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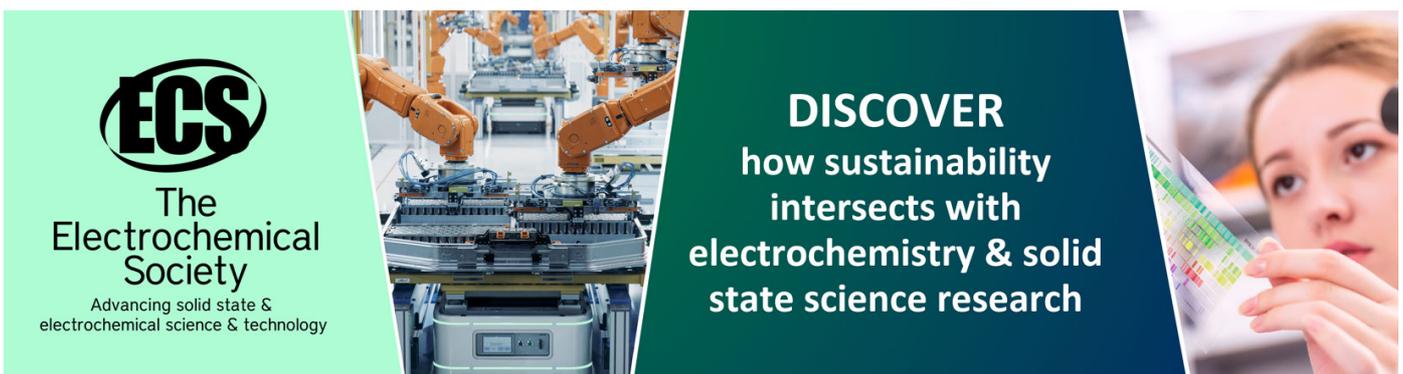
## Impact of the Underground Metal Construction Cover Layer on the Cathode Protection Efficiency

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# Impact of the Underground Metal Construction Cover Layer on the Cathode Protection Efficiency

**A Kalyutik, V Kiselev, E Rouzich**

Peter the Great St. Petersburg Polytechnic University  
Saint Petersburg, Russia, 195251, Polytechnicheskaya, 29  
E-mails: akalyutik@yandex.ru, kis\_vg@mail.ru, rouzith@mail.ru

**Abstract.** This paper presents the most probable mechanism of cover layer formation on the metal communication surfaces which are located in soil or sea water under the action of cathode protection as well as its basic properties. Basing on this analysis and data obtained during practical exploitation of the cathode protection systems the estimation of cathode protection efficiency variation in dc circuit was obtained. It was performed by estimation of both variation of cover layer electrical conductivity, and decrease of shielding current. It has been discovered that this efficiency grows with an increase of specific resistance of cover layer on the protected metal construction surface and connected with this decrease of specific shielding current density.

## 1. Introduction

Development of fuel and energy complex of Russian Federation together with improvement of community facilities system result in intensive increase of underground and underwater metal construction (UMC) length. Providing of their effective anticorrosion protection needs significant fundamental and exploitation expenses [1–24]. For example, according to the specialists' research [25], now at Saint-Petersburg there are approximately 3000 cathode protection units with average power of about 0.7 kW. Hence, decrease in power consumption of cathode protection units will significantly reduce the inputs both for their construction and exploitation. So it can be considered as a priority area of activity during the processes of cathode protection system development both for UMC as a whole and for pipelines in particular. Besides this, such activity significantly reduces corrosion hazard of soil associated with presence of ground current [26]. Further, expenses for electrochemical protection can be divided into two parts. The first one is related to improvement of the cathode protection unit itself. This means increase of transformer efficiency, usage of highly effective grounding devices, automation of anticorrosion protection systems, rational design and so on. The second one is related to actions at the protecting unit itself, for example: improvement of dielectric coat quality, elimination of electrical contacts with other metal constructions contacting with soil, extension of the longitudinal conductivity of UMC (for pipelines). This paper is devoted to solution of questions of the second part. And first of all it considers the influence of cover layer appeared on UMC at continuous operation of cathode protection unit [27] on its efficiency.

