MODELIRANJE RASPODJELE ZAŠTITNOG POTENCIJALA U SUSTAVIMA KATODNE ZAŠTITE S GALVANSKIM ANODAMA KORIŠTENJEM KOMBINIRANE BEM/FEM METODE

MODELLING OF PROTECTION CURRENT/POTENTIAL DISTRIBUTION IN CATHODIC PROTECTION SYSTEMS WITH A GALVANIC ANODE BY USING THE COUPLED BEM/FEM METHOD

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U radu je prezentirano korištenje numeričkih metoda za proračun raspodjele zaštitnih struja/potencijala u sustavima katodne zaštite s galvanskim anodama. Analizirana je kombinirana metoda BEM/FEM, tj. kombinacija metode rubnih i konačnih elemenata. Sustav katodne zaštite je vrlo učinkovit sustav za zaštitu podzemnih metalnih objekata od korozije. Optimalno i tehnički korektno definiranje raspodjele zaštitne struje predstavlja najvažniju fazu kod projektiranja sustava katodne zaštite. Određivanje raspodjele zaštitnih struja/potencijala u sustavima katodne zaštite temelji se na rješavanju Laplaceove jednadžbe uz korištenje adekvatnih, prethodno definiranih rubnih uvjeta. Ovi uvjeti su definirani preko analitičkih izraza za funkcionalne odnose između gustoća zaštitnih struja i potencijala na elektrodnim površinama, odnosno na granicama elektroda/elektrolit. Na istom objektu za kojeg su urađeni numerički proračuni izvršena su i mjerenja raspodjele zaštitnih potencijala tijekom vremena eksploatacije. Eksperimentalni podaci, koji su dobiveni tijekom puštanja sustava u funkciju te namjenski pravljenih periodičnih mjerenja tijekom održavanja sustava uspoređeni su s numerički dobivenim vrijednostima.

The use of numerical methods for calculation of protection current/potential distribution in cathodic protection systems with galvanic anodes is presented in this paper. The coupled BEM/FEM method has been analysed, i.e. a combination of the Boundary Element Method (BEM) and the Finite Element Method (FEM). The cathodic protection system is a very efficient system for the protection of underground metal structures from corrosion. The most important phase of the projecting of the cathodic protection system is the optimally and technically correct defining of protection current distribution.. The calculation of protection current/potential distribution in cathodic protection systems is based on solving Laplace's equation using adequate, previously defined, boundary conditions. These conditions are defined by using analytical expressions for the functional relationship between protection current and potential on electrode surfaces, or the electrode/electrolyte boundary. On the same structure for which the numerical calculations were made, measurements of protection potential distribution during the time of exploitation have been taken. Experimental data acquired during the start of system operations, together with intentional periodical measurements during system maintenance, are compared with data acquired by numerical calculations.

Ključne riječi: Galerkinova metoda težinskih ostataka; katodna zaštita; metoda graničnih elemenata; metoda konačnih elemenata; metoda sukcesivnih podrelaksacija; zaštitna struja/potencijal
Keywords: boundary elements method; cathodic protection; finite elements method; galerkin's method of weighted residuals; protection current/potential, successive under relaxations method

1 UVOD

U radu su dani rezultati numeričke raspodjele zaštitnih struja/potencijala na konkretnom objektu armirano betonskog cjevovoda s prenapregnutom armaturom kod funkcioniranja sustava katodne zaštite s galvanskim anodama.

Kod numeričkog rješavanja raspodjele zaštitnih struja u katodnoj zaštiti (CP) većina autora polazi od analiziranja metode graničnih elemenata (BEM metoda) [1]. Ova metoda se zasniva na diskretizaciji rubnih linija ili površina te je tako pogodna za rješavanje polja u domenama u kojima dominiraju beskonačne ili polubeskonačne regije.

Orazem i ostali [2] i [3] koriste 3D BEM metodu za proračun zaštitnih potencijala vrlo dugačkih cjevovoda s manjim ili većim oštećenjima izolacije. Riemer i Orazem su konstatirali da za duge cjevovode (> 6,0 km), kod oštećenja izolacije treba uzeti u obzir i pad potencijala u samom cjevovodu, odnosno atenuaciju koja nije ravnomjerna na cijeloj dužini. Adey [4] je primijenio potpuni 3D model za proračun potencijala uključujući i susjedne objekte koji imaju spojeve s anodama. Aoki i ostali [5] kao i DeGiorgi [6] su se bavili više zaštitom brodskih čelika.

Metoda konačnih elemenata je modularna i može se primijeniti u mnogim oblastima za rješavanje koji su opisani npr. Laplaceovom jednadžbom. Danas postoji veliki broj programskih paketa opće namjene za rješavanje problema u elektromagentizmu koji se mogu nabaviti na tržištu.

Doprinos ovog rada je korištenje kombinirane metode BEM/FEM za odgovarajuće proračune. Primjena ove metode bit će objašnjena u nastavku.

2 MATEMATIČKI MODEL

Za proračun raspodjele struje/potencijala u sustavu katodne zaštite korištena je metoda konačnih elemenata (FEM), metoda rubnih elemenata (BEM) i kombinirana metoda (BEM/FEM). Na slici 1 prikazana je principijelna shema sustava katodne zaštite s naznačenim metodama koje su korištene u pojedinim oblastima. Direktna metoda rubnih elemenata (BEM metoda) pogodna je za rješavanje jednadžbi stacionarnih elektroprovodnih polja u elektrolitu s beskonačnim granicama, tako da je ova metoda korištena za proračune zaštitnog potencijala u elektrolitu. S druge strane, FEM metoda je pogodna za rješavanje polja unutar ograničenih prostora pa je ista korištena za proračune unutar metalnih površina (elektro-

1 INTRODUCTION

In this paper, the results of numerical distribution of the protection current/potential on the specific object, reinforced concrete pipeline with pre-stressed armature, when the CP system with galvanic anodes is applied, are given.

When the numerical calculation of protection current distribution in cathodic protection system (CP) is concerned, most authors begin with analysing the Boundary Element Method (BEM method) [1]. This method is based on discretization of boundary lines or surfaces and therefore is useful when solving the field in the domains where infinite or semi-infinite regions are dominant.

Orazem et al. [2] and [3] use the 3D BEM method for the calculation of protection potentials for very long pipelines with smaller or greater isolation damage. Riemer and Orazem concluded that for long pipelines (> 6,0 km) with damaged isolation, a voltage drop in the pipeline itself should be considered because the potential attenuation is not uniform on the whole length of the pipeline. Adey [4] applied the full 3D model for the calculations of the potential including the nearby objects connected with anodes. Aoki et al. [5] like DeGiorgi [6] were more interested in protection of ship steels.

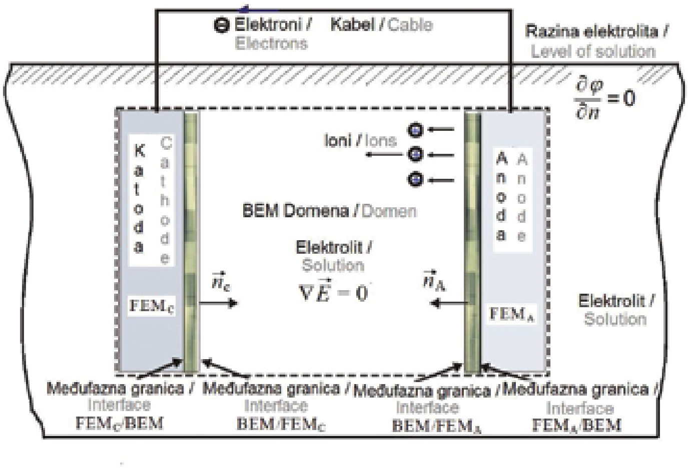
The Finite Element Method is modular and can be applied for solving problems in many areas that are described with Laplace's equation. Today, a large number of software packages that can be used to solve problems in electromagnetism can be found on the market.

The contribution of this paper is the use of the coupled BEM/FEM method for appropriate calculations. The use of this method will be explained later in the text.

2 MATHEMATICAL MODEL

For the calculation of the current/potential distribution in the CP system the Finite Element Method (FEM), the Boundary Elements Method (BEM/FEM) and the coupled method (BEM) have been used. Figure 1 shows the principle of the CP system. The used methods in some areas have been noted in Figure 1. The Direct Boundary Elements Method (BEM method) is appropriate for solving stationary fields of electrical current in electrolyte with infinite boundaries, therefore this method has been used for calculation of protection potential in electrolyte. On the other hand, the FEM method is appropriate for solving the field da). Raspodjela potencijala na međufaznoj granici (engl. interface) između elektroda i elektrolita rješavana je kombiniranom BEM/FEM metodom. Iterativno su proračunavani primjenom tzv. unaprijeđenog sekvencijalnog Dirichlet-Neumannovog postupka sukcesivnih podrelaksacija.

within limited areas and therefore this method has been used for calculations within the metal surfaces (electrodes). Potential distribution at the electrode/electrolyte boundary (interface) was calculated using the coupled BEM/FEM method. It was calculated iteratively using the so-called advanced sequential Dirichlet-Neumann procedure of successive under relaxations.



