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Considerations to estimate electrical characteristics and corrosion likelihood of cathodically protected steel pipes in steel casings

FR

Réflexions visant à évaluer les caractéristiques électriques et les risques de corrosion de conduites en acier protégées cathodiquement dans des gaines en aciers

D

Abschätzung der elektrischen Eigenschaften und der Korrosionsgefährdung von kathodisch geschützten Rohrleitungen in Mantelrohren

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Abstract

Corrosion likelihood of a cathodically protected steel-pipe that is laid in a steel-casing is generally unknown due to missing pragmatic criteria to assess effectiveness of cathodic protection for this pipe section. In order to overcome this situation a simplified electrical model will be described that characterizes the electric conditions of a casing/pipeline construction with the help from results of cathodic protection supervision measurements. Procedures are described that allow to assess effectiveness of cathodic protection of the carrier pipe within the casing on a pragmatic basis. Evaluated data also provide – among other - information on the average coating resistance (i.e. spread resistance) of a casing that may be helpful if the grounding resistance of the casing is used to mitigate high voltage interference. Results from measurements at existing casing/pipeline constructions are presented and discussed.

Abschätzung der elektrischen Eigenschaften und der Korrosionsgefährdung von kathodisch geschützten Rohrleitungen in Mantelrohren

Zusammenfassung

Die Korrosionsgefährdung einer kathodisch geschützten Stahlrohrleitung, die in einem Mantelrohr verlegt ist, ist im allgemeinen unbekannt, weil pragmatische Kriterien zur Bewertung der Wirksamkeit des kathodischen Korrosionsschutzes fehlen. Um diesen Mangel zu überwinden wird die im Mantelrohr verlegte Rohrleitung mit einem vereinfachten elektrischen Modell und unter Zuhilfenahme der Ergebnisse einer Überwachungsmessung beschrieben. Es werden dann Verfahren angegeben, die die Bewertung der Wirksamkeit des kathodischen Korrosionsschutzes anhand pragmatischer Kriterien erlauben. Die ermittelten Daten geben unter anderem Auskunft über den Ausbreitungswiderstand des Mantelrohres; dies kann hilfreich sein, wenn der Erdungswiderstand des Mantelrohres für die Verminderung der Hochspannungsbeeinflussung ausgenutzt werden soll. Es werden Ergebnisse von Messungen an bestehenden Rohrleitungen, die in Mantelrohren verlegt sind, vorgestellt und diskutiert.

Réflexions visant à évaluer les caractéristiques électriques et les risques de corrosion de conduites en acier protégées cathodiquement dans des gaines en aciers

Résumé

Les risques de corrosion d'une conduite en acier (protégée cathodiquement) placée dans une gaine en acier sont généralement méconnus en l'absence de critères pragmatiques pour évaluer l'efficacité de la protection cathodique sur la section de conduite en question.

Afin de remédier à cette situation, une présentation sera faite d'un modèle électrique simplifié qui caractérise les conditions électriques d'une conduite/gaine à l'aide des résultats des mesures de contrôle de protection cathodique.

Les procédures permettant d'évaluer de façon pragmatique l'efficacité de la protection cathodique d'une conduite de transport située dans une gaine seront décrites.

Les données mesurées fournissent aussi, entre autres, des informations sur la résistance moyenne du revêtement (c.-à.-d. la résistance à la propagation) d'une gaine qui peuvent s'avérer utiles si la gaine est utilisée pour réduire les interférences de haute tension. Les résultats des mesures réalisées sur des conduites/gaines existantes sont présentés et analysés.

1 Introduction

Steel pipelines are frequently laid in steel casing if roads, rails or rivers are crossed. In order to establish electrical isolation from the pipeline plastic spacers are generally mounted. In the past supporting plastic and wooden blocks had also been arranged where the pipeline enters or leaves the casing. Generally the annular space is tightened against ingress of water or soils by plastic caps. Experience has shown, however, that this does not prevent groundwater and/or soil particles to enter.

Different coatings have been used for the pipelines and for the casings as well during the past decades and the amount and size of coating faults is generally not known. Due to the possible contact with groundwater and/or soil a corrosion risk has to be taken into account for coating faults on the pipeline within the casing.

