Influence of Polarization Resistance on Protection Parameters While Applying Cathodic Protection on PCCP

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Abstract

In this paper we analyze attenuation of cathodic protection current/potential in pre-stressed concrete cylinder pipes (PCCP) while using galvanic anodes. We present a functional relationship between cathodic protection current/potential and the duration of system deployment in desert conditions (very high soil resistivity). We conclude that total polarization is achieved after approximately 18 months of system deployment, which is the time needed for polarization of bare steel structures in the electrolyte. Results shown in this paper have both technical and commercial value because they make long-term measurements in difficult climate conditions no longer necessary. Furthermore, said derived dependency between protective current/potential and duration of system deployment enables a more accurate computation of parameters in cathodic protection systems.

Keywords: Cathodic Protection (CP), Driving Voltage, Protection Current, Protection Potential, Correlation, Field Measurements.

Introduction

Authors of this paper have conducted an experiment with the purpose of recording of close interval pipe to soil (CIPS) current/potential following a deployment of a cathodic protection (CP) system. Experimentally recorded evidence indicates an attenuation of protection current/potential of PCCP. An attenuation of PCCP potential is recorded until the point where a full polarization of PCCP is achieved. The time of PCCP polarization is in excess of 18 months, which is an indicative of a non − isolated structure.

The attenuation of the protection current, until the point of full PCCP polarization, in the cathodic protection system is caused by:

− Polarization of the PCCP

− Partial wear of the cast zinc anode as a result of CP system operation

− Increase of anode resistance R_A during system operation

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Purpose of this paper is reaching an approximate formula for the polarization current/potential following a deployment of a CP system. Consequently, costly field measurements of said PCCP current/potential can be avoided, thus rendering a more efficient operation of the CP system.

1. Corrosion of PCCP in Desert Conditions

Figure 1.a shows polarization potential (y–axis) in terms of electrolyte current density (x–axis), for a steel cathode (line with slope β_c) and for a cast zinc anode (line with slope β_{Fe}). The CP system in Figure 1.a. operates at the point of intersection of the two lines. Following [1,2], Figure 1.a ignores the IR_{el} free voltage drop in the electrolyte ($R_{el} = 0$).
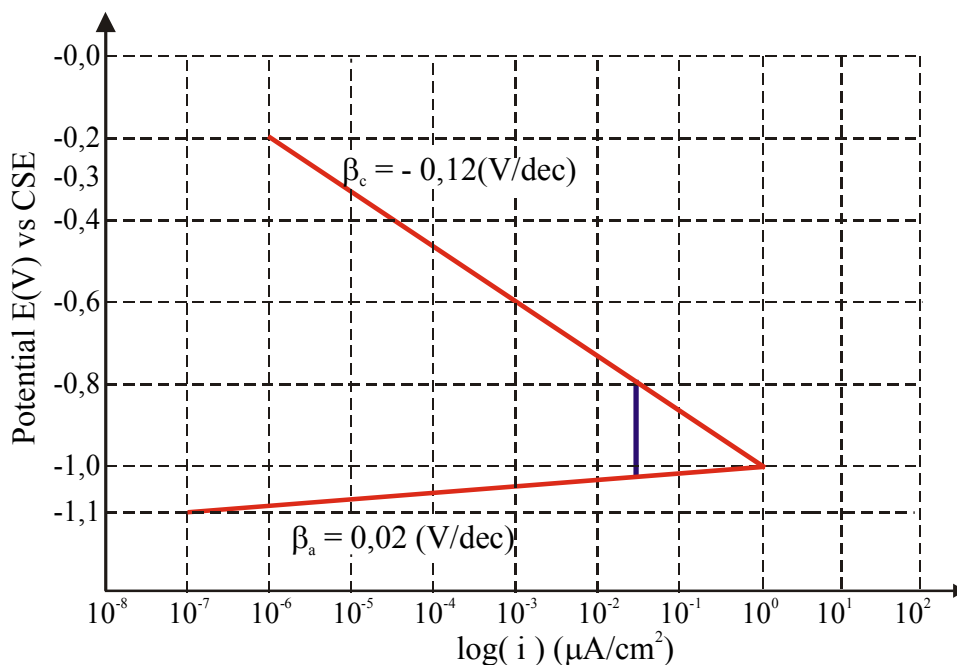

Figure 1.a.

As shown in Figure 1.a., the electrolyte current density at the operating point of the CP system is $1\mu A/cm^2$, where the polarization potential equals –1.0 V. It follows that the polarization of steel (PCCP) equals $1.0 - 0.2 = 0.8$ V.