Slika 1 — Principijelna shema sustava katodne zaštite

Figure 1 — Principle scheme of cathodic protection system

2.1 Metoda konačnih elemenata

Metoda konačnih elemenata podrazumijeva diskretizaciju promatrane domene fizikalnog sustava (u danom slučaju to su elektrode) na konačan broj elemenata volumena određene geometrije. Rješavanje jednadžbi polja obavlja se na nivou svakog konačnog elementa. Laplaceova parcijalna diferencijalna jednadžba stacionarnog strujnog polja u određenoj domeni dana je kao:

2.1 The Finite Element Method

In the Finite Element Method the observed domain of the physical system (in this case, the electrodes) is divided into a finite number of elements of a certain geometry. The Solving of the field equations is made for each finite element. Laplace's Partial Differential Equation (LPDE) of stationary current field in observed domain is:

$$\frac{\partial}{\partial x}\left(\gamma\frac{\partial\varphi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\gamma\frac{\partial\varphi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\gamma\frac{\partial\varphi}{\partial z}\right)=0\,, \qquad (1)$$

gdje je:

φ – nepoznata funkcija raspodjele potencijala, V,
γ – specifična električna vodljivost, S/m.

Poslije primjene Galerkinove metode težinskih ostataka za raspodjelu potencijala može se pisati sljedeći sustav linearnih algebarskih jednadžbi u matričnom obliku:

whereat it is as follows:

φ – unknown function of potential distribution, V,
γ – specific electrical conductivity, S/m.

After Galerkin's weighted residuals procedure for the calculation of potential distribution is applied, the following system of linear algebraic equation can be written in the matrix form:

$$\boldsymbol{H}^{\mathrm{FEM}} \cdot \boldsymbol{\varphi}^{\mathrm{FEM}} = \boldsymbol{Q}^{\mathrm{FEM}} , \qquad (2)$$

gdje je:

φ^{FEM} – jednostupčana matrica nepoznatih električnih potencijala,

$\boldsymbol{H}^{\mathrm{FEM}}$ – dvodimenzionalna matrica koeficijenata napisana za jedan $3-\mathrm{D}$ element čiji je opći član dan kao:

whereat it is as follows:

φ^{FEM} – column vector matrix of unknown potentials,

$\boldsymbol{H}^{\mathrm{FEM}}$ – two-dimensional matrix of coefficients written for one $3-\mathrm{D}$ element where the common term is given by:

$$h_{ij}^{\mathrm{FEM}} = \sum_{e=1}^{n_e} \left[\gamma \int_{V_e} \left(\frac{\partial N_i^e}{\partial x} \frac{\partial N_j^e}{\partial x} + \frac{\partial N_i^e}{\partial y} \frac{\partial N_j^e}{\partial y} + \frac{\partial N_i^e}{\partial z} \frac{\partial N_j^e}{\partial z} \right) \mathrm{d} V_e , \right] , \qquad (2a)$$

$$i = 1,\ 2,\ \ldots,\ n_f\ ,\ j = 1,\ 2,\ \ldots,\ n_f ,$$

gdje je:

V^e – volumen e–tog konačnog elementa,

n_e – ukupan broj konačnih elemenata,

n_f – ukupan broj čvorova konačnih elemenata u kojima se obavlja interpolacija potencijala,

$\boldsymbol{N}^e (x, y, z,)$ – probna funkcija kojom se obavlja interpolacija potencijala na e–tom elementu na sljedeći način:

whereat it is as follows:

V^e – volume of the eth finite element,

n_e – total number of finite elements,

n_f – total number of finite element nodes in which interpolation of potential is made.

$\boldsymbol{N}^e (x, y, z,)$ – shape functions that are used for interpolation of potential on the eth element in the following way:

$$= \sum_{j=1}^{n_f} N_j^e \cdot \ {}_j^e \ , \qquad (2b)$$

φ_j^e – vrijednost potencijala u čvorovima konačnog elementa,

$\boldsymbol{Q}^{\mathrm{FEM}}$ – jednostupčana matrica slobodnih članova čiji je opći član dan kao:

φ_j^e – value of potential in the nodes of the finite element,

$\boldsymbol{Q}^{\mathrm{FEM}}$ – column vector matrix of the free terms where the common term is given by:

$$q_i^{\mathrm{FEM}} = - \sum_{e=1}^{n_e} \left[\sum_{j=1}^{n_f} \left(\int_{S_\Delta^e} \gamma\, N_i^e \cdot N_j^e \cdot \frac{\partial \varphi_j^{\mathrm{FEM}}}{\partial n} \mathrm{d} S_\Delta^e \right) \right] , \qquad (2c)$$

S^e_Δ – granična površina e–tog elementa,

$\dfrac{\partial \varphi_j^{\mathrm{FEM}}}{\partial n}$ – Neumannov granični uvjet.

Rješavanjem sustava Galerkinovih jednadžbi težinskih ostataka, uzimajući u obzir granične uvjete, dobiju se vrijednosti potencijala u čvorovima mreže konačnih elemenata. Matrica koeficijenata $\boldsymbol{H}$ je rijetko popunjena matrica, pa je za rješavanje matričnog sustava jednadžbi (2) pogodno primijeniti Croutovu ili Dolitleovu metodu faktorizacije i

S^e_Δ – boundary surface of eth finite element,

$\dfrac{\partial \varphi_j^{\mathrm{FEM}}}{\partial n}$ – Neumann boundary condition.

Solving the Galerkin's weighted residuals system of equations, taking into consideration the boundary conditions, gives the values of potential in the nodes of the finite element mesh. The coefficient matrix $\boldsymbol{H}$ is a seldom filled matrix and therefore, in order to solve the matrix system of equations, the use of Crout's or Dolitle's factor-algoritam zamjene naprijed – nazad uz primjenu tehnike rijetko popunjenih matrica.

2.2 Direktna metoda rubnih elemenata

Metoda rubnih elemenata, koja se još naziva i metoda momenata, pogodna je za rješavanje polja u beskonačnim ili polubeskonačnim područjima. Matematički model direktne metode rubnih elemenata zasniva se na Greenovom simetričnom identitetu i jednadžbama kontinuiteta s kojima se unose granični uvjeti na granicama između domena s različitim medijima.

Neka se promatraju dva posebna slučaja proračuna 3–D elektroprovodnih polja, i to:

- slučaj kada se točka promatranja Q nalazi unutar proračunske domene V, i
- slučaj kada se točka promatranja Q nalazi na granici domene.

Neka se promatra volumen V koji je ograničen površinom S. Neka se u točki P nalazi izvor polja sa potencijalom $\varphi(\mathrm{P})$, a u točki Q se promatra funkcija potencijala $\varphi(\mathrm{Q})$.

Opća formula potencijala unutar, na granici i izvan proračunske domene, dana je izrazom:

ization method and the forward-backward switch algorithm together with the technique of rarely filled matrices is useful.

2.2 The Direct Boundary Element Method

The Boundary Element Method, also known as method of moment, is appropriate for solving the field in infinite or semi-infinite domains. Mathematical model of the direct BEM method is based on Green's symmetrical identity as well as equations of continuity. These equations serve to apply boundary conditions on the boundaries between different media. Let us consider two different cases of calculating 3D stationary currents fields:

- the case when the observed point Q falls into domain V,
- the case when the observed point Q falls on boundary media.

Volume V, which is bounded with surface S is observed. Field source with potential $\varphi(\mathrm{P})$ is at the point P, and at the point Q the function of potential $\varphi(\mathrm{Q})$ is observed.

The general formula for potential calculation inside, on the boundary, and outside of the domain is given with:

$$C(\mathrm{Q})\cdot\varphi(\mathrm{Q})+\int_S T(\mathrm{P},\mathrm{Q})\cdot\varphi(\mathrm{P})\cdot \mathrm{d}S_\mathrm{P}=\int_S G(\mathrm{P},\mathrm{Q})\cdot\frac{\partial\varphi(\mathrm{P})}{\partial \mathrm{n}_\mathrm{P}}\cdot \mathrm{d}S_\mathrm{P} \tag{3}$$

gdje je:

$G(\mathrm{P},\mathrm{Q})$ – Greenova funkcija, odabrana ovisno o vrsti koordinatnog sustava,

$T(\mathrm{P},\mathrm{Q})$ – derivacija Greenove funkcije u pravcu vektora vanjske normale $\vec{n}_\mathrm{P}$ na graničnu površinu,

$\varphi(\mathrm{Q})$ – funkcija potencijala u točki promatranja Q,

$\varphi(\mathrm{P})$ i $\dfrac{\partial\varphi(\mathrm{P})}{\partial \mathrm{n}}$ – funkcija potencijala i njena normalna derivacija u točki izvora P,

$C(\mathrm{Q})$ – konstanta koja ima različite vrijednosti i to:

$$C(\mathrm{Q})=\begin{cases}1 & \text{unutar domene } V \text{ (Poissonova formula)}\\ \dfrac{1}{2} & \text{na glatkoj granici u 3 D domeni}\\ \dfrac{\alpha_{3-\mathrm{D}}}{4\pi} & \text{na diskretnoj granici prostornog ugla } \alpha_{3-\mathrm{D}}\\ 0 & \text{izvan domene } V\end{cases}$$

dSp – elementarna površina graničnog elementa diskretizacije izvora polja $\varphi(\mathrm{P})$ i $\dfrac{\partial\varphi(\mathrm{P})}{\partial \mathrm{n}}$,

S – granična površina promatrane domene.

whereat it is as follows:

$G(\mathrm{P},\mathrm{Q})$ – Green's function, chosen depending on the type of the coordinate system,

$T(\mathrm{P},\mathrm{Q})$ – derivative of Green's function in direction of outward normal vector $\vec{n}_\mathrm{P}$ to boundary surface,

$\varphi(\mathrm{Q})$ – function of potential in observed point Q,

$\varphi(\mathrm{P})$ i $\dfrac{\partial\varphi(\mathrm{P})}{\partial \mathrm{n}}$ – function of potential and its normal derivation in point of source P,

$C(\mathrm{Q})$ – constant that can acquire different values:

$$C(\mathrm{Q})=\begin{cases}1 & \text{inside domain } V \text{ (Poisson formula)}\\ \dfrac{1}{2} & \text{on smooth boundary in 3 – D domain}\\ \dfrac{\alpha_{3-\mathrm{D}}}{4\pi} & \text{on discrete boundary of areal angle } \alpha_{3-\mathrm{D}}\\ 0 & \text{outside of domain } V\end{cases}$$

dSp – elementary surface of boundary element of field source discretization $\varphi(\mathrm{P})$ and $\dfrac{\partial\varphi(\mathrm{P})}{\partial \mathrm{n}}$,

S – boundary surface of observed domain.

