APPLICATION OF THE REMOTE EARTH POTENTIAL IN CATHODIC PROTECTION MEASUREMENTS

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The conventional potential measurements and evaluation methods of cathodic protection diagnostics do not give reliable results in some practically important cases: in systems where the whole amount of cathodic protection current cannot be interrupted for any reason or the equalizing currents affect the protection to a significant level or interference with other cathodic protection systems is encountered. The paper discusses a model and its practical application dealing with these difficult cases. The test measurement evaluation results justify the theoretical model. On the basis of the theory a very simple measurement method is proposed for the determination of the coating defects IR-free potentials.

Keywords: cathodic protection, IR-free potential, pipeline corrosion, coating defect

1. Introduction

The cathodic protection is a widely used, robust and reliable method of corrosion protection of underground pipelines, tank bottoms and underwater parts of immersed structures, e.g. ships and drilling platforms. In the past eight decades a lot of experience has been accumulated concerning the applicability and limitations of cathodic protection.

In the most widespread type of cathodic protection, the impressed current systems, the structure to be protected is connected to the negative output of a DC current source („CP station") and the positive output is connected to a so-called earthing anode which serves for the closing of the electrical circuit (see a typical arrangement for a cathodically protected pipeline in *Figure 1*). The output of the DC source is variable and, in modern devices, can be regulated, either for constant potential or for constant current.

If no cathodic protection is applied to a structure corroding in water or soil and no net current is flowing through the structure, then the sum of the anodic (corrosion) and cathodic currents is zero. The ultimate criterion of the effectiveness of cathodic protection is the level of suppression of the anodic current. This can be achieved with the cathodic polarization of the structure. The decrease of the anodic current cannot be measured directly. However, if the applied potential is sufficiently negative (cathodic) then the anodic current (and the corrosion rate) is suppressed, with increasing cathodic polarization theoretically beyond any limit; practically a decrease of 1–2 orders of magnitude can be implemented, which is satisfactory for the practical requirements in most cases.

In conclusion, the negative polarization of the structure results in the suppression of the anodic current (this was the goal) and in the increase of the cathodic current, which is an unavoidable consequence of the potential shift, sometimes with unfavourable side effects.

During the past decades a lot of empirical experience has been accumulated concerning the optimal operation conditions of cathodic protection. It has been assumed for a long time that cathodic protection has the best performance in typical applications in soils if the electrode potential of the structure is more negative than -850 mV, measured against a saturated copper/copper sulphate electrode [1] (its standard potential at 25°C is -320 mV; all potential data will be given against this type of reference electrode unless specified otherwise). The lower limit of the potential varies for different applications but it is typically assumed to be between 1100 and 1300 mV[1].

The electrode potential, as discussed above, is the potential that can be measured with a reference electrode placed to the direct vicinity of the electrode, i.e. which does not include any component from the ohmic potential drop through the electrolyte[2]. This potential, called as IR-free potential, is a central concept in cathodic protection.

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[1] At more negative potential the excessive rate of cathodic current may have adverse effects on the structure or on the coating.

[2] There is another source of the ohmic potential drop, namely, the drop in the electric conductor, which can also be significantly high in the case of pipelines, but this source will not be dealt here; in this paper the ohmic drop is understood as the ohmic potential drop through the electrolyte between the anode and the cathode.
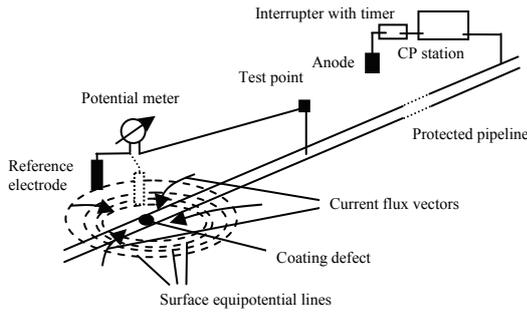
Figure 1: Schematic arrangement of cathodic protection and potential measurement circuitry

The determination of the exact value of the IR-free potential is practically impossible in case of buried structures and with conventional methods. This paper is dealing with the mathematical properties of the electric field of the cathodic protection system and provides a simple method to give a good approximation of the IR-free potential, with significant practical advantages that are facilitated by making use of the remote earth potential. The discussion below is dealing specifically with the case of coated, buried and cathodically protected steel pipelines. However, the situation with tanks bottoms and other buried structures is quite similar. For offshore and underwater structures the theory also applies but the application technology is slightly different – these cases will be dealt with in separate communications.

2. Discussion

2.1. Review of the conventional ways of determination of the IR-free potential

In the first times of application of cathodic protection the cathodic protection was assumed as effective if the polarized potential was more negative to the open-circuit potential.