During the functioning of the cathodic protection system, the resistance of the anodic groundbed is increased, resulting in an increase of the total resistance in the circuit of the cathodic protection system as well. The consequence of that is the establishment of current in the cathodic protection system, which is lower than the start value. Furthermore, an attenuation of polarization potential occurs as well. On the other hand, because of the increase of the polarization resistance of the structure (the PCCP) with time, the protection current and polarization potential of the cathode decrease as well. This happens when anodic and cathodic curves do not intersect; instead, there is a voltage drop in the electrolyte between anode and cathode, as shown on Figure 1.b.
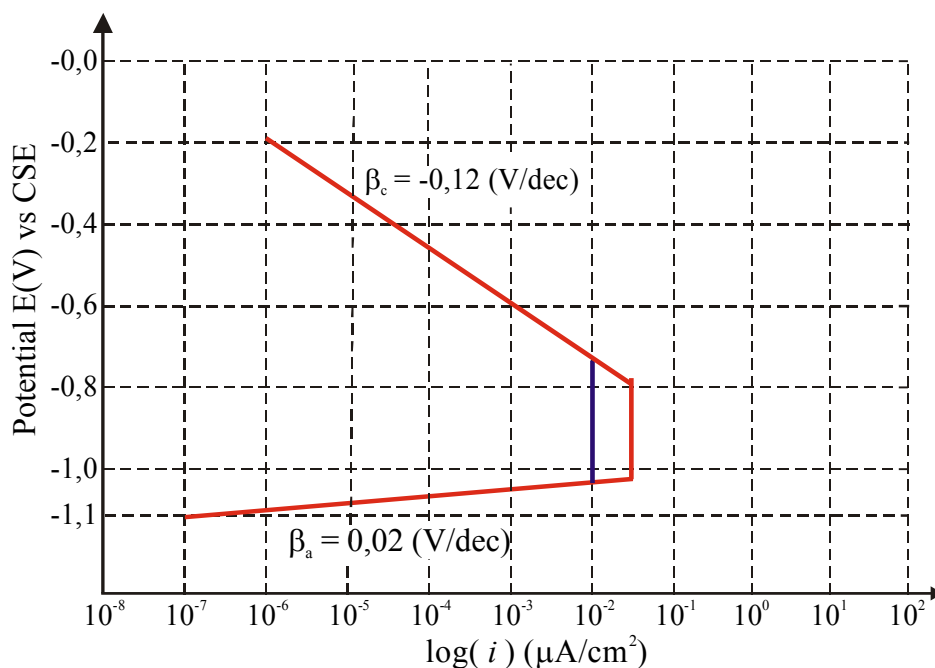
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Figure 1.b.

If we analyze Figure 2., we can conclude that the increase of the total resistance R_{tot} in the electrical circuit of cathodic protection, regardless of the protective current attenuation, leads to the increase of the total voltage drop in the electrolyte $\Delta\Phi_{AK} = I_P \cdot R_{tot}$, due to the fact that the involvement of the R_{tot} resistance component is far more pronounced than the protective current I_P [2].
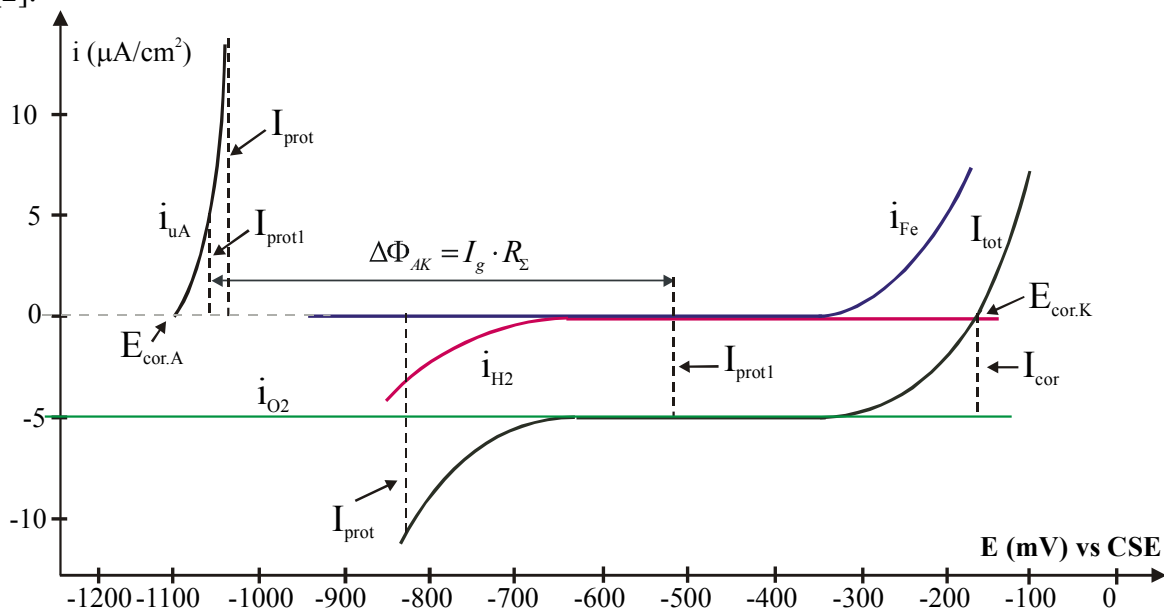

Figure 2.

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The protection current attenuation of cast zinc anodes automatically leads to a decrease of the current that the cathode receives (these currents have an equal absolute value). In essence, this paper deals with the relationship between the value changes of the resistance of anodic and cathodic surface during the time of polarization, and the changes of current values in the electrical circuit of cathodic protection system.

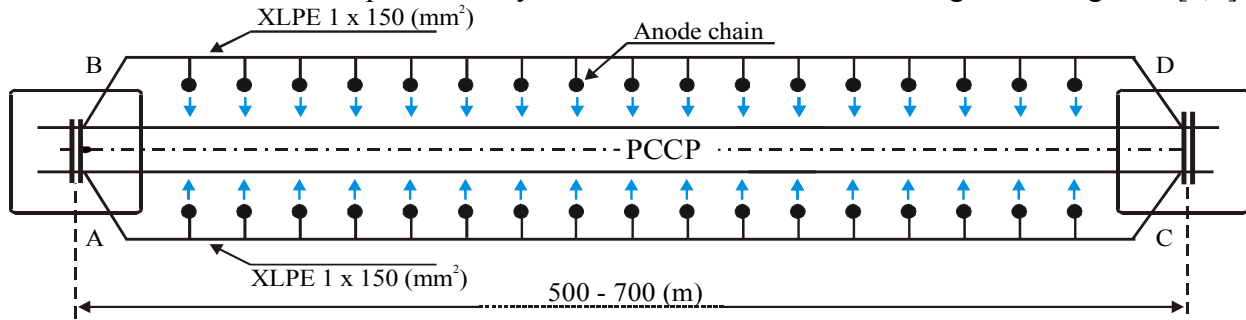The scheme of the cathodic protection system for one section of PCCP is given in Figure 3 [5,6].