In case of cathodically protected pipelines some qualitative conclusions concerning the situation around the casing/pipeline construction can be found from the results of supervision measurements:

- The resistance $R_{m/t}$ (see annex) as well as the voltage $U_{m/t,on/off}$ between pipeline and casing provide information about the effectiveness of electrical isolation (on/off means measurements taken during on- and off-periods of cathodic protection rectifiers). Furthermore some hints are given regarding coating defects on the carrier pipe in the casing and presence of groundwater/soil in the annular space.
- The casing potential $U_{ma,on/off}$ and the potential gradient of the casing $\delta U_{ma,on/off}$ provide information about cathodic protection current entering the pipeline through the steel wall of the casing.

Existing literature, guidelines and standards, however, do not provide criteria that allow an assessment of the cathodic protection status for the pipeline laid within the casing (in a sense as intensive measurements [1] may be used for pipelines with normal coverage or comparative methods [2] are applied to isolated pipeline sections, e.g. that have been buried using HDD-techniques).

Based on some general considerations of the electrical parameters that a pipeline/casing-construction this paper describes procedures to overcome the problems mentioned above, aiming for an assessment of cathodic protection effectiveness for the carrier pipe in the casing.

2 Electrical characteristics of casing, annular space and steel pipeline

2.1 Electrical circuit

A simplified electrical circuit of the casing/pipeline construction is considered to be as follows (see fig. 1 and annex for symbols).

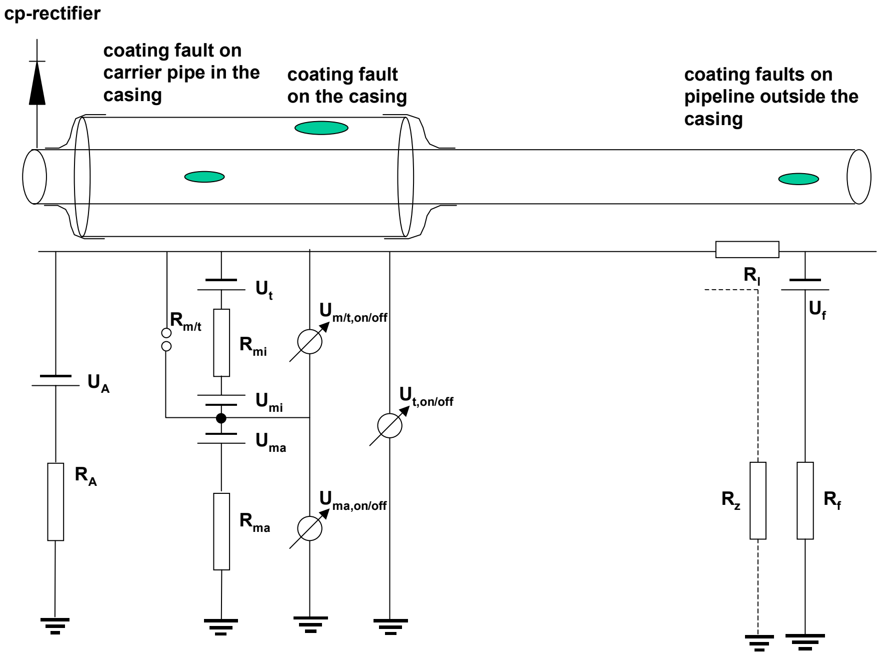


Fig. 1: Simplified electrical circuit of a casing/pipeline construction

It is assumed that the annular space is electrically isolated from the surrounding environment, e.g. by plastic caps. Each indicated coating fault, i.e. on the carrier pipe within the casing, on the casing and on the pipeline outside the casing, represents the mean electrical characteristics of all coating faults present on the pipe section respectively, e.g: The spread resistance R_f of the coating fault on the pipeline outside the casing is considered to represent the resulting resistance from the parallel arrangement of spread resistances from the entity of coating faults on this pipeline section. The combination with the longitudinal resistance, R_f, of the pipeline yields the terminating impedance R_z (see also 2.2). In an analogue way the potential U_f is considered to be the average value from the IR-free potential of all coating faults on this pipeline section. In practise U_f can be measured as the pipeline off-potential $U_{t,off}$ if $R_z << R_{mi} + R_{ma}$.