It was realized very soon that the measured potential value was dependent on the location where the reference electrode was placed (owing to the location-dependent ohmic potential drop) and the need of a criterion of effectiveness was also recognized. The determination of the IR-free potential was carried out by the switching off the current source. This technique is routinely used in the laboratory electrochemical measurements, too.

The determination of the ohmic drop compensated corrosion potential of a cathodically protected structure has an enormous literature. A short but concise general overview on the topic was given by Bushmann and Rizzo [2]. In the standard practice of cathodic protection nowadays the determination of the IR-free potential is carried out by periodically switching the current source off and on. Typically a pattern of 2–4 seconds switched on and 0.5–1 second switched off is implemented (the time values may also vary in a wider range). The potential measurements are carried out after a delay of

at least 0.1 second, in order to eliminate the effect of the inductive transients (these appear in case of long pipelines and large currents only). The potentials measured with CP stations turned on and off are generally named as ON potential and OFF potential respectively.

Under field conditions in many cases it is nearly impossible or at least very cumbersome, expensive and time-consuming to switch all the CP stations that are effective in a certain area. If some of the current sources remain switched on while measuring the OFF potential that results in a major bias in assessing the IR-free potential. This bias may be up to a few hundreds of millivolts in extreme cases, and often leads to erroneous conclusions with respect to the level of protection of structures, sometimes with serious consequences. In spite of these obvious deficiencies, in the industrial practice in most cases the measured OFF potentials are identified with the IR-free potentials.

Another source of the uncertainties in assessing the IR-free potential via the OFF potentials is the ohmic potential drop generated by the equalizing currents flowing between the more and less polarized parts of the structure. Stray current sources can also falsify the conventional IR-free potential determinations via the measured OFF potentials.

Nowadays typically GPS-driven, high precision clock operated interrupters are applied in CP measurements, which facilitate an increased measurement precision and reliability. Some manufacturers also provide CP stations with built-in interrupters and remote control options.

2.2. An alternative way of calculation of the IR-free potential from measurement data

In spite of the enormous progress in measurement technique and the apparent inadequacy of the determination of the IR-free potential via the OFF-potential, no much progress has been achieved in the theory and in the evaluation of the measurement data.

Let us assume a cathodic protection system with an anode and a single coating defect at some part of the protected structure. The potential profile as a function of the distance between the coating defect and the anode is shown in *Figure 2*. The potential field of the coating defect is defined as the domain where the potential is more negative than the remote earth potential and the potential gradients are directed towards the coating defect.
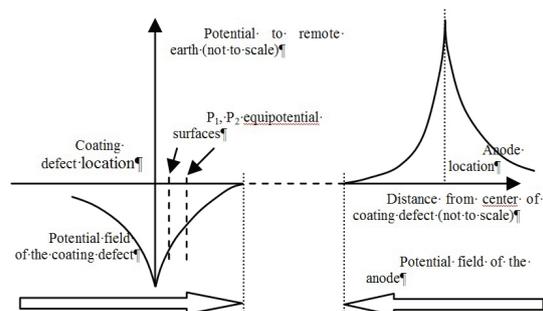

Figure 2: Potential relations in the area of the anode and the coating defect

Let us mark two points in the potential field of the coating defect as P_1 and P_2. These two points determine two equipotential surfaces that surround the coating defect. Also, these equipotential surfaces mark a domain of the space with a definite and constant (i.e. independent from the current flux) electrical resistance. Let R_1 and R_2 be the ohmic resistance between the coating defect and the points P_1 and P_2 respectively.

Further on, let us assume that some perturbation is applied to the CP system, i.e. the current is interrupted (completely or partially – it is indifferent from the point of the model). From Ohm's Law it follows that

$$R_x = \frac{E_x^{OFF} - E_0}{I^{OFF}}, \ R_x = \frac{E_x^{ON} - E_x^{OFF}}{I^{ON} - I^{OFF}}, \quad (1a, b)$$

where x=1.2 refers to any of the two surfaces and the *ON* and *OFF* superscripts refer to the potential or current in the respective states. E_0 is the IR-free potential of the coating defect[3].