Figure 3.

Measurements of the polarization potentials and the total protection current of the section were taken at points A, B, C and D. Points A and C, as well as points B and D, are connected with a header cable 1x150 [mm^2].

R_A is the resistance of the anodic groundbed (Figure 4.) [5,10], the value of which is a function of the soil resistivity and the dimensions and shape of the anode. The empiric equation used for the calculation of anodic groundbed resistance [3,12] is:

$$R_A = \frac{\rho}{2\pi l}\left(\ln\frac{8l}{d} - 1\right), \qquad l \gg d \qquad (1)$$

Where: ρ [Ωm] – Soil resistivity,
  l [m] – Length of the anodic groundbed,
  d [m] – Radius of the anodic groundbed.

In this case, for $l = 6{,}40$ [m] and $d = 0{,}15$ [m] we get:

$$R_A = 0{,}12018 \cdot \rho \approx 0{,}12 \cdot \rho \qquad (2)$$

If the solution has a soil resistivity range from $\rho = 850$ [Ωm] to $\rho = 1150$ [Ωm], the values of the anodic groundbed resistance will be from $R_A = 102$ [Ω] to $R_A = 138$ [Ω]. These values of soil resistivity are the typical values in the conditions of the desert, where the measurements were made.
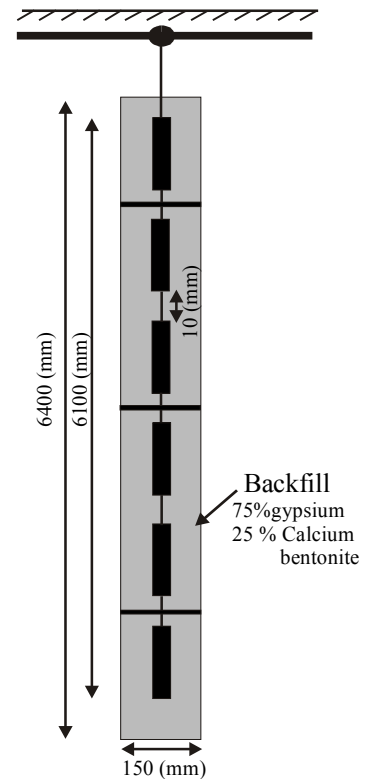

Figure 4.

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If we consider the contribution of backfill resistivity to the values of factor ρ in Equation (1), we conclude that there is a decrease in factor ρ. We assume that this influence makes factor ρ decrease to a third of its value. In that case, the value of anode string resistance changes within the range of $R_A = 34$ [Ω] to $R_A = 46$ [Ω].

With the assumption that the resistance of the concrete cover of the protected structures (PCCP) is 10 [Ω], and that the resistance of the soil cover is 10 [Ω], then the total resistance R_{tot} in the electrical circuit of practical cathodic protection is from 54 [Ω] to 66 [Ω].

If we assume that the driving voltage of the Zn/Fe system is 1000 [mV], where the steel is covered in concrete, the total protection current in one anode string equals to:

$$I' = \frac{1000}{54} = 18,52 \, [mA] \qquad \text{or} \qquad I'' = \frac{1000}{66} = 15,15 \, [mA]$$

The section analyzed has 87 anode strings, which means that the total current of the section has a range of:

$$I'_{TOT} = 18,52 \cdot 10^{-3} \cdot 87 = 1,61 \, [A] \qquad \text{and} \qquad I''_{TOT} = 15,15 \cdot 10^{-3} \cdot 87 = 1,32 \, [A]$$

The measured values of the start current, which rise to 2,0 [A] indicate that the current values of the cathodic protection system correspond to the values of factor ρ, where that factor represents the combination of the soil resistivity of cca 1000 [Ωm] and the backfill resistivity of cca 3 [Ωm]. The measured values indicate that the value of ρ is more accurate if we use the combination of soil resistivity and backfill resistivity as the "mixed" soil resistivity, for example ρ = 350 [Ωm].

As the surface of the protected pipeline section, that is cca 600 [m] long, amounts to cca 8000 [m²], then the protection current density is:

$$i' = \frac{1610}{8000} = 0,201 \, [mA/m^2] \qquad \text{or} \qquad i'' = \frac{1320}{8000} = 0,165 \, [mA/m^2]$$

Current density values decrease with the increase of soil resistivity, which is expected.

The voltage drop at the resistance of the anode string $R_A = 40,00$ [Ω] is

$$\Delta U_A = 15,15 \cdot 10^{-3} \cdot 40 = 606 \, [mV]$$

We can say that the driving voltage of 1000 [mV] is divided into a voltage drop of cca 600 [mV] in the anode string resistance, and 200 [mV] for voltage drops in the soil and pipeline surface respectively. In other words, when there is no anode polarization (the anode potential is constant, regardless of the protection current), the polarization of the PCCP is 200 [mV].

However, according to the previous calculation, we should say that the total resistance in the circuit of cathodic protection systems (for example 60 [Ω]) is considered to be the sum of the resistance of PCCP/soil, metallic circuit resistance and anode string resistance. For small values of soil resistivity, the voltage drop in the soil can be ignored, leaving the voltage drops in the anode chain resistance, cable resistance and resistance of PCCP/soil (polarization resistance).

For a shift of the PCCP polarization potential in the amount of e.g. 500 [mV] from its natural value, with a protection current of 50 [mA], the total resistance in the circuit of the cathodic

protection system will be 20 [Ω], and the voltage drop distributed to 500 [mV] in the pipeline resistance and in the anodic groundbed respectively.

For a shift of the PCCP polarization potential in the amount of e.g. 200 [mV] from its natural value, with the same protection current of 50 [mA], the total resistance in the circuit of the cathodic protection system will be 20 [Ω], and the voltage drop distributed to 200 [mV] on the pipeline resistance and 800 [mV] on the anodic groundbed. Furthermore, this means that for 87 cast zinc anode strings, the total resistance will be 20/87 = 0.23 [Ω] (which is, in fact, the sum of the anode string resistance, cable resistance and the resistance of PCCP/soil).