Primjenom metode kolokacije u točki, uzimajući za težinsku funkciju Diracovu delta funkciju, u kolokacijskim točkama koje su odabrane da se nalaze u čvorovima $\mathrm{Q_i}$ rubnih elemenata (tj. u točkama promatranja potencijala $\varphi(\mathrm{Q_i})$ može se izbjeći integriranje funkcije težinskih ostataka, ali se mora napisati sustav od n jednadžbi za n čvorova rubnih elemenata.

Nakon odgovarajućeg matematičkog postupka dobije se sljedeći sustav linearnih algebarskih jednadžbi:

The integration of weighted residuals function can be avoided by using the collocation point procedure. Dirac's delta function in this procedure is the weighted function. Collocation points are at nodes $\mathrm{Q_i}$ of boundary elements (i.e. at points where potential $\varphi(\mathrm{Q_i})$ is observed). But a system of n equations for n nodes of boundary elements must be written.

After the appropriate mathematical procedure is applied, we get the following system of algebraic equations:

$$\boldsymbol{H}^{\mathrm{BEM}} \cdot \boldsymbol{\varphi}^{\mathrm{BEM}} = \boldsymbol{G}^{\mathrm{BEM}} \cdot \left(\frac{\partial \boldsymbol{\varphi}}{\partial \boldsymbol{n}}\right)^{\mathrm{BEM}}, \tag{4}$$

gdje su:

φ^{BEM} i $\left(\frac{\partial \boldsymbol{\varphi}}{\partial \boldsymbol{n}}\right)^{\mathrm{BEM}}$ – jednostupčane matrice promjenjivih varijabli.

$\boldsymbol{H}^{\mathrm{BEM}}$ – dvodimenzionalna matrica koeficijenata koji su sastavljeni od dva dijela i čiji je opći član definiran kao:

whereat it is as follows:

φ^{BEM} and $\left(\frac{\partial \boldsymbol{\varphi}}{\partial \boldsymbol{n}}\right)^{\mathrm{BEM}}$ – vector column matrix of variables,

$\boldsymbol{H}^{\mathrm{BEM}}$ – two-dimensional coefficients of matrix, which are composed from two parts, where general term is defined by:

$$h_{i,j}^{\mathrm{BEM}} = \sum_{e=1}^{n_e} \int_S N_j^e \cdot T_{i,j}^e \cdot \mathrm{d}S_{\mathrm{P}} + \delta_{i,j} \cdot C_i, \; i = 1,\ 2,\ \ldots n_j, \; j = 1,\ 2,\ \ldots,\ n_e \ , \tag{4a}$$

G^{BEM} – dvodimenzionalna matrica koeficijenata čiji je opći član definiran kao:

G^{BEM} – two-dimensional coefficient matrix with general term defined by:

$$g_{i,j}^{\mathrm{BEM}} = \sum_{e=1}^{n_e} \int_S N_j^e \cdot G_{i,j}^e \cdot \mathrm{d}S, \; i = 1,\ 2,\ \ldots,\ n_j, \; j = 1,\ 2,\ \ldots,\ n_e \tag{4b}$$

$\delta_{i,j}$ – Drackova delta funkcija definirana kao $\int_V \delta(r)\,\mathrm{d}V = \begin{cases} 1 & za\ r \in V \\ 0 & za\ r \notin V \end{cases}$

V – volumen promatranog domena ograničen graničnom površinom promatrane domene S,

i – index koji se odnosi na točku promatranja Q,

j – index koji se odnosi na točku izvora P.

$\delta_{i,j}$ – Dirack's delta function defined as $\int_V \delta(r)\,\mathrm{d}V = \begin{cases} 1 & za\ r \in V \\ 0 & za\ r \notin V \end{cases}$,

V – volume of the observed domain bounded by the surface S,

i – index related to observed point Q,

j – index related to point of source P.

2.3 Kombinirana metoda BEM/FEM

Na granici elektrolit/zrak ili elektrolit/izolator (kada se radi o granici elektrolita s drugim elektrolitom velikog otpora) tzv. čistoj granici BEM domene, poznata je vrijednost jedne od promjenljivih (ili potencijala φ ili njegovog normalnog izvoda $\partial\varphi / \partial n_{\mathrm{p}}$). Na primjer, na granici elektrolit/zrak

2.3 The Coupled Method BEM/FEM

On solution/air or solution/dielectric (when it is a boundary of solution and another solution with high resistivity) boundary, so called boundary of the BEM domain, only one variable value (potential φ or its derivative $\partial\varphi / \partial n_{\mathrm{p}}$) is known. For example, on the solution/air (earth surface) boundary (površina zemlje), zadan je homogeni Neumannov uvjet, tj. $\partial\varphi/\partial n_{\mathrm{p}} = 0$ pa se računa φ.

Na granici FEM/BEM (granice elektrolit/anoda i elektrolit/cathoda) nepoznate su i φ i $\partial\varphi/\partial n_{\mathrm{p}}$. U tom slučaju piše se sustav jednadžbi uz uvažavanje Dirichletovih i Neumannovih rubnih uvjeta. Pišu se i dodatne jednadžbe kontinuiteta za φ i $\partial\varphi/\partial n_{\mathrm{p}}$, koje vrijede na granici FEM/BEM.
U ovom radu korišten je unaprijeđeni sekvencijalni Dirichlet – Neumannov algoritam BEM/FEM, koji se sastoji iz sljedećih koraka:

- podjela proračunske domene na BEM i FEM poddomene,
- zadavanje početnih vrijednosti potencijala na BEM/FEM granicama,
- započinjanje iterativnog ciklusa koji traje do zadovoljenja uvjeta konvergencije.

2.3.1 Rješavanje polja u BEM domeni

Na granici BEM domene, osim na samoj granici BEM/FEM, zadani su Dirichletovi ili Neumannovi granični uvjeti. U ovom slučaju matrični sustav (4), može se pisati u sljedećem obliku uzimanjem u obzir nepoznatih φ ili $\partial\varphi/\partial n_{\mathrm{p}}$ s obje strane granice (BEM)/(BEM/FEM):

the homogenous Neumann's condition is given $\partial\varphi/\partial n_{\mathrm{p}} = 0$, so φ is calculated.

In this case an equation system is made for each boundary of the domain, taking into consideration Dirichlet's and Neumann's boundary conditions. On the FEM/BEM boundary, additional equations of continuity for φ or $\partial\varphi/\partial n_{\mathrm{p}}$ are written.
In this paper, the advanced sequential Dirichlet-Neumann BEM/FEM algorithm is used. This algorithm consists of the following steps:

- partitioning of the whole domain into BEM and FEM domains,
- defining initial potential values on the BEM/FEM boundary,
- starting the iterative procedure which lasts until the set convergence condition is fulfilled.

2.3.1 Calculation of the electric field in the BEM domain

Dirichlet or Neumann boundary conditions are set for boundary of the BEM domain, except on the boundary between the BEM and FEM domains. In this case the matrix system (4), considering variables φ or $\partial\varphi/\partial n_{\mathrm{p}}$ on both boundary sides (BEM)/(BEM/FEM), could be written in the following form:

$$\boldsymbol{H}^{\mathrm{BEM}}\begin{pmatrix}\boldsymbol{\varphi}_{n+1}^{\mathrm{BEM}}\\ \boldsymbol{\varphi}_{n+1}^{\mathrm{BEM/FEM}}\end{pmatrix}-\boldsymbol{G}^{\mathrm{BEM}}\begin{bmatrix}\left(\dfrac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{n}}\right)_{\mathrm{n+1}}^{\mathrm{BEM}}\\ \left(\dfrac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{n}}\right)_{n+1}^{\mathrm{BEM/FEM}}\end{bmatrix}=\boldsymbol{0}\ , \qquad (5)$$

gdje je:

$\boldsymbol{0}$ – jednostupčana nul-matrica.

U sustavu (5) potrebno je uzeti u obzir Dirichletove i Neumannove granične uvjete uključujući i vrijednosti potencijala na granici BEM/FEM iz prethodnog koraka iteracije. Rješavanjem sustava (5) dobit će se vrijednosti normalne komponente polja na granici BEM/FEM:

whereat it is as follows:

$\boldsymbol{0}$ – column nul – matrix.