Very similar considerations are applied to the coating faults on the casing in order to define U_{ma} and R_{ma}.

U_t is defined as average value from the IR-free potential at all coating faults on the steel pipeline within the casing while R_{mi} (defined as coating resistance of the carrier pipe in the casing) is a part of the spread resistance resulting from the parallel arrangement of these coating faults (see [3]).

2.2 Pipeline outside casing

In order to evaluate the terminating impedance, R_z, the characteristic impedance Z of the pipeline (with infinite length) outside the casing is considered. Z is given by [4]:

$$Z = \sqrt{\frac{R'}{G'}} \qquad (1)$$

where $R' = \frac{4\rho_{steel}}{\pi(d_2^2 - d_1^2)}$ is the longitudinal resistance load (ρ_{steel}-resistivity of pipeline steel, d_1 and d_2 inner and outer diameter of steel pipeline respectively) and $G' = \frac{\pi d_2}{r_u}$ is the leakage load of the pipeline (r_u-average coating resistance of the pipeline). As a first approximation it may be assumed that a pipeline is terminated with its characteristic impedance, i.e. R_z=Z, if the length exceeds the characteristic length l_k:

$$l_k = \frac{1}{\sqrt{R'G'}} \qquad (2)$$

In case that the pipeline exceeds its characteristic length on both sides of the casing the terminating impedance R_z is calculated to be half of the characteristic impedance Z, i.e. R_z=Z/2.

As an example fig. 2a draws the characteristic impedance Z (equ. (1)) as a function of the average coating resistance r_u for pipelines of different diameter d_2 and different wall thickness $s=d_2-d_1$ Fig. 2b shows the characteristic length l_k (equ. (2)) for the same set of pipelines.

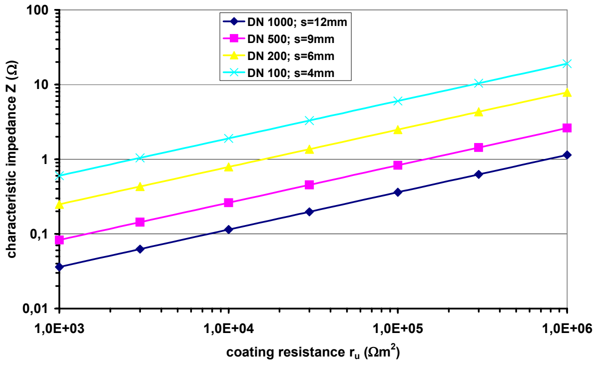


Fig. 2a: Characteristic impedance Z of pipelines with different coating resistances (calculated from equ. (1))

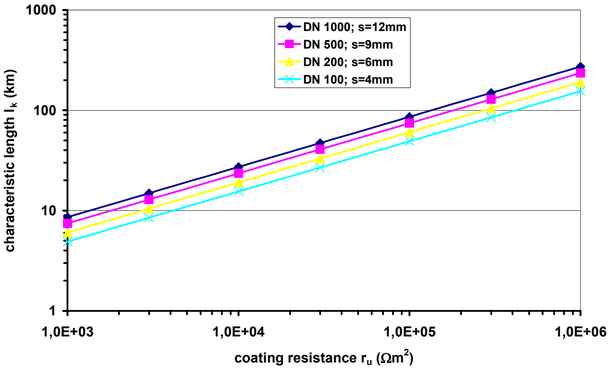


Fig 2b: Characteristic length l_k of pipelines with different coating resistances (calculated from equ. (2))

In case that the length L of the pipeline at one side of the casing is shorter than the characteristic length l_k, the terminating resistance $R_{z,L}$ of this pipeline section is estimated according to equ. (3) [4]:

$$R_{z,L} = Z * \coth(\frac{L}{l_k}) = Z * \frac{1}{\tanh(\frac{L}{L_k})} \qquad (3)$$

2.3 Casing and carrier pipe in the casing

The following data may be easily obtained during cathodic protection supervision measurements (see fig. 1):

