

## Impressed cathodic protection of underground structures

**Abstract.** *Impressed cathodic protection systems are considered as a cost effective solution for a variety of in ground placed structures and is the most effective form of cathodic protection. A wide range of structures immersed in ground have been protected by cathodic protection using either impressed or sacrificial systems. The first have been and are extensively used in the oil and gas industry for underground tanks and other metallic objects in order to protect them from corrosion. This article describes the numerical method used in design two-dimensional impressed cathodic protection systems.*

**Streszczenie.** *Metoda ochrony katodowej z zewnętrznym źródłem prądu, jest stosunkowo tanim i skutecznym sposobem ochrony obiektów metalowych takich, jak zbiorniki czy rury gazociągów umieszczonych pod ziemią. Artykuł ten opisuje metodę analizy ochrony katodowej z zewnętrznym źródłem prądu z uwzględnieniem reakcji elektrochemicznych na katodzie oraz konduktywności gruntu. (Ochrona katodowa z zewnętrznym źródłem prądu dla obiektów pod ziemią)*

**Keywords:** *impressed cathodic protection, finite element method, Butler-Volmer equation.*

**Słowa kluczowe:** *ochrona katodowa z zewnętrznym źródłem, metoda elementów skończonych, równanie Butlera-Volmera.*

### Introduction

Control of corrosion related defect is a very important problem for structural integrity in ground based structures, as for example, buried containers. Underground structures have special interest due to the constant exposure to such environmental factors as electrochemical corrosion. Repair time and costs, replacement damaged parts, sudden damage in underground structures are just few of the problems connected to corrosion for underground structures.

The reduction reaction is commonly called the cathodic reaction and the oxidation reaction is called the anodic reaction. For corrosion to occur both electrochemical reactions are necessary. The oxidation reaction causes the given metal losses but the reduction reaction must be present to consume the electrons released by the oxidation reaction, keeping charge neutrality. Otherwise, a large negative charge would be rapidly created between the given corroding metal and the electrolyte and the corrosion process would interrupt. The oxidation and reduction reactions are also treated as half-cell reactions and can take place at the same site on the metal or can be physically isolated. The place where the metal is oxidized is referred to as the anode or anodic site. From this site, direct electric current flows from the corroding surface into the electrolyte in the form of metal ions leaving the surface. This current flows through the electrolyte to the site where oxygen or some other chemical compound is reduced. This site is referred to as the cathode or cathodic site. In order the corrosion cell can occur there are four necessary conditions to be fulfilled: There must be an anode, there must be a cathode, there must be a metallic path which connects electrically the anode and cathode. Usually, this will be the metallic object itself and finally both anode and cathode have to be immersed in an electrolyte, as for example, moist soil.

A soil with high conductivity, such as that containing a lot of moisture, provides a greater degree of electrical connectivity than a medium of low conductivity. In numerical modeling of such problems, soil is typically represented as a homogeneous and isotropic continuum with a single value of the resistance properties [1] Cathodic protection systems as those, for example, designed for protecting buried steel objects, utilize electrochemical properties of materials, from which protected objects are produced, to minimize corrosion damage. The way in which material interacts in the corrosion process is partially dependent on the conductivity of the surrounding soil [2]. At the end some illustrative example is given.

The main purpose of this article is calculation of the overpotential distribution on protected structure in order to assure that adequate conditions on cathode surface are fulfilled. The most important condition is that current should flow into the structure in every point of the surface.

### Theoretical considerations

Cathodic protection system has to be designing, and monitoring on well established protection criteria. Because corrosion phenomenon consists in solution of anodic material and productions of atomic hydrogen molecules on cathodic metal, the normal component of current density on cathode-electrolyte surface and electric overpotential are mostly chosen as protection criteria. One of the protection criterion based on field experience, is that a negative potential change of 100 - 300 mV from the free corrosion potential is a good measure of adequate protection. Another condition depending on normal component of current density says that for bare metal in the ground, a current of 11 to 22 mA/m<sup>2</sup> of bare metal-electrolyte surface has been found sufficient, except under extreme or extraordinary conditions. This is seldom justifiable economically for widespread lines, however, and the necessary protection is usually achieved by the use of cathodic protection to limited to small areas called "hot spots." This value must then be modified to suit the particular conditions. For coated pipelines, the current density required to protect is difficult to guess without field tests. The primary reason is the unknown condition of the protective coat which can vary from nearly 0% to 98% overall pipe surface [3].