Expressing R_x and rearranging the equation, the IR-free potential can be expressed as:

$$E_0 = E_x^{OFF} + \left(E_x^{OFF} - E_x^{ON}\right)\frac{I^{OFF}}{I^{ON} - I^{OFF}}. \quad (2)$$

If $I_{OFF}=0$, i.e. all the current is switched, then *Eq. 2* is simplified to $E_0=E^{OFF}$, that is, the measured OFF potential is equal to the IR-free potential. However, if $I_{OFF}\neq 0$ then the determination of E_O from *Eq. 2* is impossible, because the current values are indeterminable. Let I^{OFF} and I^{ON} be expressed from the rearrangement of *Eq. 1a* (for the determination of I^{ON} the *OFF* superscripts have to be changed to *ON*, but this is allowed because the equation is valid also in the ON state of the system). From Ohm's Law it is obtained that

$$I^{OFF} = \frac{E_1^{OFF} - E_2^{OFF}}{R_{1,2}}, \quad (3a)$$

$$I^{ON} = \frac{E_1^{ON} - E_2^{ON}}{R_{1,2}}, \quad (3b)$$

where $R^{1,2}$ is the resistance between the two distinct equipotential surfaces. Substituting *Eq. 3a* and *Eq. 3b* into *Eq. 2* it follows that

$$E_0 = E_x^{OFF} +$$

$$\left(E_x^{OFF} - E_x^{ON}\right)\frac{E_1^{OFF} - E_2^{OFF}}{\left(E_1^{ON} - E_2^{ON}\right) - \left(E_1^{OFF} - E_2^{OFF}\right)}, \quad (4)$$

where x=1.2.

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[3] Throughout in this paper it is assumed that the polarization resistance is negligible to the ohmic resistance of the soil between the coating defect and the point of the reference electrode. In most practical cases of buried structures in soil this assumption is valid. Effects of the transient decay of the charge/discharge of the electrochemical double layer and other transients related to the inductivity of the pipelines will be dealt with in a separate paper.

By means of *Eq. 4* the IR-free potential is obtained from measurable potential data also in the case if the current, flowing to the coating defect, is interrupted only partially or perturbated in any other way.

Let us introduce the following notation:

$$\rho = \frac{E_1^{OFF} - E_2^{OFF}}{(E_1^{ON} - E_2^{ON}) - (E_1^{OFF} - E_2^{OFF})}, \quad (5)$$

and note that ρ is the quotient of the "not switched" and "switched" currents, flowing to the coating defect, and thus is invariant within the potential field of a certain coating defect. ρ is named foreign current ratio hence because it denotes the ratio of the foreign (i.e. not switched) and switched current.

Using *Eq. 5*, *Eq. 4* can be rewritten as

$$E_0 = E^{OFF} + (E^{OFF} - E^{ON})\rho, \quad (6)$$

where the x subscripts are no more needed because the equation is valid for potentials measured at any point in the potential field of the coating defect.

By means of this calculation the value of the IR-free potential, which is not directly measurable if any current is flowing in the OFF state, can be determined by means of measurable potential data.

An equation formally analogous to *Eq. 6* had earlier been reported by Baeckmann and Schwenk [3], but the evaluation presented in their work is started from a quite different approach and also their conclusions are very different. The practical implementation of their measurement method is published in [4].

An important consequence of *Eq. 6* is that E_0 and ρ are linearly dependent if E^{OFF} and E^{ON} are substituted with the constant values of the remote earth potentials:

$$E_0 = E_\infty^{OFF} + (E_\infty^{OFF} - E_\infty^{ON})\rho, \quad (7)$$

Taking into consideration that for the determination of ρ it is not necessary to connect to the structure with a measurement cable because it is calculated from the differences of potentials at two different places in the ON and OFF state (cf. *Eq. 5* and *Fig. 1*), *Eq. 7* provides a simple and fast method to determine the IR-free potential of coating defects where there is no test post in the vicinity. This method is a powerful alternative of the widely used CIPS (Close Interval Potential Survey) or intensive surveys [4]: the coating defect IR-free potentials are practically calculated from potential gradient data and the remote earth potentials recorded with a static data logger. Further, by fitting the data received on different coating defects in a cathodic protection system using *Eq. 7*, it is possible to provide data quality control facility: those data which are not fitting on the linear relationship and deviate over a threshold value are to be discarded. *This is a unique feature in the practice of cathodic protection.*

2.3. A practically important case: more coating defects in a system

The calculation in Section 2.2 is strictly valid if the cathodic protection system includes one anode and one coating defect. Obviously, real systems are more complicated. Further difficulty is that in real systems the potential of the coating defects is varying; small coating defects with less ohmic potential drop[4] can be polarized to a more negative potential than the larger coating defects. This potential difference between the coating defects generates equalizing currents superimposed on the cathodic protection current and, consequently, on changing of the shape of the cathodic protection current vector space, the shape of the equipotential surfaces will be also changed. Therefore the resistance between two equipotential surfaces, denoted as $R_{1,2}$ above, will not be the same quantity for the ON and the OFF state in *Eq. 3a* and *Eq. 3b*.