In the system (5) it is necessary to take into account the Dirichlet and Neumann boundary conditions includingthe potential values at the BEM/FEM boundary from the previous iteration step. By calculating the system (5), the normal components of the electric field at the BEM/FEM boundary will be found:

$$\left(\frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{n}}\right)_{n+1}^{\mathrm{BEM/FEM}} . \qquad (6)$$

2.3.2 Primjena jednadžbi kontinuiteta na granici BEM/FEM

Na granici površina rubnih i konačnih elemenata $S_{\text{BEM}} - S_{\text{FEM}}$ moraju biti zadovoljeni uvjeti kontinuiteta:

2.3.2 Calculation of the Continuity Equation at the BEM/FEM Boundary

On the interface between the finite and boundary elements $S_{\text{BEM}} - S_{\text{FEM}}$, the equation of continuity must be satisfied:

$$\gamma^{\text{FEM}}\left(\frac{\partial \varphi}{\partial n}\right)_{n+1}^{\text{FEM/BEM}} = -\gamma^{\text{BEM}}\left(\frac{\partial \varphi}{\partial n}\right)_{n+1}^{\text{BEM/FEM}} \Rightarrow$$
$$\left(\frac{\partial \varphi}{\partial n}\right)_{n+1}^{\text{FEM/BEM}} = -\frac{\gamma^{\text{BEM}}}{\gamma^{\text{FEM}}}\left(\frac{\partial \varphi}{\partial n}\right)_{n+1}^{\text{BEM/FEM}} \quad . \tag{7}$$

Za katodnu i anodnu površinu uzimaju se u obzir polarizacijske krivulje, kako slijedi:

Polarization curves are considered for the anode and cathode surfaces, as follows:

$$j_{\text{totalC}} = \gamma\left(\frac{\partial \varphi}{\partial n}\right)_{n+1}^{\text{BEM/FEM}} \quad ; \qquad j_{\text{totalA}} = \gamma\left(\frac{\partial \varphi}{\partial n}\right)_{n+1}^{\text{BEM/FEM}} \quad , \tag{8}$$

gdje je:

j_{totalC} – ukupna gustoća struje na katodi, mA/m^2,
j_{totalA} – ukupna gustoća struje na anodi, mA/m^2.

Kao rezultat se dobiju Neumannovi granični uvjeti, koji važe u pravcu normale na FEM strani interfejsa FEM/BEM na anodi i katodi. (Nije mi rečenica jasna pa Vas molim obratite pozornost i uskladite sa stručnom terminologijom, ako treba. Lektor)

2.3.3 Rješavanje polja u FEM domeni

U ovom koraku obavlja se rješavanje polja u FEM domeni. Na granici FEM domene, osim na samoj granici FEM/BEM, zadani su Dirichletovi ili Neumannovi granični uvjeti. U ovom slučaju matrični sustav (2) može se pisati u sljedećem obliku s uzimanjem u obzir nepoznatih φ i $\partial\varphi/\partial n_{\text{p}}$ s obje strane granice (FEM)/(FEM/BEM):

whereat it is as follows:

j_{totalC} – total current density on the cathode, mA/m^2,
j_{totalA} – total current density on the anode mA/m^2.

As result we get the Neumann boundary conditions that are applicable in the direction of the normal vector on the FEM side of the BEM/FEM interface at the anode and the cathode.

2.3.3 Calculation of the Electric Field in the FEM Domain

In this step the electric field in the FEM domain is calculated. The Dirichle or Neumann boundary conditions are set for the FEM domain boundary except for the FEM/BEM boundary itself. Therefore, considering the variables φ or $\partial\varphi/\partial n_{\text{p}}$ on both boundary sides (FEM)/(FEM/BEM), the matrix system (2) can be written in the following form:

$$\boldsymbol{H}^{\text{FEM}} \cdot \begin{pmatrix} \boldsymbol{\varphi}_{n+1}^{\text{FEM}} \\ \boldsymbol{\varphi}_{n+1}^{\text{FEM/BEM}} \end{pmatrix} = \begin{pmatrix} \boldsymbol{Q}_{n+1}^{\text{FEM}} \\ \boldsymbol{Q}_{n+1}^{\text{FEM/BEM}} \end{pmatrix} \quad , \tag{9}$$

gdje se elementi matrice $\boldsymbol{Q}_{n+1}^{\text{FEM}}$ izračunavaju primjenom izraza :

where the matrix elements $\boldsymbol{Q}_{n+1}^{\text{FEM}}$ are calculated using the expression:

$$q_i^{\text{FEM}} = -\sum_{e=1}^{n_e}\left[\sum_{j=1}^{n_f}\left(\int_{S_\Delta^e} \gamma \cdot N_i^e \cdot N_j^e \cdot \frac{\partial \varphi_j^{\text{FEM}}}{\partial n} \cdot \mathrm{d}S\right)\right] \quad . \tag{9a}$$

Kao rezultat se dobije potencijal $\varphi_n^{\mathrm{FEM/BEM}}$ na sučelju FEM/BEM.

2.3.4 Korekcija proračunatih potencijala na granici BEM/FEM

U ovom koraku obavlja se korekcija proračunatih potencijala na granici BEM/FEM iz prethodnog koraka. Korekcija se obavlja primjenom metode sukcesivnih podrelaksacija:

The outcome of the calculation are potentials $\varphi_n^{\mathrm{FEM/BEM}}$ at the FEM/BEM interface.

2.3.4 The Correction of Calculated Potentials at the BEM/FEM Boundary

In this step, the correction of the potentials calculated in the previous step at the FEM/BEM boundary is performed. The correction is made by using the successive under-relaxation method:

$$\varphi_{n+1}^{\mathrm{BEM/FEM}} = (1-\theta)\cdot\varphi_n^{\mathrm{BEM/FEM}} + \theta\cdot\varphi_{n+1}^{\mathrm{FEM/BEM}} , \qquad (10)$$

gdje je:

θ – faktor podrelaksacije koji se uzima u intervalu od 0 do 1.

2.3.5 Provjera konvergencije iterativnog ciklusa i zaustavljanje kada se postigne odgovarajuća točnost

Napravljen je računarski program CP_Zildžovski_2009.f90 u kojem je korištena opisana kombinirana metoda konačnih i rubnih elemenata. Kompletan proračun je oblikovan u navedenom programu.

3 GRANIČNI UVJETI NA POVRŠINI ANODE I KATODE

Parcijalne elektrokemijske reakcije, koje se odvijaju istodobno na površini katode, a koje su interesantne za koroziju čelika, dane su u sljedećim jednadžbama:

- $Fe \rightarrow Fe^{2+} + 2e^-$ parcijalna anodna reakcija,
- $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ reakcija redukcije kisika,
- $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ parcijalna reakcija razvijanja vodika .

Ove reakcije se odvijaju istodobno na površini čelika u realnim korozivnim uvjetima.

Ukupna vrijednost polarizacijske struje na katodnoj površini definirana je jednadžbom:

whereat it is as follows:

θ – under-relaxation factor whose value is in the range from 0 to 1.

2.3.5 The Verification of the Convergence of the Iterative Cycle and Shutting Down When the Required Accuracy Is Reached

Computer software, CP_Zildzovski_2009.f90, was created for CP calculation. The described coupled method of finite and boundary elements was implemented in this program. The complete calculation was made using this program.

3 BOUNDARY CONDITIONS ON THE ANODE AND THE CATHODE SURFACE

Partial electrochemical reactions, which happen simultaneously on the cathode surface and are of interest in the corrosion of steel, are as follows:

- $Fe \rightarrow Fe^{2+} + 2e^-$ partial anode reaction,
- $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ oxygen reduction reaction,
- $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ partial hydrogen evolution reaction.

These reactions occur simultaneously on the steel surface in real corrosion conditions.

Total polarization current density on the cathode surface is defined by:

$$j_{\mathrm{totalC}} = j_{0\,\mathrm{Fe}}\cdot 10^{\frac{\varphi-\varphi_{\mathrm{el}}-\varphi_{\mathrm{Fe}}}{\beta_{\mathrm{Fe}}}} - j_{\mathrm{lim,O_2}}\cdot\left(1+10^{\frac{\varphi-\varphi_{\mathrm{el}}-\varphi_{\mathrm{O_2}}}{\beta_{\mathrm{O_2}}}}\right)^{-1} - j_{0\,\mathrm{H_2}}\cdot 10^{\frac{-(\varphi-\varphi_{\mathrm{el}}-\varphi_{\mathrm{H_2}})}{\beta_{\mathrm{H_2}}}} , \qquad (11)$$

gdje je:

$j_{0\mathrm{Fe}}$ – gustoća struje koja odgovara reakciji otapanja metala $\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^-$,
$j_{0\mathrm{H}_2}$ – gustoća struje koja odgovara reakciji razvijanja vodika $2\mathrm{H}_2\mathrm{O} + 2\mathrm{e}^- \rightarrow \mathrm{H}_2 + 2\mathrm{OH}^-$,
$j_{\mathrm{lim,\,O}_2}$ – gustoća struje koja odgovara reakciji redukcije kisika $\mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^- \rightarrow 4\mathrm{OH}^-$,
φ – potencijal metala u odnosu na $\mathrm{Cu/CuSO}_4$ referentnu elektrodu,
φ_{el} – potencijal elektrolita u neposrednoj blizini čeličnog objekta,
$\beta_{\mathrm{Fe}}, \beta_{\mathrm{O}_2}$ i β_{H_2} – Tafelovi koeficijenti (nagibi) za odgovarajuće reakcije na katodi [7],
$\varphi_{\mathrm{Fe}}, \varphi_{\mathrm{O}_2}$ i φ_{H_2} – korozivni potencijali za odgovarajuće reakcije, respektivno.