Protecting metal surfaces in contact with water which is movement presents other difficulties. Water in motion produces a rinsing effect which prevents the creation of the coating and even the formation of a hydrogen film. Therefore, surfaces exposed to water in motion need a higher current density. The amount of this value required is difficult to predict. In this case, an experimental and field tests determination of the current requirements should be carried out.

A galvanic impressed cathodic protection system (ICPS) is commonly used to avoid corrosion of steel underground and underwater structures. Usually it works under varying environmental conditions. They can be caused by such factors as: dependence of water content on different soil depth, dependence of soil conductivity on falls of rain, changing composition of chemical components in chemical reactors. System of impressed cathodic protection consists of protected object (cathode), impressed anode, electrolyte

and external electrical power source, which is connected between cathode and anode. This connection is usually made from isolated wires. Mostly as external power sources are used voltage sources because it is relatively easy to build feed arrangement consisting of transformer stations and rectifier circuit.

Author of this article propose the use of the electric current source instead of the voltage source as energy supply. This should improve substantially protecting conditions and relative independence on weather or environmental conditions. At the end some numerical example is given.

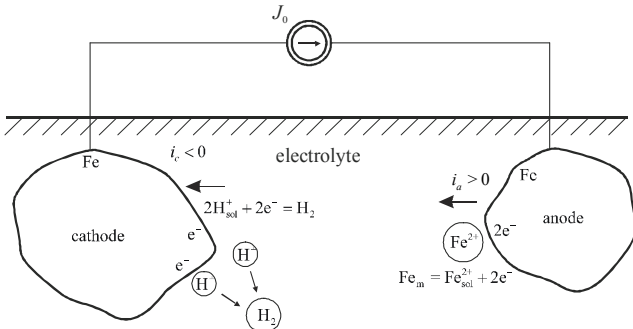


Fig. 1. Current source connected between cathode and anode in order to protect cathode against corrosion.

When a steady-state condition is considered, solution of the problem can be formulated mathematically by a Laplace equation with adequate boundary conditions. Because of the complexity of the geometries involved in the solution of practical problems and highly nonlinear boundary conditions, the mathematical model has to be solved numerically by any known method. In the last years, many investigation have been made in developing computer codes, mainly by using finite difference methods [2], finite element methods or boundary element methods [1,3,4]. The last one is more efficient for those problems in cathodic protection design where electrolyte is homogeneous, isotropic and linear and moreover the geometrical aspect ratio of the problem is sufficiently small. The finite element method, on the other hand, has not these limitations but instead the whole computational should be divided into finite elements. In fig.1 galvanic protection system with current source connected between cathode and anode is shown.

At the cathode hydrogen evolution is present according the reaction



with equilibrium potential  $E_{0c} = 0V$ , and on the cathode dissolution of iron according with the relation:



with  $E_{0a} = -0.44V$ .

In corrosion reactions a partial electrochemical reactions occurs that are influenced by electric current and potential. As electric current we assume flow of positive ions in electrolyte. On both sides of metal-electrolyte surface some potentials are present. The difference of this potential is called overpotential [5]:

$$(3) \quad \eta = V - E_0$$

where  $V$  is potential distribution on the corroding electrode and  $E_0$  is a potential of the electrode in equilibrium state and

$$(4) \quad E_0 = E^0 - \frac{RT}{nF} \ln \frac{a_R}{a_O}$$

where  $E_0$  is a standard cell electromotive force,  $a_R$  is a cathodic substrate activity,  $a_O$  is anodic product activity. At equilibrium state  $\eta = 0$ .

It is important to understand that both values  $V$  and  $E_0$  are in fact potential differences between metal and electrolyte as it is seen in fig.2.

