strings are placed at a depth of 2.5 (m), whilst the anode string is 6.4 (m). The used SA-s are composed of 6 individual cylindrical anodes, which are arranged in a deep anode strings as shown in Figure 2 [20, 21].

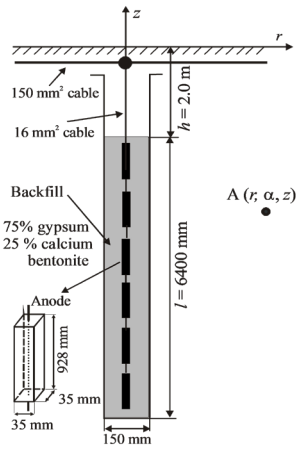


Figure 2: Sacrificial anode string [20,21]

Due to their simplicity, the sacrificial anode strings were modelled as single cylindric anode of 6.4 (m) length. Since the considered problem is symmetrical, only one pipeline section of 12 (m) length was analysed as shown in Figure 3.

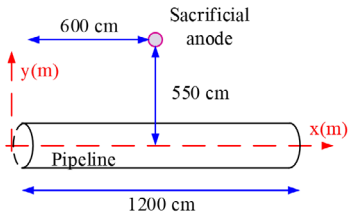


Figure 3: The part of the pipeline on which the calculation was performed

In consideration of the previously described cathodic protection system, the polarizing characteristic of the protected object surface is defined by equation (3). On the other hand, equation (4) is used to represent the polarizing characteristic of the sacrificial anode surfaces. The parameters of the used polarizing characteristics are given in Table I.

Table I: Polarization characteristics parameters [20]

Parameter	Value
j_{0Fe}	0.1(μA/cm2)
φ_{Fe}	-200 (mV) vs. CSE
β_{Fe}	60 (mV/dec)
j_{limO_2}	0.1 (μA/cm2)
φ_{O_2}	100 (mV) vs. CSE
β_{O_2}	59 (mV/dec)
j_{H_2}	0.1 (μA/cm2)
φ_{H_2}	-750 (mV) vs. CSE
β_{H_2}	132 (mV/dec)
j_{O_2}	1(μA/cm2)
φ_a	-1100 (mV) vs. CSE
β_a	59 (mV/dec)

B&H Electrical Engineering, Volume 16, Special Issue, 2022:25-30
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0010

It was assumed that the analysed pipeline is buried in the homogenous soil with soil resistivity of 200 (Ωm). Figure 4 shows the electric potential distribution results obtained over the external wall of the analysed pipeline section.

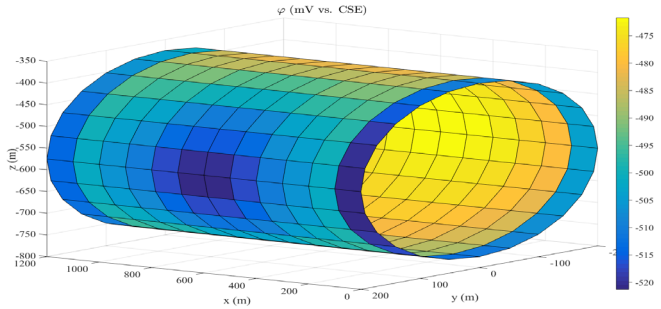


Figure 4: Electric potential distribution on the protected pipeline surface

According to the presented calculation results of the electric potential distribution, Figure 4, it is noticeable that the most negative value of the electric potential corresponds to the pipeline area closest to the sacrificial anode. Furthermore, it can be observed that by increasing the distance from the anode, the electric potential on the surface of the protected pipeline becomes more positive.

The results of the current density distribution over the external wall of the analysed pipeline section is given in Figure 5.

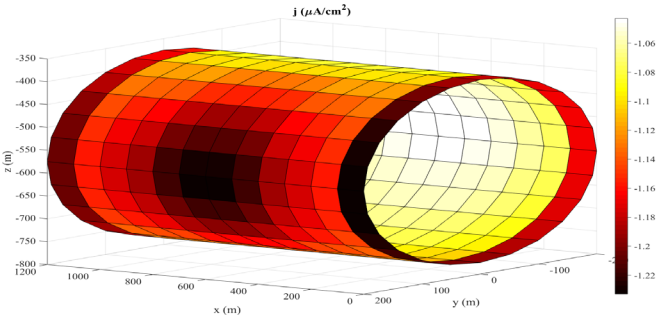


Figure 5: Protection current density distribution on the protected pipeline surface

The results in Figure 5 show that the highest current density values are found at the pipeline surface closest to sacrificial anode. Also, the current density decreases, both longitudinally and axially, with the increscent of distance from sacrificial anode.

4. CONCLUSION

In order to determine the efficiency of the cathodic protection system, the calculation of the electric potential and current density distribution on the electrode surfaces is required. In this paper, for the calculation of the electric potential and current density distribution over the external surface of a large-diameter pipeline protected by sacrificial anodes, the direct boundary element method has been used. The non-linear boundary conditions (polarizing characteristics) take into account electrochemical reactions on electrode surfaces. Due to non-linear nature of the boundary conditions, the considered solution was based on Newton-Raphson method.