## 2. Formation of cover layers on metal surface and their impact on efficiency of UMC cathode protection unit

### 2.1. Terminology



According to our experience, some terminological explanations should be given for electrical engineers, as technology of underground communication protection from corrosion belongs to the intersection of various science fields. From the traditional point of view, the efficiency of electrical unit means the relation between output power and consumed power. Thus, the difference between these powers is energy loss at unit elements. The work on improvement of power sources for cathode protection is done permanently in view of their significant amount and considerable average power and is rather successful [25]. However, this area of activity has indirect bearing upon cathode protection technology itself. In the latter case, the following terms are under analysis: shielding current and its density, UMC and anodic protection spreading resistances, value and polarity of ground current which are generated by cathode protection unit and so on. Besides this, according to paragraph 7.1.1 of Russian State Standard 9.602 – 2005 [28]: "cathode polarization of constructions (besides pipelines which transfer medium heated above 20°C) is performed so that polarization potential of metal relative to saturated copper-sulphate electrode of comparison is between maximum and minimum values according to Table 9". Thus, according to Table 9, the criteria for UMC protection is a shift of polarization potential from its stable value to the region from -0.85 to -1.15 V according to copper-sulphate electrode of comparison. From the point of view of cathode protection realization this electrical work is considered to be useful.

So, cathode protection experts use the term "efficiency" for relation between energy consumption for obtaining polarization potential at UMC and energy expenses at dc circuit of cathode protection unit. Basing on this, it is accepted to calculate optimum number of anodes at anodic ground [27], or optimum cable cross section at dc circuit [29]. Furthermore, activities for reducing of shielding current (useful load according to classical electrical engineering) are attributed to measures for improving of electrochemical protection efficiency. This work presents analysis of effect of cover layers formation at UMC isolation defects on efficiency of cathode protection unit.

### 2.2. *Basic regularities of cover layers formation on metal surface and their properties*

Experience has shown that while exploitation of cathode protection units an active formation of cover layers on UMC metal surface takes place in presence of its cathode protection. This fact is well-known and is widely discussed in literature [27,30]. Furthermore, the cover layer possesses unique properties, namely: after turn-off of cathode protection unit the potential of underground (underwater) metal construction remains protective for a long period of time. It means that this potential is between -1.15 and -0.85 V according to copper-sulphate electrode of comparison [30,31]. Besides this, authors [32] associate protection capability of cathode unit with formation of oxide protection layer on metal surface. This statement makes sense because diffusion speed of iron ions in solid body (oxide layer) is usually about 3 orders less than that one in liquid electrolyte (wet soil, sea water and so on). Consequently, according to this model, the very presence of cover layer on metal surface guarantees its effective anticorrosion protection. It should be noted that authors [30] state that the speed of formation of protection layer on metal surface increases in presence of ions  $Ca^{2+}$ ,  $Al^{3+}$ ,  $HCO_3^-$  and some other substances, for example, oxygen, phosphates. Whereas destruction is stimulated by a number of neutral salt, particularly containing ions  $Cl^-$  и  $SO_4^{2-}$ .

These features of protection cover layer are responsible for development of an independent approach for cathode protection from corrosion. This approach was entitled "cathode anticorrosion protection of steel constructions by discontinuous current" [33,34].

However, authors [35] do not make a final conclusion about effectiveness of this approach, furthermore it is said that "there is no unified technique for investigation of pulsed polarization effectiveness". And their neutral conclusion is "Pulsed polarization technique, as well as polarization by continuous dc current technique might provide rather high level of steel construction protection from corrosion". Besides this, they highlighted a number of negative factors, which are related to the usage of this approach, namely:

1. "Current density at pulsed polarization should be more than that one for polarization by continuous dc current technique";

2. "A concentration cell appears at elongate constructions at the moment of current switch-off and its action is aimed at reducing of protection degree at increased potentials (at drainage point)".

All these together, taking into account complexity of practical implementation of this approach (which includes estimation of UMC anti-corrosion protection degree) didn't give it an opportunity to become a reliable technique for anti-corrosion protection and it isn't even mentioned in [28,36].

Alongside this the very presence of the cover layer has a positive impact on classical cathode protection. According to [37], total resistance of electrical current  $R$  in the presence of isolation defect of a round shape, which is situated, for example, at a pipeline with polyethylene coating can be calculated using the formula:

$$R = R_p + R_G \quad (1)$$

It is obvious that in this case the total resistance of defect  $R$  is a sum of polarized  $R_p$  and ohmic  $R_G$  resistances. Where  $R_G$  denotes ohmic potential drop in a defect and can be calculated using the following equation:

$$R_G = R_D + R_F + R_S \quad (2)$$

Further, values from expressions (1) and (2) can be denoted using the following formulas [27]:  
Expression which denotes polarization resistance of defect:

$$R_p = \frac{r_p}{A}, \quad (3)$$

where:  $r_p$  is specific polarization resistance of metal surface near the cover defect (according to [27]  $r_p = 1 \text{ Ohm} \cdot \text{m}^2$ , and in this case shielding current is  $0.3 \text{ Am}^{-2}$ );  $A$  is cover defect area.