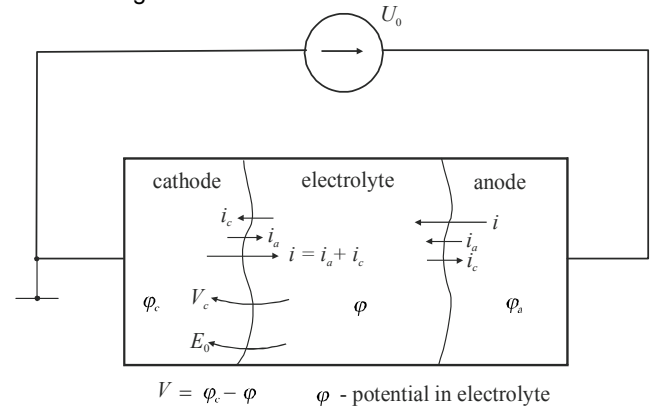


Fig.2. The cathodic and anodic reactions on metal surface.

The potential  $V$  on the electrode-electrolyte surface of the cathode is given by expressions:

$$(5) \quad V_c = \varphi_c - \varphi$$

where  $\varphi_c$  is potential of the cathode and  $\varphi$  is a potential in the electrolyte directly near a double layer [8]. For the anode we have similar relation:

$$(6) \quad V_a = \varphi_a - \varphi$$

where  $\varphi_a$  is potential of the anode and  $\varphi$  is a potential in the electrolyte directly near a anodic double layer. Between anodic and cathodic electric potentials following relation is fulfilled

$$(7) \quad \varphi_a - \varphi_c = U_0$$

Taking into account (12) one can write:

$$(8) \quad \eta_a = \varphi_c + U_0 - \varphi - E_{0a}$$

In the electrolyte the current density is related to the electric field strength by relation

$$(9) \quad \mathbf{J} = \sigma \mathbf{E}$$

where  $\sigma$  is a electrolyte conductivity. Electric strength vector is related to the potential  $\beta$  in electrolyte by formula

$$(10) \quad \mathbf{E} = -\text{grad } \varphi$$

Current density field is divergence free vector thus

$$(11) \quad \mathbf{J} = \sigma \mathbf{E}$$

From the above relation we get well known partial differential equation which has to fulfil potential in electrolyte:

$$(12) \quad \text{div}(-\sigma \text{grad } V) = 0$$

This equation has to be fulfilled together with Dirichlet's and Neumann's boundary conditions [4]. On the surface of the impressed electrode the potential has the value of the connected voltage source:

$$(13) \quad V|_{r \in \Gamma} = V_{\text{given}}$$

On the protected electrode current density flowing through the boundary between pipe and soil is given by following nonlinear relation [5]:

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$$(15) \quad \left. \frac{\partial V}{\partial n} \right|_{r \in \Gamma} = -\mathbf{E} \cdot \mathbf{n} = -\frac{1}{\sigma} \mathbf{J} \cdot \mathbf{n} = -\frac{1}{\sigma} j$$

where current density is given by modified Butler equation

$$(16) \quad j = \frac{\exp\left(\frac{\eta}{\beta_a}\right) - \exp\left(-\frac{\eta}{\beta_c}\right)}{\frac{1}{j_0} + \frac{1}{G_A} \exp\left(\frac{\eta}{\beta_a}\right) - \frac{1}{G_C} \exp\left(-\frac{\eta}{\beta_c}\right)}$$

where  $j_0$  is exchange current density, and corresponds to the magnitude of the equally fast forward and reverse reactions in the equilibrium;  $G_A$  and  $G_C$  are the limiting diffusion current densities and are proportional to the concentration of the reactants concerned and increase according to the first law of diffusion with the flow velocity; and  $\beta_a$  and  $\beta_c$  are the anodic and cathodic Tafel slopes.

Equation (4) together with boundary conditions (5) and (6) are solved by finite element method which is based on minimization of the following functional:

$$(17) \quad I_e = \int_{V_e} \frac{1}{2} \sigma(x, y) \left[ \left( \frac{\partial \varphi_e}{\partial x} \right)^2 + \left( \frac{\partial \varphi_e}{\partial y} \right)^2 \right] dV + \iint_{S_e} [J_a(x, y) \varphi_e] dS$$