Elektrokemijska reakcija na anodnoj površini je:

whereat it is as follows:

$j_{0\mathrm{Fe}}$ – current density due to reaction $\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^-$,
$j_{0\mathrm{H}_2}$ – current density due to reaction, $2\mathrm{H}_2\mathrm{O} + 2\mathrm{e}^- \rightarrow \mathrm{H}_2 + 2\mathrm{OH}^-$,
$j_{\mathrm{lim,\,O}_2}$ – current density due to reaction $\mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^- \rightarrow 4\mathrm{OH}^-$,
φ – metal potential regarding the CSE (Copper Sulphate Electrode) referent electrode,
φ_{el} – potential of the soil close to the steel structure,
$\beta_{\mathrm{Fe}}, \beta_{\mathrm{O}_2}$ and β_{H} – Tafel's coefficients (slopes) of corresponding cathodic reactions [7],
$\varphi_{\mathrm{Fe}}, \varphi_{\mathrm{O}_2}$ i φ_{H_2} – corrosion potentials of corresponding reactions, respectively.

Electrochemical reaction on the anode surface is:

whereat it is as follows:

$$\mathrm{Me} \rightarrow \mathrm{Me}^{z+} + z\mathrm{e}^- \quad , \tag{11}$$

gdje je:

z – valentnost metala Me, odnosno broj izmijenjenih elektrona u reakciji.

Ovoj reakciji odgovara analitički izraz za polarizacijsku struju:

z – valence of metal Me (number of exchanged electrons in reaction).

For this reaction corresponding analytical equation for polarization current is:

whereat it is as follows:

$$j_{\mathrm{totalA}} = j_{0,\mathrm{O}_2}\left(10^{\frac{\varphi - \varphi_{\mathrm{el}} - \varphi_{\mathrm{corA}}}{\beta_{\mathrm{A}}}} - 1\right) , \tag{12}$$

gdje je:

j_{0,O_2} – granična gustoća struje prijenosa mase za redukciju kisika,
β_{A} – Tafelov koeficijent (nagib) za reakciju na anodi,
φ_{corA} – korozivni potencijal za reakciju na anodi.

Na osnovi prethodnih jednadžbi može se konstatirati da se radi o izrazito nelinearnim polarizacijskim dijagramima, posebno na katodnoj površini.

3.1 Granični uvjeti s nelinearnim polarizacijskim karakteristikama

Ako se analizira polarizacijska karakteristika katodne čelične površine u sustavu primijenjene katodne zaštite s galvanskim anodama od cinka, vidi se da je dijagram za ukupnu struju nelinearan. Ova nelinearnost je utoliko veća što je manje odstupa-

j_{0,O_2} – mass transfer limited current density for oxygen reduction,
β_{A} – Tafel's coefficients (slopes) of anodic reactions
φ_{corA} – corrosion potentials of reaction on the anode.

Based on the previous equation, it can be concluded that the polarization diagrams are nonlinear, especially on the cathode surface.

3.1 Boundary Conditions with Nonlinear Polarization Characteristics

If we analyze the polarization characteristic of the steel cathode surface when the CP system with galvanic cast zinc anodes is applied, we notice that the total current diagram is non linear. This non linearity is greater if the deviation (over voltage or polarization) from corrosion potential nje (prenapon ili polarizacija) od korozivnog potencijala. U realnim uvjetima radi se o korozivnom potencijalu od oko – 0,2 V u odnosu na $Cu/CuSO_4$ referentnu elektrodu. Spajanjem cinkove anode s katodnom površinom katodna površina se polarizira za oko 200 mV do 300 mV, što znači da se uspostavlja novi potencijal na katodnoj površini od oko – 0,4 V do – 0,5 V u odnosu na $Cu/CuSO_4$ referentnu elektrodu. U intervalu od – 0,2 V do – 0,5 V polarizacijska karakteristika je potpuno nelinearna. Nelinearnost ima veću važnost za praktičan proračun kada se radi o većim Tafelovim nagibima, odnosno što je slabija izolacija čelika.

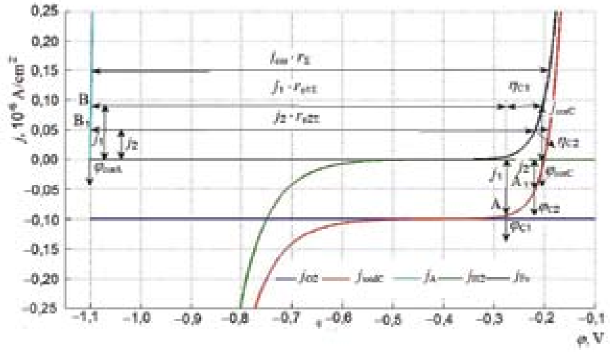
Kada se radi o velikim nelinearnostima, mora se voditi računa o donjoj i gornjoj granici potencijala u kojima se obavlja proračun potencijala i najčešće se to rješava uvođenjem logaritamske osi za struju.

Slika 2 dovoljno jasno objašnjava fizikalni model analize elektrokemijskih elektrodnih reakcija te njihov utjecaj na polarizacijske dijagrame anodne i katodne površine.

is smaller. In real conditions corrosion potential is approximately – 0,2 V vs CSE. When we connect a cast zinc anode with a cathode surface that surface polarizes for approximately 200 mV to 300 mV which means that new potential of approximately – 0,4 V to – 0,5 V vs CSE is established at the cathode surface. In the interval from – 0,2 V to – 0,5 V the polarization characteristic is completely non linear. This non linearity has greater influence to the calculation if the Tafel slopes are greater, meaning that the steel isolation is weaker.

When this non linearity is greater, we must consider the upper and lower potential limits in which potential calculation takes place. This problem is usually solved by introducing a logarithmic axis for current.

The physical model used for analysis of electrochemical reactions on the anode and cathode surfaces, as well as their influence to anode and cathode polarization diagrams, is shown in Figure 2.



Slika 2 — Polarizacijski dijagram za galvanski element čelik – cink
Figure 2 — Diagram of polarization for galvanic element steel –zinc

Za crtanje navedenih polarizacijskih dijagrama na slici 2 korištene su vrijednosti dane u tablici 1.

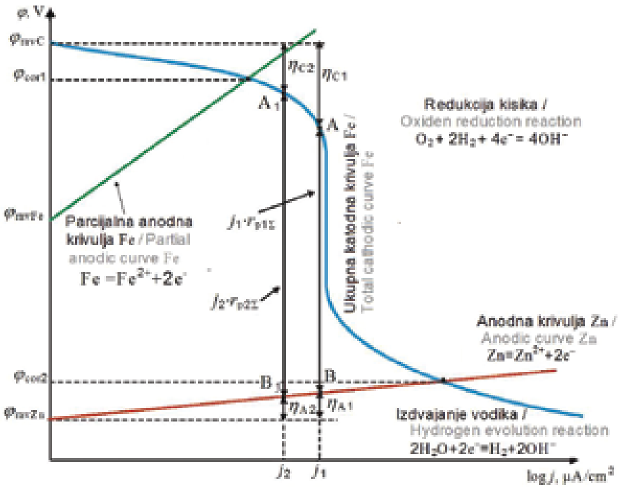
To plot the polarization diagram from Figure 2, the parameters listed in Table 1. were used.

Tablica 1 – Vrijednosti koeficijenata za crtanje polarizacijskog dijagrama
Table 1 – Values of polarization parameters

Parametar / Parameter	Vrijednost / Value	Parametar / Parameter	Vrijednost / Value
j_{lim, O_2}	0,1 μA/cm²	φ_{Fe}	– 200 mV
j_{0,O_2}	1,0 μA/cm²	φ_{O_2}	+100 mV
$j_{0, Fe}$	0,1 μA/cm²	φ_{H_2}	– 750 mV
j_{0, H_2}	0,1 μA/cm²	φ_{corA}	– 1 100 mV
β_{Fe}	0,06 V/dekadi / dec	β_{H_2}	0,1326 V/dekadi / dec
β_{O_2}	0,059 V/dekadi / dec	β_A	0,059 V/dekadi / dec

Na slici 3 prikazan je pojednostavljeni polarizacijski dijagram u polulogaritamskom razmjeru. Kada sustav katodne zaštite nije uključen, oba metala (čelik i cink) imaju svoje ravnotežne potencijale.

Figure 3 shows a simplified polarization diagram in a semi-logarithmic scale. When the CP system isn't applied, both metals (steel and zinc) have their own equilibrium potentials.



Slika 3 — Shematski radni uvjeti galvanskog elementa čelik – cink

Figure 3 — Scheme work conditions of galvanic element steel –zinc

U trenutku puštanja sustava katodne zaštite u pogon, radna točka na polarizacijskom dijagramu katodne površine je točka A s gustoćom zaštitne struje j_1. Istodobno, pri istoj zaštitnoj struji, radna točka polarizacijskog dijagrama anodne površine je točka B. Pad napona u elektrolitu je $j_1 \cdot r_{p1\Sigma,}$ Ωm^2 gdje je sa $r_{p1\Sigma,}$ Ωm^2 označen ukupni specifični polarizacijski otpor u elektrolitu koji obuhvaća i prijelazne polarizacijske otpore anoda/elektrolit i katoda/elektrolit.

Ukoliko je specifični električni otpor elektrolita mali, onda je i pad napona u elektrolitu mali. Pri istim ostalim uvjetima, iz zbroja padova napona može se zaključiti da je veća i polarizacija katodne površine, odnosno veća gustoća zaštitne struje j.