$U_{t,on}$	on-potential of pipeline, measured against remote earth
$U_{t,off}$	off-potential of pipeline, measured against remote earth
$U_{ma,on}$	on-potential of casing, measured against remote earth
$U_{ma,off}$	off-potential of casing, measured against remote earth
$U_{m/t,on}$	voltage measured between casing and pipeline (cp-rectifier switched on)
$U_{m/t,off}$	voltage measured between casing and pipeline (cp-rectifier switched off)
$R_{m/t}$	resistance measured between pipeline and casing

The measurement techniques used should take into account:

- Potentials and voltages measured during the on-phase and also during the off-phase of cp-rectifiers are to be taken simultaneously if the pipeline is interfered by d.c.-stray currents. The magnitude of stray current interference should be constant while on/off-potentials/voltages are measured.
- The resistance $R_{m/t}$ between pipeline and casing may be measured using a hand held megger; more accurate results, however, are obtained if $R_{m/t}$ is calculated from the voltage drop $\Delta U_{m/t}$ across pipeline and casing while injecting a galvanostatically controlled d.c. current puls ΔI: $R_{m/t}=\Delta U_{m/t}/\Delta I$ (d.c. current injection test). For both measurement techniques separate electrical circuits are required for current- and voltage-measurements
- Potentials have to be measured against remote earth; this should be considered if coating faults on pipeline and/or casing cause far reaching potential gradients in the soil.

For further calculations the ratio $A=R_{ma}/R_{mi}$, i.e. the ratio from spread resistance of the casing R_{ma} and the resistance within the annular space of the casing R_{mi} (see fig. 1), will be defined. According to fig. 1 the variable A may be evaluated from the voltage drops $U_{ma,on}$-$U_{ma,off}$ and $U_{m/t,on}$-$U_{m/t,off}$ across R_{ma} and R_{mi} respectively:

$$A=\frac{R_{ma}}{R_{mi}}=\frac{(U_{t,on}-U_{m/t,on})-(U_{t,off}-U_{m/t,off})}{U_{m/t,on}-U_{m/t,off}}=\frac{U_{ma,on}-U_{ma,off}}{(U_{t,on}-U_{ma,on})-(U_{t,off}-U_{ma,off})} \qquad (4)$$

According to fig. 1 the resistance $R_{m/t}$ measured between pipeline and casing is:

$$R_{m/t}=\frac{R_{mi}*(R_{ma}+R_z)}{R_{mi}+R_{ma}+R_z} \qquad (5)$$

Combination with equ. (4) yields for R_{mi}:

$$R_{mi}=\frac{R_{m/t}(1+A)-R_z}{2A}+\sqrt{(\frac{R_{m/t}(1+A)-R_z}{2A})^2+\frac{R_{m/t}R_z}{A}} \qquad (6)$$

In case that R_z may be neglected compared to R_{ma}, i.e. $R_z \ll R_{ma}$ (see equ. (5)), which is generally fulfilled for long bituminous coated pipelines reaching the characteristic length l_k (equ. (2)), a simple expression is obtained for R_{mi}:

$$R_{mi} = R_{m/t} \frac{1+A}{A} \tag{7}$$

With respect to the explanations given for fig. 1 R_{mi} will be interpreted as part of the accumulated spread resistance of coating faults on the carrier pipe in the casing.

The spread resistance of the casing, R_{ma}, may be calculated from equ. (4). Taking into account the geometry (length, diameter) of the casing, some conclusion can be drawn concerning the quality of the coating. In case that casings are used to reduce the level of any induced ac-voltage, e.g. by establishing an electric connection between pipeline and casing via a capacitor [5], R_{ma} is the grounding resistance that has to considered, e.g. by any calculation of inductive interference.