The formula which defines resistance of cover layer, arising on metal surface during the process of cathode protection unit operating is the following:

$$R_D = \frac{r_d}{A}, \quad (4)$$

where:  $r_d$  is specific resistance of cover layer, arising at continuous operating of cathode protection unit (according to handbook data [27])  $r_d = (1 - 10) \text{ Ohm} \cdot \text{m}^2$ .

An expression which denotes ground resistance in a round shape defect is the following:

$$R_F = \frac{\rho l}{A}, \quad (5)$$

where:  $\rho$  is specific resistance of ground, and  $l$  is width of pipeline dielectric coat.

The formula which denotes spreading resistance in a round shape defect is:

$$R_S = \frac{\rho}{2a}, \quad (6)$$

where  $a$  is diameter of round shape defect.

The ion conductivity of cover layer is extremely low, so it guarantees low corrosion level [38]. Simultaneously it possesses high electronic conductivity. The latter case guarantees ability of presence of cathode process on its surface at electrochemical protection of UMC. The specific resistance of cover layer  $r_d$  which enters formula (4) is from 1 to 10  $\text{Ohm} \cdot \text{m}^2$  [27]. Specific polarization resistance  $r_p$ , which enters formula (3), according to the same literary source is one  $\text{Ohm} \cdot \text{m}^2$ .

Taking into account that after electric current shutdown, for example, while changing of polarization potential by switching off, the protection potential at UMC still remains for a long time (from several minutes to several weeks) [30]. This fact can be interpreted as dissolve of cover layer which takes place at a certain protection potential. This fact is generally well-known and is reported in a number of publications [27,30,38].

This model is in agreement with both electrochemical processes theory and practice. So, it can be said that in this case UMC protection from corrosion is provided by the presence of cover layer. Such representation allows one to take a fresh look at UMC cathode protection efficiency calculation. Under these conditions polarization potential should gradually decrease at shielding current decrease [39]. However, this fact cannot be discovered using traditional techniques of potential measurements (for example, switch-off or model electrode techniques), as UMC stationary potential is shifted to protection potential region. At the same time, this phenomena provide UMC protection from corrosion due to low diffusion speed of metal ions through cover layer. Furthermore, shielding current decrease

driven by high electronic resistance of cover layer guarantees a raise of economic efficiency of cathode protection. This phenomenon will be discussed in more details in the next section.

### 2.3. Calculation of impact of cover layer electrical resistance on UMC cathode protection efficiency

**The starting point.** We will use the following model representations in order to calculate the impact of variation of cover layer specific resistance on pipeline cathode protection efficiency:

We assume that the UMC (pipeline) is characterized by the following parameters:

- material (steel) specific resistance  $\rho_s$  is  $0.18 \cdot 10^{-6} \text{ Ohm}\cdot\text{m}$ ;
- external pipeline diameter  $d$  is 321 mm;
- pipeline wall width  $s$  is 6 mm.

For direct buried pipelines which possess polymeric (for example, polyetylene) insulation the specific shielding current  $j_s$  varies within the limits from  $10^{-5}$  to  $10^{-6}$  A per square meter [39]. We shall accept that this value is equal to  $10^{-5}$  A per square meter.

2. We assume that the pipeline has a dielectric (for example, polyethylene) coating of 5 mm width (polyethylene specific resistance  $\rho_D$  is about  $10^{18} \text{ Ohm}\cdot\text{cm}$ ). Laboratory and practical measurements show that polyethylene specific resistance decreases by 2-3 orders of magnitude and is about  $10^{15} \text{ Ohm}\cdot\text{cm}$  when it is buried in ground for a long time. Let us denote this value by  $\rho_u$ .

3. We assume that 100000 identical round shape defects are located on the pipeline starting from the point of current drainage.

4. We assume that each defect has an area of  $6.25 \text{ cm}^2$ , i.e. it is equal to area of potential controller which is used for polarization potential measurements according to Russian State Standard 9.602 – 2005, which is equivalent to round shape defect of  $a = 2.822 \text{ cm}$  diameter.