with

$$(18) \quad \varphi_e(x, y) = \sum_{i=1}^n N_i(x, y) \varphi_{ei}$$

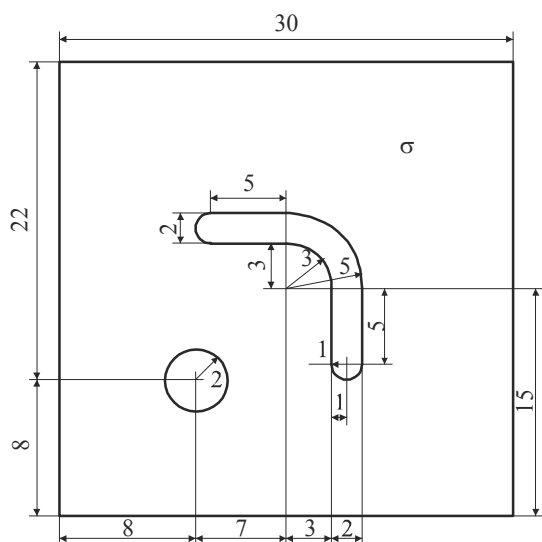


Fig. 3. Geometrical dimensions of the example problem

### Results

Fig. 4 shows in two dimensions the curved pipe, which should be protected against corrosion, and impressed electrode with circular shape. Between the impressed anode and protected cathode voltage source  $V_0 = 1V$  is connected.

Because this voltage is greater than an equilibrium half-cell electrode potential the current should flow from anode to protected cathode.

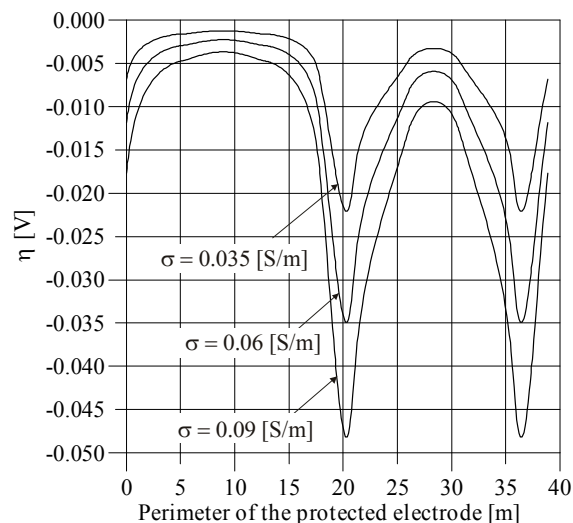


Fig.4. Distribution of the overpotential along protected object perimeter.

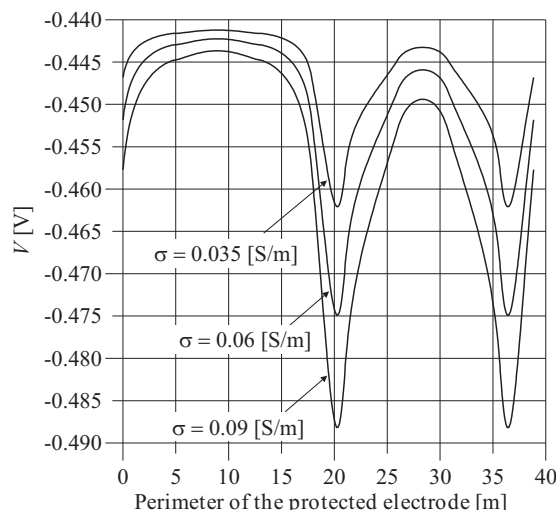


Fig. 5. Dependence of the potential on the perimeter of the protected pipe in function of the soil conductivity.

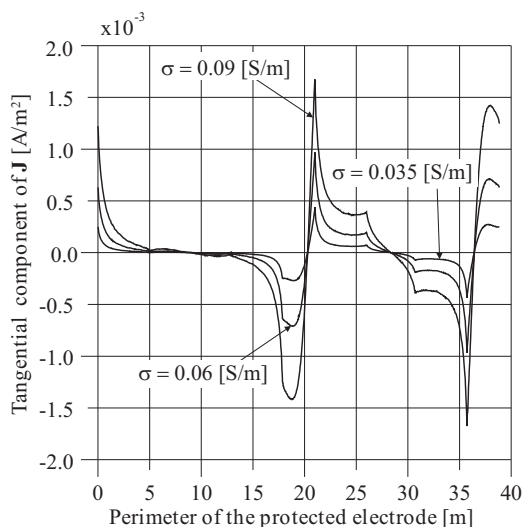


Fig. 6. Dependence of the tangential component of the current density J on the perimeter of the protected pipe in function of the soil conductivity.