When the soil resistivity of the surrounding electrolyte is small, we can conclude that the most important factor affecting the protection current attenuation is the resistance of the anode string. On the other hand, where the voltage drop in solution and PCCP (with high soil resistivity values) is dominant, any increase in the value of anode resistance doesn't reflect very much on the change of protection current because the percentile participation of this resistance is relatively small.

The start values of protection current density, in the function of soil resistivity, are given in Figure 5 [8,9], which shows that the lower the value of the soil resistivity, the smaller the need for protection current.
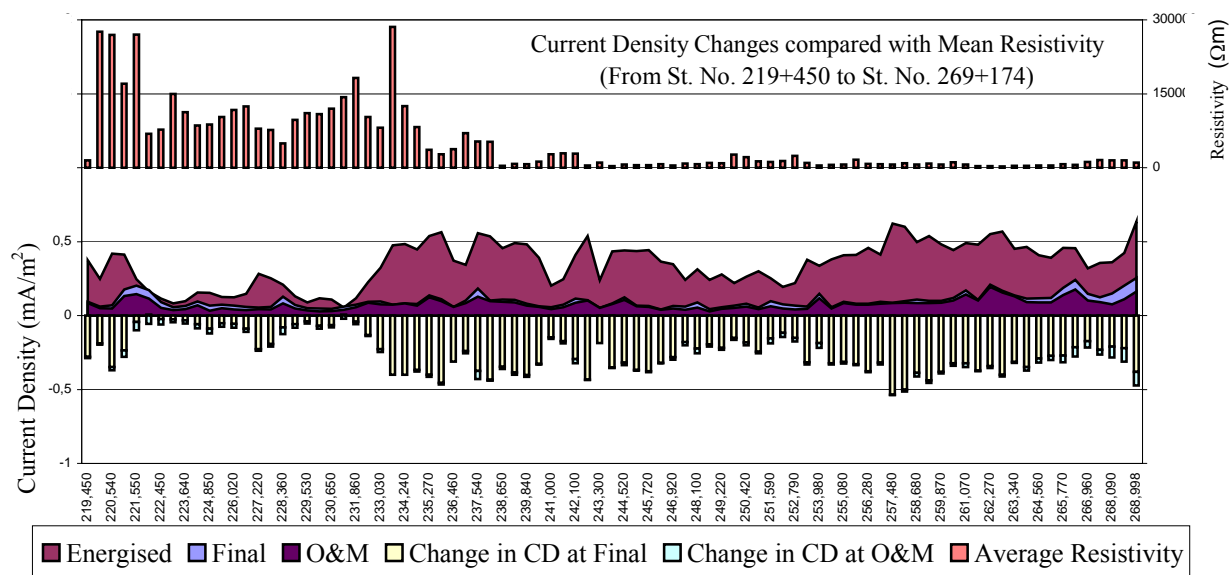

Figure 5.

If we analyze Figure 2[12], we can see that the system works in the interval between natural PCCP potential (cca -50 [mV]) and the protection potential, when the i_{O2} component is dominant (cca 400-500 [mV]). We also can see, that with the change of current, the potential changes approximately according to the i_{uk} curve.

Figure 6 shows the shift of static protection potential with respect to the natural potential, which can be used for further analysis [8,9].

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The results of polarization potential and protection current measurement through time in one PCCP point indicates that the total current decreases from cca 2.0 [A] to 0,4 [A] (Tables 1. and 2.) or, with regard to current densities, the values range from 0.25 [mA/m^2] to 0.08 [mA/m^2] or from 23 [mA] to 5 [mA] per anode chain.

The same can be said about the polarization potential of PCCP, which only decreases at a slower pace. For example, the protection potential decreases from –350 [mV] at the beginning, to –200 [mV] after a two – year exploitation of the cathodic protection system.
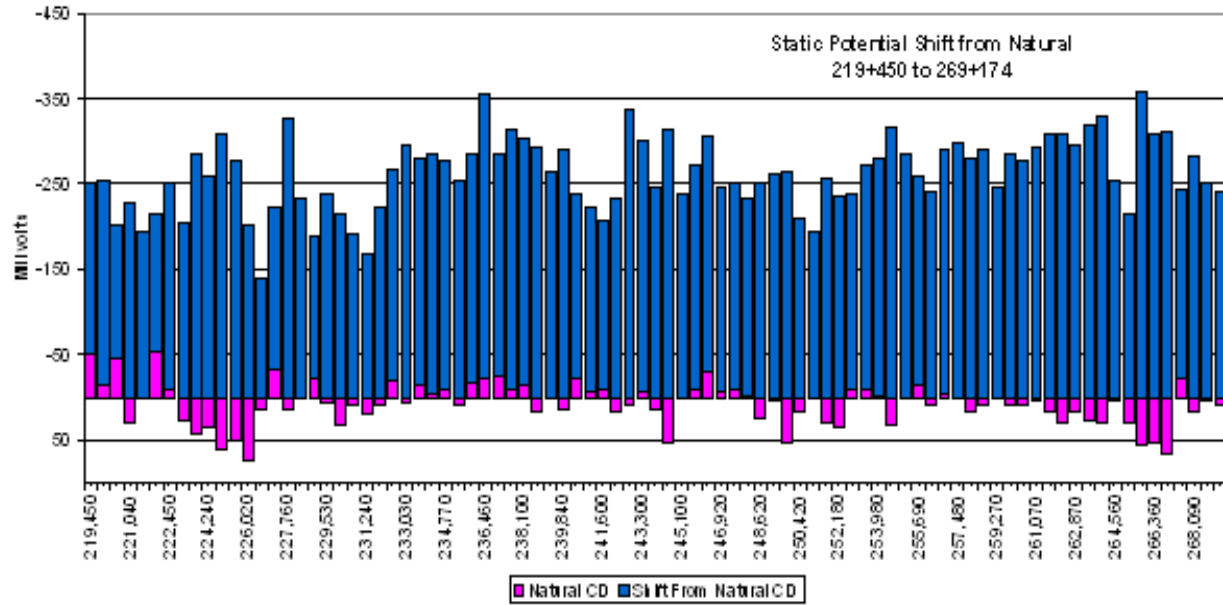

Figure 6.