Poslije određenog vremena, to jest nakon polarizacije katodne površine i povećavanja prijelaznog otpora galvanske anode dolazi do smanjivanja zaštitne struje. To smanjivanje je rezultat povećanja ukupnog polarizacijskog otpora u električnom krugu katodne zaštite. U tom slučaju je radna točka A_1 (katodna površina), odnosno B_1 (anodna površina) sa zaštitnom strujom j_2.

U ovom slučaju, pojavljuje se pad napona na ukupnom polarizacijskom otporu koji iznos $j_2 \cdot r_{p2\Sigma}$. Ovaj pad napona je, bez obzira na smanjenje struje, veći od početnog pada napona na ukupnom pri-

When the CP system is put into service, initial operating point on the polarization diagram is the point designated by A with the corresponding current density j_1. Simultaneously, for the same protection current, the operating point of the anode is B. The voltage drop in electrolyte is equal to, $j_1 \cdot r_{p1\Sigma,}$ Ωm^2 where $r_{p1\Sigma,}$ Ωm^2 is the total specific polarization resistance in electrolyte including the polarization resistances at both the anode/electrolyte and the cathode/electrolyte boundary.

If soil resistivity is small, then the voltage drop in the electrolyte is small as well. From the sum of voltage drops it can be concluded that the polarization of the cathode surface is greater as is the current density j, if the other conditions remain constant.

After the polarization of the cathode surface, the galvanic anode resistance increases which leads to the decrease of protection current. That decrease leads to the increase of total polarization resistance in the cathodic protection electric circuit. The new CP operating point is A_1 (cathode surface) and B_1 (anode surface) with protection current j_2.

In this case there is a voltage drop at the total polarization resistance. This voltage drop is, regardless of reduced current density, greater than the initial voltage drop at the total boundary rejelaznom otporu. Ovo pokazuje da je povećanje ukupnog polarizacijskog otpora dominantnije u odnosu na smanjenje gustoće zaštitne struje.

sistance. This shows that an increase of total polarization resistance is more dominant than a decrease of current density.

4 KRATAK OPIS SUSTAVA KATODNE ZAŠTITE NA KOJEM SU OBAVLJANI PRORAČUNI I MJERENJA

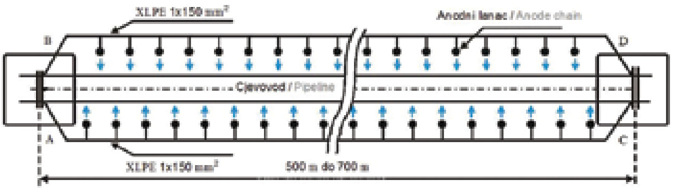
Katodna zaštita s galvanskim anodama primijenjena je na sustavu za vodoopskrbu koji je napravljen od armiranobetonskih cijevi bez izolacije promjera 4 000 mm. Na ovom objektu su obavljeni i numerički proračuni i mjerenja potencijala. Cjevovod je položen u tlo (pustinjski pijesak) na odgovarajućoj dubini. Šahtovi, koji predstavljaju krajeve dionica, pristupačni su za spajanje kabelskih instalacija, kontrolno-mjernih mjesta i slično. Dužine pojedinih dionica između šahtova su 500 m do 600 m. Na kompletnom sustavu osiguran je električni kontinuitet prenapregnute žice. S unutarnje strane cjevovoda postavljen je limeni plašt radi vodonepropusnosti. S vanjske strane limenog plašta, zbog mehaničkih razloga, postavljena je spiralno prenapregnuta čelična žica promjera 4 mm do 6 mm. Ova prenapregnuta žica je predmet katodne zaštite.

Projekt katodne zaštite odnosi se na postavljanje zaštitnog sustava s galvanskim anodama od legura cinka. Na slici 4 dana je principijelna shema sustava katodne zaštite jedne dionice cjevovoda.

4 A SHORT DESCRIPTION OF THE CP SYSTEM ON WHICH THE MEASUREMENTS HAVE BEEN MADE

Cathodic protection with galvanic anodes was applied on a watering system made of steel armored-concrete pipes 4 000 mm in diameter. Numerical calculations and potential measurements were performed at this object. The pipeline is situated in the ground (desert sand) on an adequate depth. Manholes, which represent the end of sections, are accessible for connections of cable installations, control-measurement points etc. Each section is of a 500 m to 600 m length on which electrical continuity is enabled. The inner layer of the pipeline is coated with steel for waterproofing reasons. Besides the steel cylinder, placed spirally for mechanical reasons, on the outer side of the tin pipe a pre-stressed steel wire (4 mm to 6 mm in diameter) is helically wrapped around the steel cylinder. This pre-stressed steel wire is the subject of cathodic protection.

This project refers to the installation of the protection system with galvanic cast zinc anodes. The CP system for one section applied to this object is presented in Figure 4.



Slika 4 — Sustav katodne zaštite jedne dionice cjevovoda

Figure 4 — CP system for one section of the pipeline

Katodna zaštita je realizirana, prema projektu, postavljanjem dubinskih cinkovih lanaca izmjenično, s obje strane cjevovoda na međusobnom razmaku od 6 m. Anodni lanci su postavljeni na dubini od 5 m do 15 m i udaljeni su od osi cjevovoda za 5,5 m.

Anodni materijal je cinkova legura s teoretskim elektrokemijskim kapacitetom 820 Ah/kg, ukupne mase 45,14 kg. Dimenzije anodnog lanca su 6 400 mm x 150 mm uključivo i punilo (engl. backfill). U jednom anodnom lancu ima 6 anoda. Principijel-

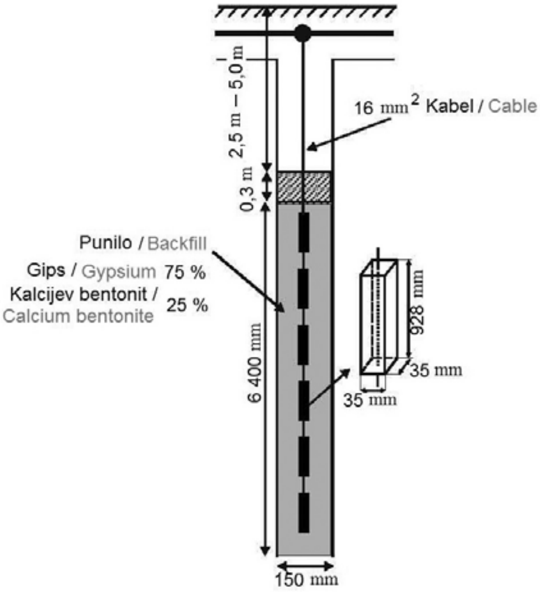
Cathodic protection is realised by means of cast zinc anodic strings, placed on both sides of the pipelines at a 6 m distance between each anode. Anodic strings are also placed vertically at a depth between 5 m and 15 m, and are 5,5 m away from the pipeline axis.

The anodic material used is a zinc alloy with a theoretical electrochemical capacity of 820 Ah/kg and a total mass of 45,14 kg. Anodic strings are constructed with 6 pcs of cast zinc anodes with an anodic groundbed measuring 6 400 mm x 150 mm na shema anodnog lanca prikazana je na slici 5.

Anode od legure cinka (cink preko 99 %) liju se u kalupe dimenzija oko 930 mm x 33 mm x 33 mm poprečnog presjeka u obliku trapeza kroz čiju sredinu prolazi galvanizirana čelična žica promjera 4 mm. Po jednom lancu instaliraju se tri centralizera.

(including the backfill). Anodic strings are connected as shown in Figure 5.

Zinc alloy anodes (zinc over 99 %) are cast in models measuring approx. 930 mm x 33 mm x 33 mm and their cross-section is trapeze shaped. Galvanized steel wire, 4 mm in diameter, goes through the center.



Slika 5 — Anodni lanac
Figure 5 — Anode groundbed

Proračun otpora rasprostiranja za anodni lanac ukopan na dubini h izvršen je pomoću sljedeće formule koja se često koristi u anglosaksonskoj literaturi:

Calculation of resistance for anodic groundbed, buried at depth h is made using the following equation. This equation is often used in technical literature in English:

$$R_{AL} = \frac{\rho}{2 \cdot \pi \cdot l}\left(\ln\frac{2 \cdot l}{r_B} + \frac{1}{2}\ln\frac{4h+l}{4h-l} + \frac{\rho_B}{\rho}\ln\frac{r_B}{r_A} \right) , \qquad (14)$$

gdje su:

R_{AL} – otpor rasprostiranja za anodni lanac,
l – dužina anodnog lanca (u projektu: l=6400mm),
r_B – polumjer anodnog ležišta s punilom (u projektu: $2r_B$ = 150 mm),
r_A – polumjer anodnog ležišta bez punila (u projektu: $2r_A$ = 35 mm),
ρ_B – specifični električni otpor punila (u projektu: ρ_B = 3,0 Ωm),
ρ – specifični električni otpor elektrolita, Ωm,
h – prosječna dubina ukapanja anodnog lanca (u projektu: h = 5 000 mm).

whereat it is as follows:

R_{AL} – resistance for anodic groundbed,
l – anodic chain length (in this project l=6400mm),
r_B – anodic groundbed (including backfill) diameter (in this project $2r_B$ = 150 mm),
r_A – anodic groundbed (without backfill) diameter (in this project $2r_A$ = 35 mm),
ρ_B – soil resistivity of backfill (in this project ρ_B = 3,0 Ωm),
ρ – soil resistivity of electrolyte, Ωm,
h – average depth at which anodic chains are buried (in this project h = 5 000 mm).