A better accuracy for R_{ma}, R_{mi} and R_z will be obtained if $R_{m/t}$ is calculated from the results of a d.c. current injection test (see before). Simultaneously the variation of $U_{ma,on}$ and $U_{t,on}$ due to the current pulse ΔI, i.e. $\Delta U_{ma,on}$ and $\Delta U_{t,on}$ respectively, can be measured. Analogue to equ. (4) a ratio $B=R_z/R_{ma}$ may be defined. According to fig. 1 B is evaluated from the voltage drops $\Delta U_{t,on}$ and $\Delta U_{ma,on}$ across R_z and R_{ma} respectively:

$$B = \frac{R_z}{R_{ma}} = \frac{\Delta U_{t,on}}{\Delta U_{ma,on}} \tag{8}$$

Combination with $A = \frac{R_{ma}}{R_{mi}}$ (see equ. 4) and $R_{m/t} = \frac{R_{mi}(R_{ma}+R_z)}{R_{mi}+R_{ma}+R_z}$ (equ. 5) yields

$$R_{mi} = R_{m/t}\left(1+\frac{1}{A(1+B)}\right) \tag{9}$$

R_{ma} and R_z may be obtained from the definitions of A and B.

2.4. Cathodic protection of the carrier pipe in the casing

In the following paragraphs two pragmatic approaches are described that are aiming to assess if coating faults on the carrier pipe in the casing are cathodically protected. These procedures are of importance in case of non piggable pipelines, where no information about metal loss features on the carrier pipe are available.

2.4.1 Resistance comparison method

This method first comprises the estimation of the minimum spread resistance, $R_{a,min}$, of a single circular coating fault on the carrier pipe in the casing that can be cathodically protected with the cathodic protection system of the pipeline and by taking into account the electrical characteristics of the casing construction (see 2.3). The comparison of $R_{a,min}$ with R_{mi} allows to conclude to the effectiveness of cathodic protection. Very analogue procedures have been described to assess the effectiveness of cathodic protection for long electrically isolated pipeline sections, e.g. HDD-pipeline sections [2,6] and for cathodic protection remote control of well coated pipelines [7,8].

Considering a circular geometry, diameter d_{max}, of a coating fault the spread resistance $R_{a,min}$ is given by (pore- and polarization resistance are neglected):

$$R_{a,\min} = \frac{\rho}{2d_{\max}} \tag{10}$$

and

$$R_{a,\min} = \frac{4|U_d|}{|J_s|\pi d_{\max}^2} \tag{11}$$

Hence U_d is the driving voltage and J_s is the current density for cathodic protection of this coating fault needed to achieve the protection potential U_s, e.g. according to EN 12954 [9].

Substituting d_{max} by combining equ. (10) and (11) yields:

$$R_{a,\min} = \frac{|J_s|\pi\rho^2}{16|U_d|} \tag{12}$$

$R_{a,min}$ may be estimated as follows:

- If not directly measured cathodic protection current density J_s=0.1A/m^2 may be assumed as a reasonable default value for cp-current density under stagnant groundwater conditions as present in the annular space of casings
- If not directly measured ρ=30Ωm may be assumed as a reasonable default value for the resistivity of the medium in the annular space of the casing.
- In order to estimate U_d for a coating fault on the carrier pipe within the casing it has to be taken into account that a part $\frac{R_{ma}}{R_{mi} + R_{ma}}$ of the voltage $|U_{t,on}-U_s|$ (which is the driving voltage for cathodic protection at a given adjustment of cp rectifiers) appears as voltage drop across R_{ma} (fig. 1), i.e. $U_d = \frac{R_{ma}}{R_{mi} + R_{ma}}|U_{t,on} - U_s|$. Combination with equ. (4) yields:

  $$U_d = \frac{1}{A+1}|U_{t,on} - U_s| \tag{13}$$

  Note: These considerations imply that polarization of the steel surface within coating faults on the casing is negligible, i.e. $U_{ma} \approx U_{mi}$. In case that polarization has to be considered $|U_{t,on}-U_s|$. (according equ. (13)) has to be reduced by $|U_{ma}-U_{mi}|$.

Fig. 3 draws the minimum spread resistance $R_{a,min}$ for different parameter values J_s, ρ and $|U_d|$ according to equ. (12).