This is a normal result because these are cast zinc anodes, which basically cannot be polarized, as we can see in Figure 7. (Curve A – The anode potential in the function of anode current change has a very high slope). This differs from the curve representing PCCP potential shift in the function of cathode current changes I$_{u,K}$, when we have potential values within the protection zone.

The formulae that can be used to express current change during the exploitation of cathodic protection should be looked for in exponential decreasing curves, e.g.[7]

$$i = 10^{\frac{V-\phi-E_{F_e}}{\beta_{F_e}}} - \left(\frac{1}{i_{\lim,O_2}} - 10^{\frac{V-\phi-E_{O_2}}{\beta_{O_2}}} \right)^{-1} - 10^{\frac{-(V-\phi-E_{H_2})}{\beta_{H_2}}} \qquad \text{(cathode)} \qquad (3)$$

$$i = i_{O_2} \left[10^{\frac{V-\Phi-E_{kor}}{\beta_{anode}}} - 1 \right] \qquad \text{(anode)} \qquad (4)$$

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Where i_{0Fe} is iron exchange current density, i_H is hydrogen exchange current density, i_{lim} is oxygen limiting diffusion current density on a cathode surface, V is the potential of the iron obtained from electrolytes in the inner domain, Φ is the potential of the electrolyte adjacent to the iron obtained from electrolytes in the outer domain [7], and β_{Fe} and β_{an} are the Tafel's slopes [12].

Figure 7. shows diagrams of curves of cathodic and anodic surface current in cases where there is no free voltage drop in the electrolyte, which fits the diagram in Figure 1.
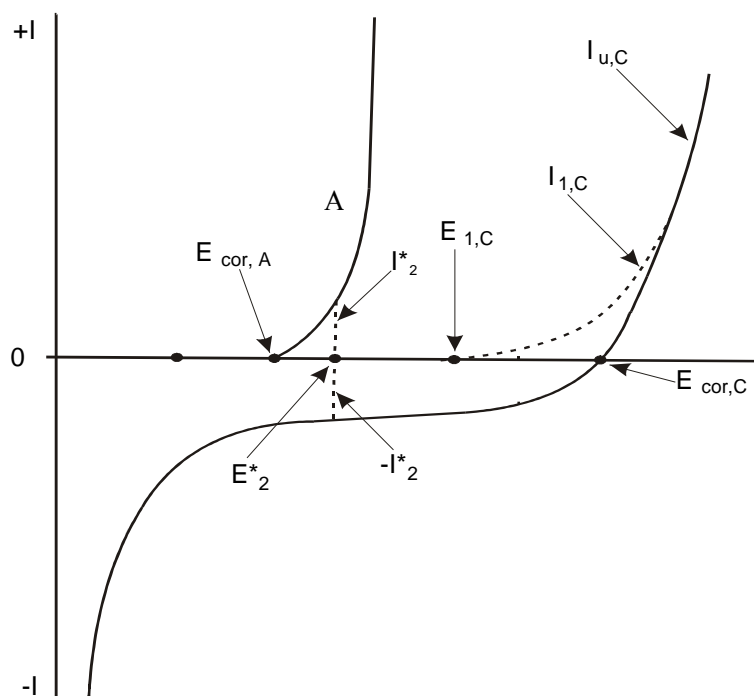

Figure 7.

1.1. Over Philosophy External Cathodic Protection Project for PCCP [10]

The cathodic protection system is implemented on sections of the water pipeline which is cca 600 [m] long and situated in desert conditions, with a high soil resistivity. There is electrical conductivity between the sections of the pipeline. The pipeline was constructed by means of 4.000 [mm] internal diameter PCCPs - prestressed concrete cylinder pipes. The prestressed wire, made of high quality steel, is protected by a concrete cover about 20 [mm] thick. Since the concrete cover is constructed from sprayed gunite and can therefore have a high porosity, an insulating coating is also applied. Nevertheless, when PCCP comes in contact with a chloride-containing water table, chloride ions can reach the steel wires by diffusion through the concrete cover. To avoid the corrosion of the steel and the subsequent hydrogen embrittlement, cathodic protection (CP) by means of zinc galvanic anodes is applied from the start of the exploitation of the pipeline. The cathodic protection system is designed for a life span of 25 years.

Cathodic protection is effected by means of cast zinc anodic strings, placed on both sides of the pipelines at a 5 [m] distance between each anode. Anodic strings are also placed vertically at a depth between 10 and 15 [m], and are 5.5 [m] away from the pipeline axis. The anodic material use is a zinc alloy with a theoretical electrochemical capacity of 820 [Ah/kg], measuring 37 x 37 [mm] x 928 [mm]. Anodic strings are constructed with 6 pcs of cast zinc anodes, of a total mass of 45.14 [kg] with an anodic groundbed measuring 6.400 x 150 [mm] (including the backfill). Anodic strings are connected as shown in Figure 3. The header cable has a 150 [mm ^{2}] cross-section, while the anodic cables have 16 [mm^2] cross-section, of the XLPE/XLPE type.