5 REZULTATI PRORAČUNA I MJERENJA

Za sustav katodne zaštite s galvanskim anodama od cinka koji je primijenjen na objektu opisanom u prethodnom poglavlju obavljeni su numerički proračuni korištenjem softwera CP_Zildžovski_2009.f90. U radu su prezentirani proračuni napravljeni za jednu dionicu dužine oko 30 m. Pretpostavlja se da je elektrolit homogen s vrijednošću specifičnog električnog otpora od 500 Ωm. Grafički rezultati numeričkih proračuna su dani u nastavku. Na istom dijelu dionice su tijekom instaliranja sustava katodne zaštite i kasnije tijekom njegove eksploatacije obavljana periodična mjerenja potencijala i gustoće struje. Rezultati mjerenja potencijala dani su u nastavku.

5.1 Rezultati proračuna

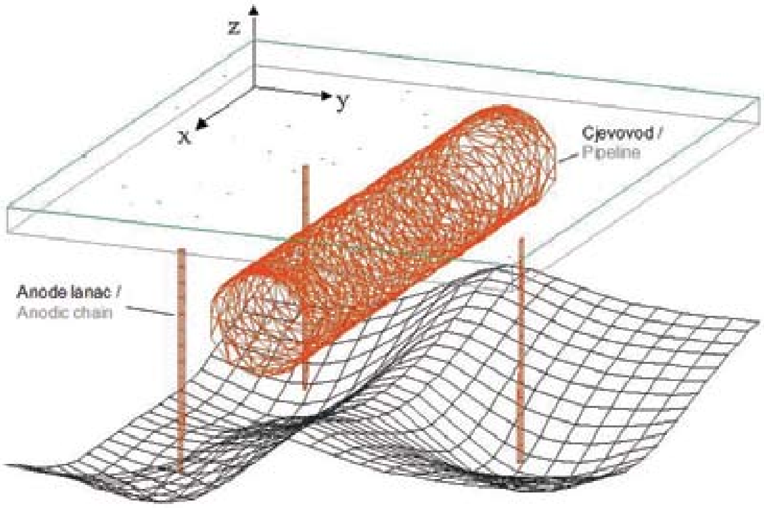
Slika 6 ilustrira raspodjelu zaštitnih potencijala u 3D prostoru na jednoj sekciji od 18 m. Razmak izmedju dva anodna lanca s iste strane cjevovoda je 12 m. Najnegativnija vrijednost potencijala u elektrolitu je u neposrednoj okolini anodnog lanca.

5 RESULTS OF NUMERICAL CALCULATIONS AND MEASUREMENTS

For CP systems with galvanic zinc anodes, applied to the object described in previous chapter, numerical calculations using CP_Zildzovski 2009.F90 software have been made. These calculations refer to the 30 m long section. Soil resistivity in this section is 500 Ωm. The results of the numerical calculations are given in diagrams. The potential measurement data for this section are given as well. Periodic measurements of current density and potential have been made on the same section during and after the installment of the cathodic protection system.

5.1 Results of Numerical Calculations

Figure 6 shows the protection potential distribution in a 3D area on one 18 m long section. Distance between two anodic chains is 12 m. The most negative value of potential in the electrolyte is around the anodic chains.



Slika 6 — Raspodjela zaštitnih potencijala

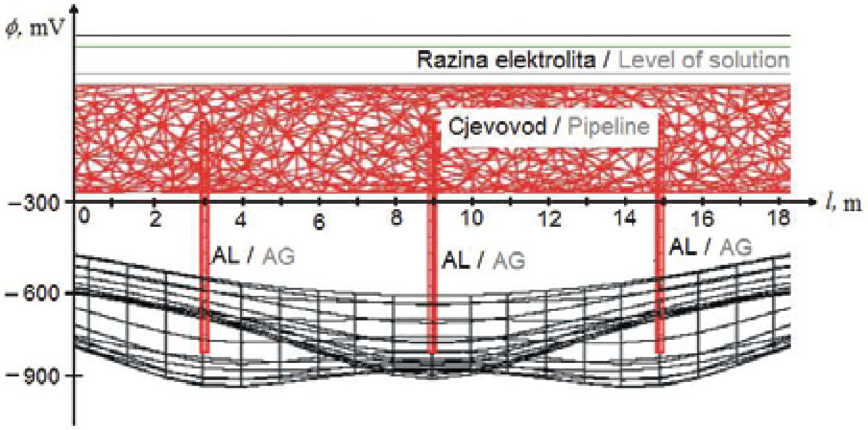
Figure 6 — Protection potential distribution (cross-section)

Uzdužni profil cjevovoda s odgovarajućom proračunatom raspodjelom potencijala dani su na slici 7. Ovakav način prikazivanja proračunatih vrijednosti raspodjele potencijala pogodan je za definiranje medjusobnog razmaka anodnih lanaca (na slici označeno sa AL) odnosno primjene kriterija minimalnih zaštitnih potencijala duž objekta.

The longitudinal profile of the pipeline with adequate calculated potential distribution is shown in Figure 7. This way of showing calculated values of potential distribution is useful for defining the distance between anodic chains so we can apply minimal protection criteria on the object.

Ako se obavi kompariranje raspodjele potencijala sa slike 7 i izmjerenih vrijednosti zaštitnih potencijala sa slike 11, vidi se da postoji relativno dobro slaganje rezultata. Naravno, odstupanja su prisutna, što je rezultat oštećenja betonskog omotača u fazi instaliranja cjevovoda, promjene vrijednosti specifičnog otpora tla, itd.

If we compare potential distribution shown in Figure 7 with measured protection potential values, we can see that there is a relatively good matching. Of course, deviations occur as a result of damage to the concrete shell. The shell was damaged in the installation phase as a result of change in specific soil resistivity.



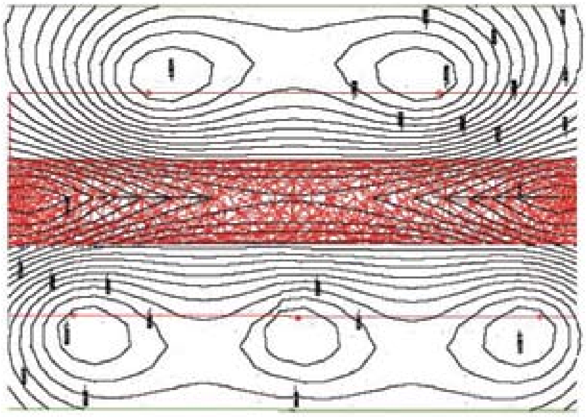
Slika 7 — Raspodjela potencijala (uzdužni presjek)
Figure 7 — Potential distribution (longitudinal profile)

Najnegativnija vrijednost potencijala je na mjestima gdje su locirana anodna ležišta, što je i logično. S dijagrama se može vidjeti da na tim dijelovima potencijal doseže vrijednosti i do – 1 000 mV na samom mjestu anodnog ležišta. Isto tako, vidi se da je potencijal iznad samog cjevovoda koji su najbliži anodnim lancima jednak oko – 600 mV. Vrijednosti potencijala iznad cjevovoda mijenjaju se unutar granica – 550 mV do – 600 mV, što je dosta dobro slaganje s izmjerenim vrijednostima danim na slici 11.

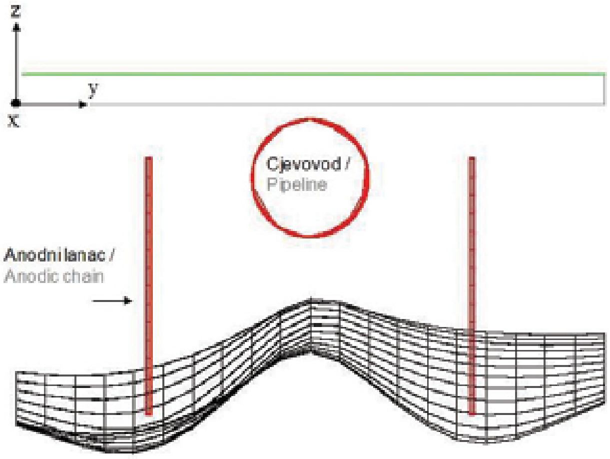
Poprečni presjek armirano betonskog cjevovoda s prenapregnutom armaturom i raspodjela potencijala u odnosu na anodne lance dani su na slici 9. Primjećuje se opadanje (smanjivanje negativnih vrijednosti) potencijala od anodnog lanca prema cjevovodu. Ova promjena potencijala je također, vidljiva i na slici 8.

Figure 7 shows potential distribution along the pipeline. The most negative value of potential is at the points where the anode groundbeds are positioned. We can see from the diagram that the potential is up to – 1 000 mV at the exact place where the anode groundbed is positioned. Also, we can see that potential just above the pipeline, the closest to the anode chains, is – 600 mV. The values of potential above the pipeline are from – 550 mV to – 600 mV which is a very good matching with the measured values given in Figure 11.