This problem can be diminished by selecting the optimal measurement points for which the equipotential surfaces have the possible smallest distortion caused by the equalizing currents of vicinal coating defects. Obviously, the closer the measurement point is to the coating defect the less the shape of the equipotential surface varies on changing of the equalizing current flowing to/from the vicinal coating defect. On the other hand, the remote earth potential is also invariant to the local changes in the vicinity of any coating defect. In conclusion the point nearest to the coating defect (where the measured potential has an extreme as a function of the surface coordinates) and the remote earth potential are to be chosen to maximize the precision of the determination of the IR-free potential.

3. Experimental verification

3.1. Conditions

In order to verify the above conclusions, a test measurement was conducted on a pipeline. The pipeline was a DN 300 gas transfer line with polyethylene coating which was known to be in a bad condition. The measurement was a modified CIPS carried out with a CPM 401 universal cathodic protection diagnostic measurement system. Unlike conventional CIPS measurements, here the two reference electrodes of the mobile data logger measured different potentials: one reference electrode (electrode No. 2) was measuring the potential above the pipeline and the other electrode (electrode No. 1) was measuring the potential some 3 m apart from the pipeline (cf. *Fig. 1*). In this way the potential gradient, perpendicular to the axis of the

pipeline, was determined both for the ON and OFF states from the data of the mobile data logger. The switching time was 3 second ON and 1 second OFF, the delay time after the switching was 0.1 second and the sampling time was also 0.1 second. The remote potentials were measured with a static data logger.

3.2. Results

The ON and OFF potential data for the two mobile reference electrodes and the remote potentials are shown in function of the distance in *Figure 3*, which also includes the IR-free potentials calculated for the localized coating defects determined by means *Eq. 4* and *Eq. 7*.

The IR-free potential as a function of the foreign current ratio (both determined from the data of the mobile data logger, based on *Eq. 4* and *Eq. 5*) are shown in *Figure 4*, with the best fitting line. As follows from *Eq. 7*, the slope of this linear relationship gives the difference of the remote earth ON and OFF potentials and the intercept gives the remote earth OFF potential. The obtained data, compared to the average of the experimentally measured ones are included in *Table 1*.

The "calibration curve" of the IR-free potentials obtained from *Eq. 4* and from *Eq. 7*, using the remote earth potential data and the foreign current ratio obtained from the mobile logger data are shown in *Figure 5* (the line is the y=x calibration line) and the numerical values, with the absolute value of the differences are shown in *Table 2*.

3.3. Evaluation

In *Fig. 3* six well developed coating defects are localized. The coating defects at 24 and 40 meters are very large, most likely they are more or less continuous series of coating defects of different sizes and positions. They are assumed to be "open" coating defects, where the damaged coating does not cover the exposed pipe area and the larger the coating defect the more positive the IR-free potential. The coating defect at 68 meter is presumably a blistering, because the apparent size is very small but the IR-free potential is very positive which is the sign of high ohmic potential drop due to the "coverage" by the damaged coating. The coating defects at 95, 125 and 130 meters are decreasing in apparent size but shifting to positive direction in IR-free potential and from this tendency it is assumed that their "coverage" is increasing. In conclusion, coating defects of different sizes and types are detected on the selected relatively short pipe section.

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[4] A smaller coating defect has a higher resistance. However, the resistance of a coating defect decreases (approximately) linearly with the diameter of the coating defect, while the electrode surface increases with second order. Therefore a larger coating defect will always give larger ohmic potential drop in case of a similar geometry.
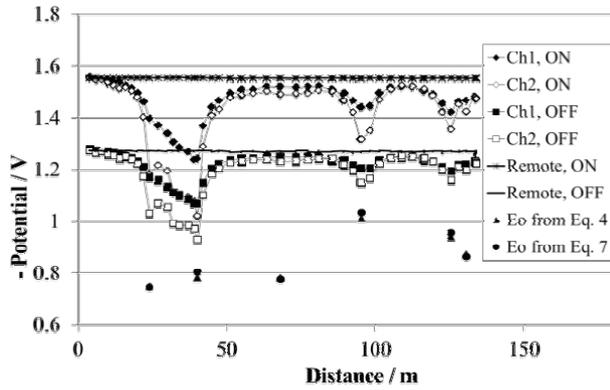
Figure 3: Measured and calculated potential data of the test measurement vs. distance
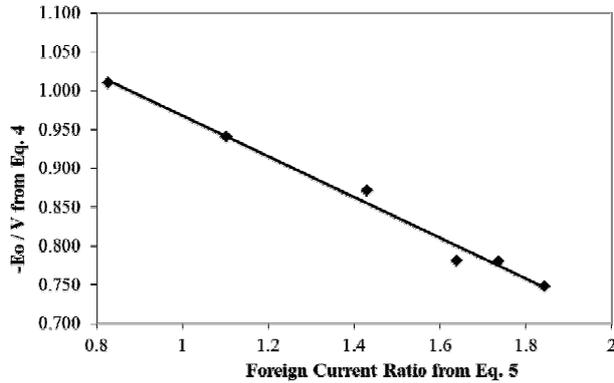