Figure 8. shows CIPS recording (the close interval pipe to soil potential) [8,9] during a 12-month period for section between St. 224+240 and St. 224+850. This section was selected as a test section to demonstrate the application of cathodic protection for white (bare steel) pipes in moderate to high soil resistivity areas by using zinc alloy galvanic anodes.
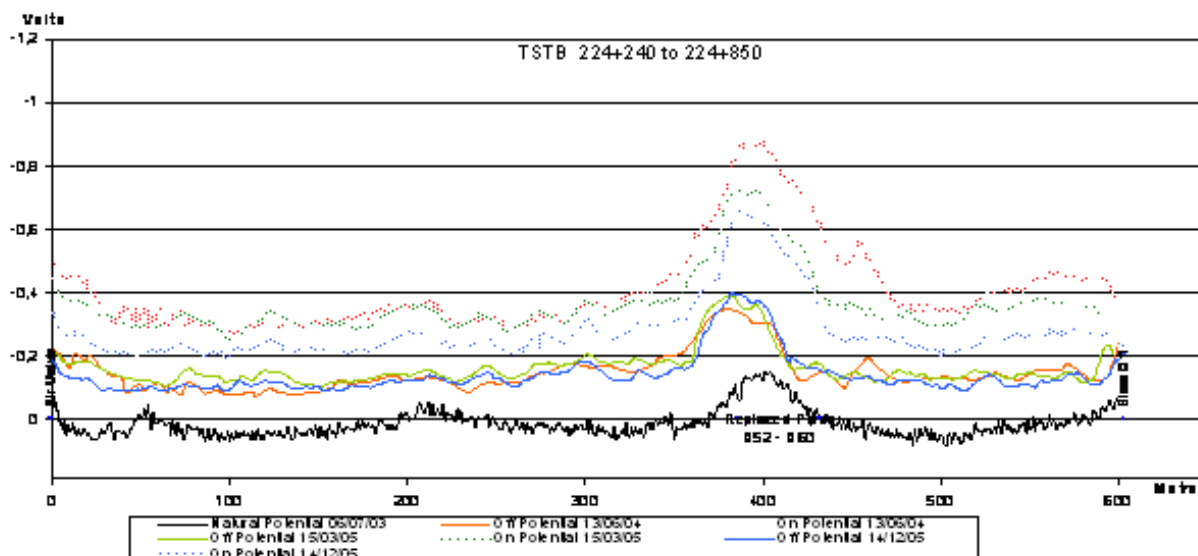

Figure 8.

2. Measurements Results [8]

Table 1. The change in the groundbed current over time

Section	St 224+240	St 224+850	St 225+420	St 226+020	St 228+950
Date	I [A]	I [A]	I [A]	I [A]	I [A]
Mar 2004	1,36	1,26	1,08	1,06	1,08
April 2004	1,23	1,06	1,00	1,00	1,00
June 2004	1,18	0,96	0,94	0,94	0,96
Sep 2004	1,06	0,84	0,86	0,82	0,82

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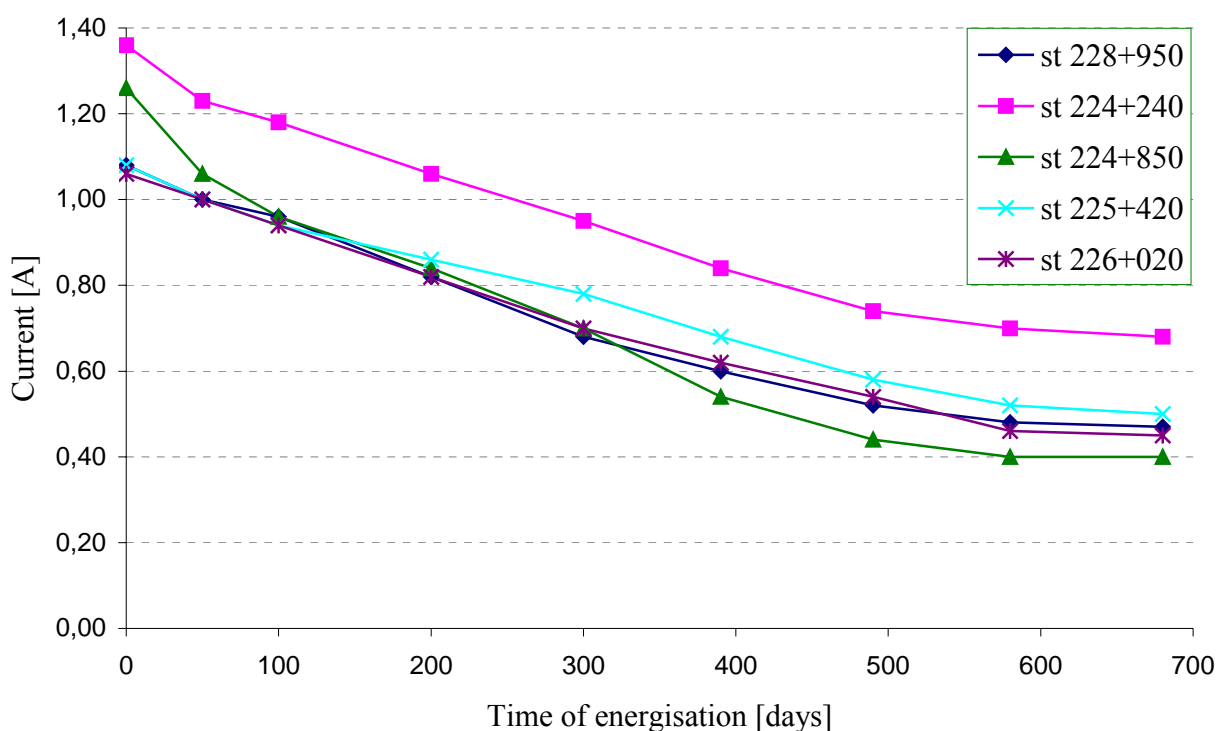|				
Dec 2004	0,95	0,70	0,78	0,70	0,68
Mar 2005	0,84	0,54	0,68	0,62	0,60
July 2005	0,74	0,44	0,58	0,54	0,52
Oct. 2005	0,70	0,40	0,52	0,46	0,48
Dec 2005	0,68	0,40	0,50	0,45	0,47
ρ [Ωm]	860	875	1030	1170	970

Figure 9.