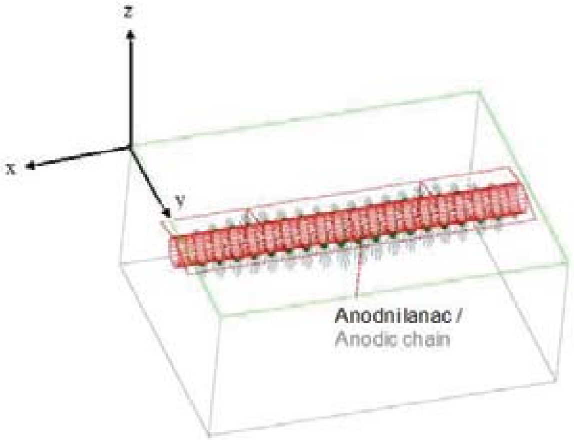
A cross section of pipeline with PCCP and potential distribution compared to the anode chains is given in Figure 9. We notice a potential attenuation (decrease of negative values) from the anode chains towards the pipeline. This potential shift is also shown in Figure 8.



Slika 8 — Raspodjela potencijala na površini zemlje
Figure 8 — Potential distribution on the earth surface



Slika 9 — Raspodjela potencijala (poprečni presjek)
Figure 9 — Potential distribution (cross-section)



Slika 10 — Raspodjela struje katodne zaštite (ρ = 500 Ωm, rastojanje anodno ležište – cjevovod 5,5 m)
Figure 10 — CP current distribution (ρ = 500 Ωm), anode groundbed-pipeline distance 5,5 m)

5.2 Rezultati mjerenja

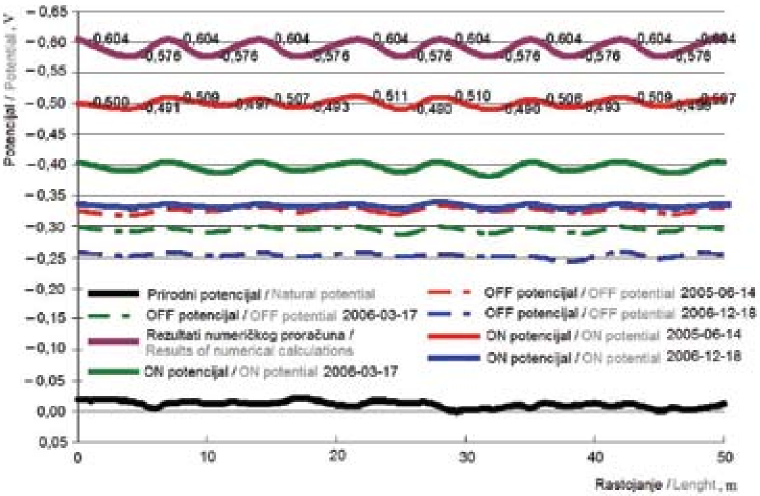
Na slici 11 OFF potencijal predstavlja izmjerenu vrijednost potencijala cjevovoda neposredno nakon isključenja sustava katodne zaštite, a ON potencijal predstavlja vrijednost potencijala cjevovoda izmjerenu kada je sustav katodne zaštite u radu.

Sa slike 11 se vidi da vrijednosti koje su proračunate pomoću numeričkog programa odstupaju od inicijalnog ON potencijala (2005-06-14) za manje od 20 %. Numerički proračun raspodjele potencijala rađen je za homogeni elektrolit uz zanemarivanje utjecaja otpora spojnih vodova, i drugo, tako da se odstupanja od izmjerenih vrijednosti mogu smatrati zadovoljavajućim.

5.2 Results of Measurements

On Figure 11 the OFF potential represents the potential value measured shortly after the CP system was shut down and the ON potential is the potential value of the pipeline measured while the CP system was operating.

On Figure 11 we can see that there is a 20 % deviation of values calculated using the numerical program from the initial ON potential (2005-06-14). The numerical calculation of potential distribution has been made for homogenous electrolyte. The influence of outside wire resistance is neglected so the deviations from measured values can be considered satisfying.



Slika 11 — Rezultati mjerenja potencijala

Figure 11 — Potential measurements results

Isto tako, može se zaključiti da tijekom eksploatacije sustava katodne zaštite dolazi do znatnog opadanja ON potencijala. ON potencijal nakon 18 mjeseci eksploatacije sustava opada za oko 35 % od svoje početne vrijednosti. U trenutku puštanja sustava u rad veća je gustoća zaštitne struje, jer je viši i pogonski napon. Tijekom vremena eksploatacije pogonski napon se snižava, odnosno potencijal štićenog objekta postaje manje negativan. Ovo se događa zbog povećanja polarizacijskog otpora armature, povećanja otpora rasprostiranja anodnih lanaca, odnosno zbog smanjivanja ukupne gustoće zaštitne struje. Gustoća zaštitne struje se smanjuje i zbog postojećeg pada napona na kabelima, anodnim lancima itd.

Moreover, we can conclude that, during the exploitation time of the cathodic protection system, there is a significant decrease of the ON potential. The ON potential, after 18 months of system exploitation, decreases for approximately 35 % from its initial value. In the moment when the CP system is put into work, current density is greater because the driving voltage is higher as well. During the exploitation time, the driving voltage decreases i.e. the potential of the protected object becomes less negative. This happens due to the increase of armature polarization resistance and anode chain resistance, which leads to decreased protection current density. Protection current density also decreases due to the voltage drops on wires, anodic chains, etc.

Može se primijetiti da se razlika između ON i OFF potencijala s vremenom smanjuje. Ova razlika predstavlja ustvari *IR* pad napona u elektrolitu. Ovo je posljedica uspostavljanja polarizacije, odnosno povećanja polarizacijskog otpora, s tim što se mora računati da su vremena polarizacija ovakvih objekata mnogo duža nego ako se radi o objektima s kvalitetnom izolacijom.

S dijagrama se vidi da je i nakon razdoblja eksploatacije od 18 mjeseci pomak potencijala u odnosu na prirodni veći od 200 mV na negativnu stranu. Prema međunarodnim propisima (npr NACE standard za zaštitu cjevovoda dovoljno je da pomak potencijala, kada se eliminira *IR* komponenta, u odnosu na prirodni potencijal bude minimalno 100 mV nakon depolarizacije od 4 sata. Na osnovi ovog kriterija vidi se da je predmetni cjevovod katodno zaštićen u skladu s propisima.

6 ZAKLJUČAK

Korištene numeričke metode za proračun raspodjele zaštitnih struja/potencijala u sustavima katodne zaštite s galvanskim anodama daje rezultate koji ne odstupaju puno od izmjerenih vrijednosti. Eventualna značajnija odstupanja proračunatih od izmjerenih vrijednosti zaštitnih potencijala mogu biti uzrokovana:

- promjenom električnih kvaliteta betonske obloge cjevovoda,
- promjenom vrijednosti specifičnog električnog otpora elektrolita,
- promjenom međusobnog razmaka anodnih lanaca nastalih u fazi instaliranja,
- prisutnost drugih podzemnih metalnih objekata, itd.

Naravno, kod pojave značajnijih odstupanja izmjerenih vrijednosti zaštitnih potencijala od proračunatih treba uraditi dodatnu analizu radi utvrđivanja uzroka.

Dane numeričke metode posebno su pogodne za proračune zaštitnih potencijala/struja podzemnih dugačkih metalnih objekata velikih dimenzija. Pogodno je prikazati proračunske vrijednosti kao što je dano na slici 7 radi jednostavnije usporedbe s mjerenim vrijednostima.

Rješavanje raspodjele zaštitnih potencijala/struja kod primjene sustava katodne zaštite s većim brojem galvanskih anoda jedino je moguće obaviti primjenom numeričkih metoda. U radu je primijenjena kombinirana BEM/FEM metoda. Primjena ove metode ima veliku praktičnu važnost za projektante sustava katodne zaštite

We can see that the difference between the ON and OFF potentials decreases over time. This difference in fact represents the *IR* voltage drop in electrolyte. This is caused by the establishment of polarization or the increase of polarization resistance. Objects with quality isolation need more time until polarization is reached and this should be taken into consideration.

We can see from the diagram that even after 18 months of system exploitation, the potential shift from the natural value is 200 mV negatively. According to the international standards (NACE Standard) in order for a pipeline to be protected, the potential shift, without the *IR* component, must be minimally 100 mV after a 4 hour depolarization. Based on this criterion we can see that the observed pipeline is properly protected.

6 CONCLUSION

The numerical methods used for the calculation of the protection current potential/current in the cathodic protection system show small deviations from measured values. Possible significant deviations of calculated from measured values of protection potential can be caused by:

- changing the electrical quality of the concrete shell of the pipeline,
- changing the specific soil resistivity of the electrolyte,
- changing the distance between anode chains made in the installing phase,
- presence of other underground metal objects.

Of course, if any significant deviations occur, further analysis must be performed to determine the cause of that deviation.

The given numerical methods are suitable for the calculation of protection current/potential of large underground metal objects. It is useful to show the calculated values, like on Figure 7, for a simpler comparison to the measured values.

To solve the distribution of protective current/potential distribution when the CP system is applied with a larger number of galvanic anodes, in cases where the system is functioning, the numerical method is most likely to be used. In this paper the coupled BEM/FEM method was used. The use of this method has a practical importance for future designers of CP systems in all conditions, especially when bearing in mind different electrolyte characteristics. This way, we get technically correct data about protection current distribution, which in practice repu svim uvjetima, posebno imajući u vidu različite karakteristike elektrolita. Tada se dobivaju tehnički korektni podaci o raspodjeli zaštitnih potencijala, što praktično predstavlja osnovu za optimalno projektiranje sustava katodne zaštite.

resents the basics for optimal projecting of the cathodic protection system.

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Uredništvo primilo rukopis:
2009-07-14

Prihvaćeno:
2009-07-31

Manuscript received on:
2009-07-14

Accepted on:
2009-07-31