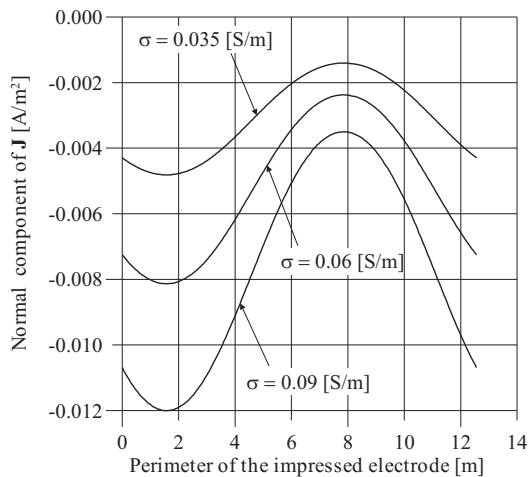


Fig. 7. Dependence of the tangential component of the current density  $J$  on the perimeter of the protected pipe in function of the soil conductivity.

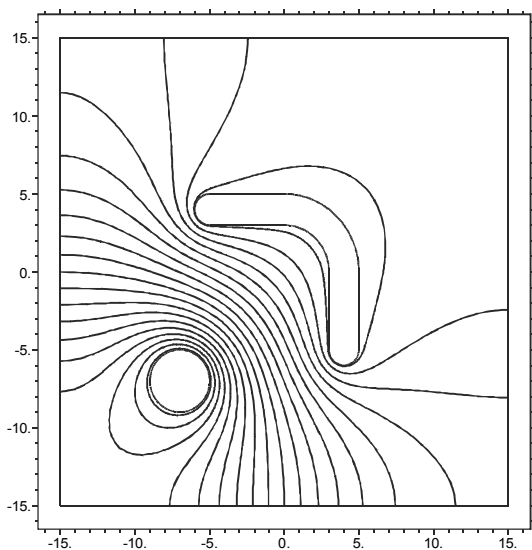


Fig. 8. Equipotential lines in electrolyte.

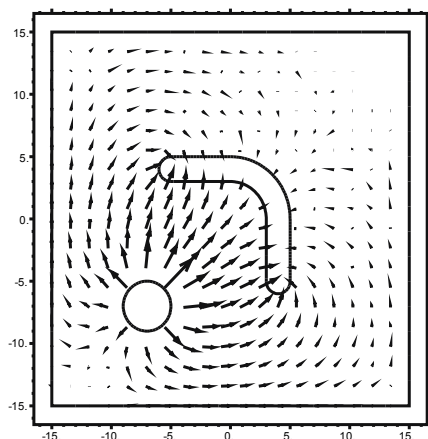


Fig. 9. Current density shown as vectors.

For following geometrical and physical constants (all dimensions are in SI system):  $j_0a = 0.015$  [A/m<sup>2</sup>],  $\beta_a = 0.2$  [V],  $E_{eq} = -0.44$  [V]. All numerical simulations was conducted for three different values of soil conductivity:  $\sigma = 0.035$ ,  $0.06$  and  $0.09$  [S/m]. Both electrodes are connected to voltage source by isolated wires so we can assume that on their surfaces there is not current flow.

### Conclusions

Computational modeling has been used to determine the effects of moderate changes in soil conductivity on corrosion effects. The range of conductivity chosen in simulation is representative for variation which may be seen in real life situations. The range of changes is moderate and does not consider extreme changes resulting from transition from great rain falls into drought environments. Computational results show that even moderate changes in soil conductivity have significant effects on corroding of protected object. The total current required to maintain anode voltage levels at prescribed values is computed by the analyses. Presenting in article figures show resulting profile of normal component of current on the boundary of the protecting object for exposed steel areas.

The total current required to maintain anode voltage levels at prescribed values is computed by the analyses. Presenting in article figures show resulting profile of normal component of current on the boundary of the protecting object for exposed steel areas. As expected, as the conductivity increases, the current required to maintain anode voltage levels also increases. With increasing conductivity the percentage of current which reaches the exposed steel area also increases.

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