As shown in Table 1, the values of protection current decrease with time. The same can be said for the values of protection potential (Table 2). More than one representative section has been analyzed. These sections, 600 [m] long, are installed in sand with extreme high soil resistivity values (850-1150 [Ωm]). This paper presents the measurement data for five such sections.

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Table 2. Changes of polarization potential over time

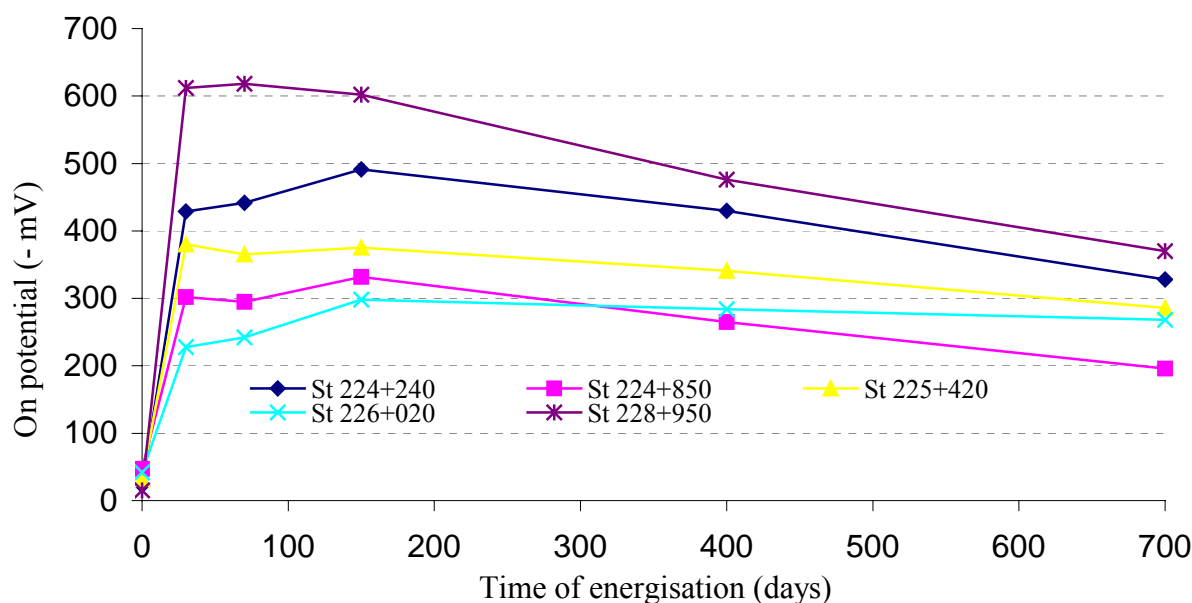|	st 224+240	st 224+850	st 225+420	st 226+020	st 228+950
Date	−V [mv]	−V [mv]	−V [mv]	−V [mv]	−V [mv]
$V_{natural}$	23	47	32	42	15
Mar 2004	429	302	380	228	612
April 2004	442	295	365	242	618
June 2004	491	332	375	298	602
Mar 2005	430	265	341	284	476
Dec 2005	328	196	286	268	370
ρ [Ωm]	860	875	1030	1170	970

Figure 10.

The results of the measurements point to a conclusion that protection current attenuation is smaller in areas where the soil resistivity is high. This can be explained as follows. The cathodic protection system does not work in "short circuits", when the resistance of the electrolyte can be ignored. (Figure1.a). The system operates at a driving voltage which equals:

$$E_{Nat.Zn} - E_{Nat.Fe} = -1100 - (-50) = -1050 \text{ [mV]}.$$

As is shown on Figure 7, the change of the potential of the cast zinc anode is negligible even for significant current changes. The change of potential of cast zinc anodes is therefore negligible in the conditions of closed circuit i.e. during the operation of the cathodic protection system, which means that the driving potential is approximately −1000 [mV] /CSE during the time of

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exploitation. On the other hand, the PCCP potential (steel in concrete) changes by e.g. (absolute) 500 [mV]. This leaves the possibility of a further potential drop of cca 500 [mV].These differences are spread to voltage drops:

−   In the resistance of the anodic groundbed,

−   In the resistance of the soil, and

−   In the resistance of the PCCP/soil.

As what we have is ground with high soil resistivity, the increase of anode groundbed resistance does not have as much influence as it would do if the soil resitivity values were low. If the ground has low values of soil resistivity, and seeing as the voltage drop IR_{el} is relatively small in comparison to voltage drops at anode groundbed resistance R_A and PCCP (resistance PCCP/solution), each change in these resistances will significantly affect the total current in the circuit of cathodic protection system.