REFERENCES

[1] A. Bahadori, Cathodic Corrosion Protection Systems: A Guide for Oil and Gas Industries, Gulf Professional Publishing, USA, Massachusetts, Waltham, 2014

[2] A. Mujezinović, S. Martinez, A. Muharemović and I. Turković, "Application of the Coupled BEM/FEM Method for Calculation of Cathodic Protection System Parameters," International Journal of Computational Methods and Experimental Measurements, Vol. 5, No. 5, pp. 659 – 666, 2017

[3] D. P. Riemer, "Modeling Cathodic Protection for Pipeline Networks" Ph.D. dissertation, University of Florida, Gainesville, FL, 2000

[4] L. Lazzari and P. Pedeferri, "Cathodic Protection", Polipress Milano, 1st edition, 2006

[5] J. H. Morgan, "Cathodic Protection", 2nd Edition, NACE, Houston, TX, USA, 1993

[6] A. Mujezinovic and I. Turkovic, "Review on Cathodic Protection System Modelling," B&H Electrical Engineering, Vol. 11, pp 81-91, 2017

[7] S. Martinez, "Evaluation of the uniform current density assumption in cathodic protection systems with close anode-to-cathode arrangement" Materials and Corrosion, Vol. 61, No. 4, pp. 338-342, April 2010

[8] J. A. F. Santiago and J. C. F. Telles, "On Boundary Elements for Simulation of Cathodic Protection System with Dynamic Polarization Curves" International Journal for Numerical Methods in Engineering, Vol. 40, No. 14, pp. 2611-2627, July 1997

[9] J. A. F. Santiago and J. C. F. Telles, "A solution technique for cathodic protection system with dynamic boundary conditions by the boundary element method" Advances in Engineering Software, Vol. 30, No. 9, pp. 663-671, September 1999

[10] C. A. Brebbia, J. C. F. Telles, L. C. Wrobel, Boundary Element Techniques Theory and Applications in Engineering, Springer-Verlag, Berlin/Heidelberg, 1984

[11] D. P. Riemer, M. E. Orazem, "A Mathematical Model for the Cathodic Protection of Tank Bottoms" Corrosion Science. Vol. 47, No. 3, pp. 849-868, 2005

[12] A. Mujezinovic, A. Muharemovic, I. Turkovic and A. Muharemovic, "Calculation of the Protective Current Density Distribution of a Cathodic Protection System with Galvanic Anodes in Terms of Double-layer Electrolyte" 34th International conference on Boundary Elements Method and Other Reduction Methods, BEM/MRM, Croatia, Split, 2012

[13] J. M. Chuang, N. G. Zamani and C. C. Hsiung, "Some Computational Aspects of BEM Simulation of

Cathodic Protection Systems" Applied Mathematical Modelling, Vol. 11, No. 5, pp. 371 – 379, October 1987
[14] N. G. Zamani, J. M. Chuang and J. F. Porter, " BEM Simulation of Cathodic Protection System Employed in Infinite Electrolytes" International Journal for Numerical Methods in Engineering, Vol. 24, No. 3, pp. 605 – 620, March 1987
[15] W. Sun, "Relaxation iterative algorithms for solving cathodic protection systems with non-linear polarization curves" International Journal for Numerical Methods in Engineering, Vol. 55, pp. 401 – 412, 2002
[16] A. Mujezinović, S. Martinez, S. Milojković, " On the use of Boundary Element Method for Cathodic Protection System Modeling," In Advanced Technologies, Systems, and Applications II, Springer International Publishing, 2018
[17] R. A. Pfeiffer, J. C. Young, J. R. Adams and S. D. Gedney, "Higher-order simulation of impressed current cathodic protection systems" Journal of Computational Physics, Vol. 394, pp. 522-531, 2019
[18] T. V. Gortsas, S. V. Tsinopoulos and D. Polyzos, "An accelerated boundary element method via cross approximation of integral kernels for large-scale cathodic protection problems" Computer-Aided Civil and Infrastructure Engineering, Vol. 37, No. 7, pp. 848-863, 2022
[19] C. Qiu, " Model for interpretation of pipeline survey data" Ph.D. dissertation, University of Florida, Gainesville, FL, 2003
[20] A. Muharemović, H. Zildžo, I. Turković and H. Matoruga, "Modeling of Protection Current/Potential Distribution in Cathodic Protection Systems with a Galvanic Anode by Using the Cupled BEM/FEM Method" Journal of Energy, Vol. 58, No. 6, pp. 496 – 517, October 2009
[21] A. Muharemović, N. Behlilović, I. Turković and A. Muharemović, "Functional relationship between cathodic protection current/potential and duration of system deployment in desert conditions" Advances in Engineering Software, Vol. 42, No. 6, pp. 359-367, June 2011

BIOGRAPHY

Adnan Mujezinović received his B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from University of Sarajevo (Bosnia and Herzegovina), in 2009, 2011 and 2017, respectively. Currently, he is an associate Professor at the Faculty of Electrical Engineering, University of Sarajevo. His topics of interest are numerical calculations of electromagnetic fields, cathodic protection and grounding systems.

Sanja Martinez received his B.Sc. In experimental physics and M.Sc. and Ph.D. degrees in electrical engineering from University of Zagreb (Croatia), in 1993, 1998 and 2000, respectively. Currently, she is a Professor at the Faculty of Chemical Engineering, University of Zagreb. Her topics of interest corrosion phenomena and innovative coating monitoring techniques.