5. We accept that ground specific resistance is equal to  $\rho = 62.26 \text{ Ohm}\cdot\text{m}$ .

6. We assume that pipeline length is 1000 m, and the drainage point is located in the middle of it, so the polarization protection potential might be considered as a constant value throughout the pipeline.

7. We accept that shielding current density at non-isolated metal surface in the presence of polarization resistance in pipeline defect is 0.3 ampere per square meter.

8. We assume that at cover layer formation the shielding current is decreasing proportional to its resistance increase by 5 times.

Basing on these starting points, we will calculate cathode protection parameters. After that we will evaluate its efficiency as a function of cover layer electrical specific resistance and shielding current.

#### **Calculation of power at direct current circuit of cathode protection unit, which is spent at polarization resistance and resistance of pipeline cover layer.**

1. Calculation of pipeline isolation resistance at protection zone length of 1000 m. It is obvious that total isolation resistance in this case will be expressed by the following formula:

$$R_i = \rho_i \frac{l}{2\pi dL} \quad (7)$$

We substitute the numerical values into this formula and so we get  $R_i = 4.96 \cdot 10^{11} \text{ Ohm}$ . As we will see further, this value is significantly more than total resistance of all coating defects and, consequently, it can be omitted at further calculations.

2. We will calculate the defect polarization resistance  $R_p$  using formula (3). We substitute the numerical values into this formula and so we get that polarization resistance for one defect is:  $R_p = 1600 \text{ Ohm}$ . We put this value in Table 1 (column 2, row 2). It is known, that in ground UMC polarization is driven by diffusion oxygen overvoltage and it decreases with shielding current decrease, which we observe at cover layers formation [39]. From the other side, while formation of semiconducting cover layers, the transient overvoltage should increase. We assume that the total effect will be a half of the initial value, i.e.  $800 \text{ Ohm}$ . We put this value in Table 1 (columns 3, 4, 5, 6, row 2). It should be noted that at cover layer resistance growth and corresponding shielding current drop, the role of polarization resistance for cathode protection efficiency becomes less significant. In

other words, if there are some mistakes in defect polarization resistance evaluation, the end result will change numerically, with no tendency change.

3. We will calculate defect cover layer resistance  $R_D$  using formula (4). We substitute the numerical values into this formula. Taking into account handbook data [27], We assume that cover layer specific resistance  $r_d$  varies from 0 to 10  $Ohm \cdot m^2$  in increments of 2.5  $Ohm \cdot m^2$ .

The calculations show that cover layer resistance does not depend on ground and specific polarization resistances and remains constant at their variation. So this value is governed only by cover layer properties. We put these data into the table.

4. The calculation of combined polarization resistance and cover layer resistance  $R_{PD}$  of a defect will be performed by addition of corresponding values in rows 2 and 3 of Table 1. We put these results into row 4 of the table.

5. To obtain combined polarization resistance and cover layer resistance for all pipeline defects  $R_{PDT}$  we will divide one defect resistance on their quantity. We put these results into row 5 of Table 1.

6. We will calculate the one defect current  $I_d$  assuming that shielding current density (at presence of pipeline surface free of isolation) is 0.3 ampere per square meter. In this case defect current is 0.188  $10^{-3}A$  according to its geometrical parameters. We put this value in row 6, column 2 of Table 1.

Further we will calculate one defect current  $I_d$  in presence of both polarization and cover layer resistances assuming that shielding current decrease is proportional to cover layer resistance increase. We put these results into row 6 of Table 1.

7. Total shielding current through pipeline is equal to one defect current multiplied by amount of pipeline defects (100000 items). We put these results into row 7 of Table 1.

8. We will calculate the power  $P_{PDT}$  which is released at polarized resistance as well as at combined resistance of cover layer and polarization using the well-known expression:

$$P_{PDT} = I_T^2 R_{PD} \quad (8)$$

We put these results into row 8 of Table 1.

### **Calculation of power in direct current circuit of cathode protection unit, which is spent at ohmic resistance of pipeline defects.**

1. We will calculate ohmic resistance of ground in defect  $R_F$  at the chosen ground specific resistance and defect size parameters using the formula (5). We substitute the numerical values into this formula. And we get  $R_F = 498 Ohm$ . We put these data into row 9 of Table 1.

2. We will calculate spreading resistance of defect  $R_S$  at chosen ground specific resistance and defect size parameters using the formula (6). We substitute the numerical values into this formula. And we get  $R_S = 1103 Ohm$ . We put these data into row 10 of Table 1.