3. Protection Current vs. Duration of System Deployment

On the basis of the measured values of current over time, given in Table 1, a sample correlation of the results was conducted so as to obtain the functional relationship (i.e. dependency) of current change over time. To express said correlation, we select an exponential regression line

$$I = I_{01} \cdot e^{a \cdot t} + I_{02} \cdot e^{b \cdot t} \tag{5}$$

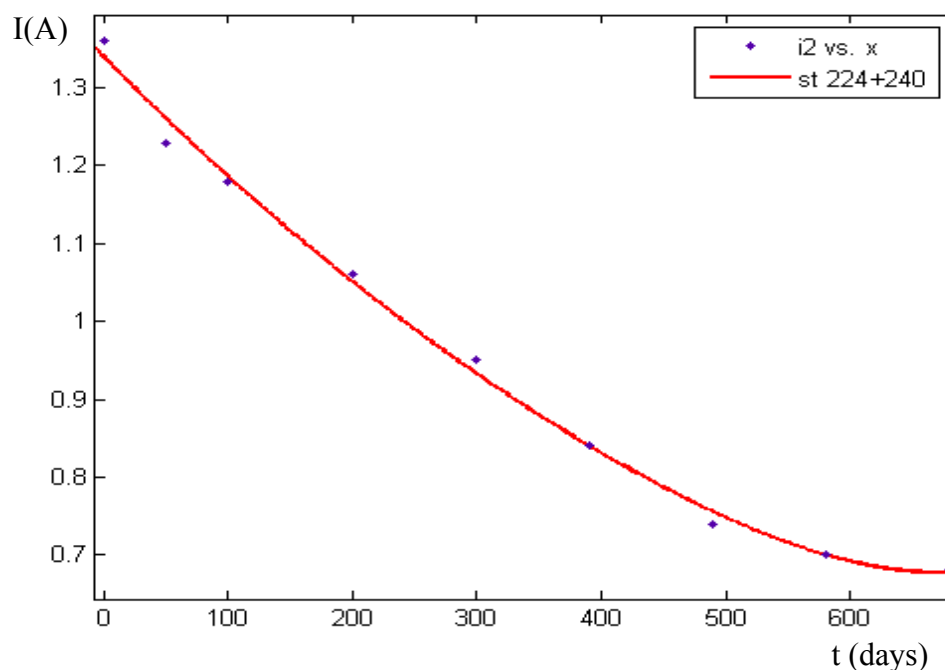An example of a regressive curve for St 224+240 (ρ = 860 [Ωm]) is given in Figure 11.

Figure 11.

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For this section, the functional relationship is:

$$I = 1{,}339 \cdot e^{-0{,}001224 \cdot t} + 0{,}000336 \cdot e^{0{,}008299 \cdot t}$$

In the case of nonlinear regression, following formula is used to determine the correlation coefficient:

$$k = \sqrt{1 - \frac{s_y^2}{\sigma_y^2}} = \sqrt{1 - \frac{\sum \left(y_{measured} - y_{regression}\right)^2}{\sum \left(y_{measured} - \bar{y}\right)^2}} \tag{6}$$

where: $y_{measured}$ – the measured values of current at given points

$y_{regression}$ – the measured values of current at given points, calculated with regression curve

$\bar{y} = \dfrac{1}{n} \displaystyle\sum_{i=1}^{n} y_{measured}$ - the sample mean of the measured values of current at given points.

Values of the correlation coefficient k that are close to 1 indicate that the selected regression curve is in close proximity to the measured data. In that case, we say that there is high stochastic nonlinear relationship between the varying values.

Another factor that can determine the quality of the stochastic correlation of results is the standard deviation of the random error component of the measurement results. This is calculated as follows:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(y_{regresije} - \bar{y}\right)^2} \tag{7}$$

The values of the standard deviation that are close to 0 indicate that the chosen model has a small random error component and that the regression was done properly.

In this case, the values of these factors are k = 0.996 and s = 0.0201, which suggests that that the functional relationship between protection current and time of polarization is almost complete.

Table 3 gives the coefficients for the correlation function for specific sections.

Table 3

Section	St 224+240	St 224+850	St 225+420	St 226+020	St 228+950
I_{01}	1,339	1.224	1,080	1,0674	1,093
a	− 0,001224	− 0,002120	− 0,001149	− 0,001387	− 0,001568
I_{02}	0,0003364	0,0014390	-0,0081710	-0,0143800	0,0005780
b	0,0082990	0,0062330	0,0009247	-0,0451900	0,0005780
k	0,996	0,9899	0,9931	0,9963	0,9968
s	0,02010	0,04008	0,02251	0,01795	0,04169

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The contribution of the second factor of equation (5) during the first year of operation of the cathodic protection system does not surpass the value of 2 % of total protection current. Thus, we can ignore the second factor in the equation during the first year of operation, without any significant effect on the accuracy of results.

If we analyze the data in Table 3, we see that the I_{02} and b coefficients, in regressive function (5), are becoming more significant when the values of protection potential fall below the allowed protection level. This coefficient becomes important only when we have a low resistivity of surrounding soil or a prolonged period of operation of the cathodic protection system.

The conclusions we have made about changes in protection current values can be used effectively in the periodical recording of cathodic protection parameters in similar facilities, which cannot be considered as being isolated by means of a proper passive isolation.

This is a simpler and more efficient way to reach valuable and realistic conclusions, especially in difficult climates, about:

- A realistic calculation of cathodic protection system lifetimes (seeing as the protection current decreases, as does the driving voltage),
- A realistic calculation of anode groundbed configuration from the viewpoint of anode/solution resistance, considering that there is a decrease of total protection current,
- An estimation of the length of protective zone (a decrease of protection current and PCCP potential),
- The elimination of costly and long measurements, CIPS recording, as the values of protection current can be determinate at any moment during the time of exploitation of the cathodic protective system.

Naturally, the defining of approximate analytical equations to express the functional relationship of changes in potential and in protection current values during the time of exploitation, are followed by appropriate recordings on the object.

4. Conclusion

Extensive and cost – intensive field measurements confirm that there is a substantial reduction of CP current magnitude following initial CP system deployment. Thus, there exists a need for repetitive field measurements in order to establish and confirm the scope of CP protection for the object of interest. Field data shown in this paper confirm the existence of the correlation between CP current and duration of system deployment, until the point where full system polarization occurs. Specifically, the case of extreme desert conditions necessitates a high soil resistivity, where the CP current decays exponentially with the duration of deployment. Here, this paper provides a set of parameters which enables a computation of CP current at any point of system deployment thus enabling CP system architects to estimate the CP current without making expensive filed measurements.

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