Figure 4: IR-free potential data, calculated via *Eq. 4*, vs. Foreign Current Ratio
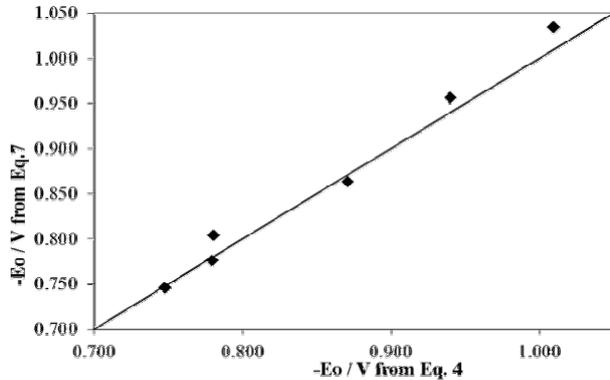

Figure 5: Calibration of IR-free potential data calculated via *Eq. 7* vs. IR-free potential data calculated via *Eq. 7*

Fig. 4 justifies the assumptions of *Eq. 7*. The linear relationship between the foreign current ratio and the IR-free potential has a "double nine" (0.993) correlation coefficient. This data has to be qualified considering the extreme differences in type and size among the coating defects. This relatively good result has to be considered also in the light of the fact that the first two defects are actually a series of defects, which decreases the applicability of the theory of the equipotential surfaces. In short, these circumstances can be considered as a near-worst-case scenario.

According to *Eq. 7*, the remote potentials can be determined from the IR-free potential vs. foreign current

ratio plot. From *Tab. 1* a moderate difference of a few tens of millivolts is concluded which justifies the theoretical expectations.

Table 1: Comparison of measured and calculated values of remote earth potentials

Parameter	Measured /V	Calculated from *Eq. 7*/V	Absolute value of difference/V
Slope $\left(E_\infty^{OFF} - E_\infty^{ON}\right)$	0.284	0.262	0.022
Intercept $\left(E_\infty^{OFF}\right)$	-1.269	-1.229	0.04

Table 2: Values of IR-free potential at the coating defects, calculated from *Eq. 4* and *Eq. 7*

Distance/m	Calculated from *Eq. 4*/V	Calculated from *Eq. 7*/V	Absolute value of difference/V
24	0.748	0.746	0.002
40	0.780	0.804	0.023
68	0.780	0.776	0.004
95	1.010	1.034	0.025
126	0.940	0.956	0.016
131	0.871	0.863	0.008
Average			0.013

From *Eq. 7* it is also concluded that the IR-free potential of a coating defect can be determined from the potential differences measured with the two reference electrodes of the mobile data logger (i.e. it is not necessary to apply a contact to the pipeline (cf. *Fig. 1*)). In *Tab. 2* it is shown that the error of the determination of the IR-free potentials using *Eq. 7*, compared to the data using *Eq. 4*, are an average of 13 mV which is far below the practically required precision limit.

Summary

It has been shown that based on the concept of the equipotential surfaces and Ohm's Law a linear formula can be provided for the determination of the IR-free potential.

The precision of the formula is the highest if the points used for the determination of the foreign current ratio are the points nearest to the coating defect (i.e. where the measured potential data have an extreme) and the remote earth.

The theory also provides the value of the foreign current ratio.

It was pointed out that the foreign current ratio and the IR-free potential are in a linear relationship where the coefficients of the linear relationship are related to the remote earth ON and OFF potentials. This relationship establishes the connection between the "global" remote

and the locally, above the pipeline measured potentials. Also this relationship provides an alternative method for the assessment of the IR-free potential, which does not require a measuring cable to be pulled alongside the pipeline.

All these theoretical results were confirmed with a test measurement made on a section of pipeline with coating defects of different size and type. The evaluation of the test measurements justified the theoretical assumptions and proved that the determination of the IR-free potential, based on the measurement of the over-the-line potential gradients and the remote ON and OFF potential, is applicable and accurate enough for the practical requirements.

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