3. Let us introduce the term "ohmic potential drop in ground" and let us denote it  $R_{FS}$ . According to the new term, we can write the following formula:

$$R_{FS} = R_F + R_S \quad (9)$$

Let us carry on the calculations using expression (9) and we get  $R_{FS} = 1601 Ohm$ . We put this result into row 11 of Table 1.

4. To obtain combined resistance of all ohmic parts of all pipeline defects  $R_{FST}$  we will divide "ohmic potential drop in ground" for one defect  $R_{FS}$  on their quantity. We put this result into row 12 of Table 1.

5. We will calculate power  $P_{FST}$ , which is produced at ground resistance in pipeline defects using the well-known formula:

$$P_{PDT} = I_T^2 R_{FST} \quad (10)$$

We put these results into row 13 of Table 1.

### **Calculation of power in direct current circuit of cathode protection unit, which is spent at ohmic resistance of cable.**

1. According to handbook data [39-40] we assume that potential drop in cable of direct current circuit is 2 V and we put these data into Table 1 (row 14).

2. We will calculate power  $P_k$ , which is produced at cable resistance in direct current circuit of cathode protection unit using the well-known formula:

$$P_k = I_T U_K \quad (11)$$

We put these results into row 15 of Table 1.

### Calculation of power in direct current circuit of cathode protection unit, which is spent at spreading resistance of anodic protection.

1. We assume that spreading resistance of anodic protection in each case is 1 Ohm and we put these data into Table 1 (row 16).

2. We will calculate power  $P_A$  which is produced at spreading resistance of anodic protection using the well-known formula:

$$P_A = I_T^2 R_A \quad (12)$$

We put these results into row 17 of Table 1.

### We will perform the calculation of efficiency of separate variants of cathode protection $\eta_i$ using traditional expression:

$$H_i = \frac{P_{PDT}}{P_{tr}} \quad (13)$$

where:

$$P_{tr} = P_{PDT} + P_{FST} + P_k + P_A \quad (14)$$

denotes necessary power for cathode protection transmitter at direct current. We put these results into rows 18 and 19 of Table 1.

**Table 1.** Technical parameters of pipeline cathode protection which are caused by cover layer formation.

№	1	2	3	4	5	6
1	$r_d, \text{Ohm} \cdot \text{m}^2$	0	2.5	5	7.5	10
2	$R_p, \text{Ohm}$	1600	800	800	800	800
3	$R_D, \text{Ohm}$	0	4000	8000	12000	16000
4	$R_{PD}, \text{Ohm}$	1600	4800	8800	12800	16800
5	$R_{PDT}, 10^{-3} \text{Ohm}$	16	48	88	128	168
6	$I_d, 10^{-3} \text{A}$	0.188	0.150	0.113	0.075	0.0375
7	$I_T, \text{A}$	18.75	15.0	11.25	7.50	3.75
8	$P_{PDT}, \text{W}$	5.625	10.8	11.09	7.20	2.362
9	$R_F, \text{Ohm}$	498	498	498	498	498
10	$R_S, \text{Ohm}$	1103	1103	1103	1103	1103
11	$R_{FS}, \text{Ohm}$	1601	1601	1601	1601	1601
12	$R_{FST}, 10^{-3}, \text{Ohm}$	16.01	16.01	16.01	16.01	16.01
13	$P_{FST}, \text{W}$	5.629	3.602	2.026	0.901	0.225
14	$U_K, \text{V}$	2	2	2	2	2
15	$P_k, \text{W}$	37.5	30.0	22.5	15.0	7.5
16	$R_A, \text{Ohm}$	1	1	1	1	1
17	$P_A, \text{W}$	351.6	225.0	126.6	56.25	14.06
18	$P_{tr}, \text{W}$	428.5	269.4	162.2	79.4	24.1
19	$\eta_i, \%$	1.313	4.009	6.837	9.074	9.782

## Conclusions

This paper presents the most probable mechanism of formation of cover layer on the metal communication surfaces which are located in soil or sea water under the action of cathode protection as well as its basic properties. Basing on this analysis and data obtained during practical exploitation of the cathode protection systems the estimation of cathode protection efficiency variation in dc circuit

was obtained. It was performed by estimation of both variation of cover layers electrical conductivity, and decrease in shielding current. The following results were obtained:

1. When cover layers are forming at UMC due to long-term operation of cathode protection units, a steady trend to cathode protection system efficiency growth is observed.
2. Growth of efficiency of cathode protection systems is governed both by cover layer specific resistance growth and by shielding current decrease.

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