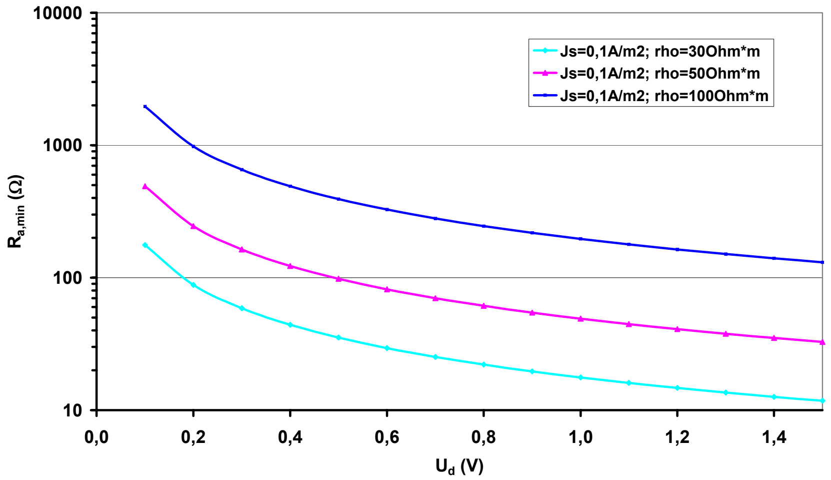


Fig 3
Minimum spread resistance in order to achieve effective cathodic protection of a circular coating fault at various conditions characterized by driving cp-voltage $|U_d|$, cp-current density J_s and soil resistivity ρ (equ. (12)).

The comparison of $R_{a,min}$ with R_{mi} (from equ. (6) or (7)) may yield:

- $R_{mi} > R_{a,min}$
- This result indicates effective cathodic protection for coating faults on the pipeline within the casing, provided $R_{a,min}$ had been estimated using reasonable values for the resistivity ρ of the medium in the annular space of the casing and the current density J_s that is required to achieve effective cathodic protection.
- $R_{mi} < R_{a,min}$
- In this case cathodic protection for coating faults on the carrier pipe within the casing should be assessed to be questionable because it cannot be excluded that there is a single circular coating fault with a spread resistance smaller than $R_{a,min}$ that cannot be cathodically protected. The following hints should help to interpret this situation in more detail:
  - It may be assumed that R_{mi} results not only from one individual but from a number of differently sized coating faults. If mutual interference of neighbouring coating faults can be neglected (i.e. potential gradients do not significantly overlap) effective cathodic protection will be achieved if the spread resistance of each individual coating fault is smaller compared to $R_{a,min}$.
  - In case that the distance between casing and pipeline is small, e.g. 100mm or smaller, it may be assumed that the resistance between casing and pipeline that has to be attributed to an individual coating fault on the carrier pipe within the casing is considerably smaller than calculated according to equ. (10). Consequently cp-current density J_s (e.g. $0.1 A/m^2$) will be achieved on larger coating faults, showing lower $R_{a,min}^*$ compared to $R_{a,min}$ as calculated from equ. (12), (see also [3]).
  - It is frequently found that $U_{ma,on}$ significantly differs from $U_{ma,off}$ thus indicating a possible polarization of the casing which reduces the driving voltage $|U_d|$ for cathodic protection (see equ. (13)).

2.4.2 Polarisation comparison method

It is generally not possible to determine the IR-free potential of a single coating fault on the carrier pipe in the casing, e.g. by intensive measurement technique, because the carrier pipe is shielded by the casing. It is also not possible to determine the average potential U_t as there is no reference electrode located in the annular space of the casing. Criteria mentioned in EN 12954 [9] are therefore not applicable in this situation.

From fig.1 it is possible, however, to calculate the difference U_t-U_{mi} and thus to estimate the average polarization of coating faults on the carrier pipe compared to the potential at the internal steel surface of the casing that is considered to be rest potential. Following this assumption a pragmatic criterion may be applied as described in [10,11] and cathodic protection may be considered to be achieved if
$U_t - U_{mi} \leq -0{,}1\text{V}$.

In case that cp-rectifiers are temporarily switched off U_t-U_{mi} can be described by the elements of the electric circuit from fig. 1:

$$U_t - U_{mi} = \frac{U_{m/t,off}(R_{mi} + R_{ma} + R_z) - (U_f - U_{ma})R_{mi}}{R_{ma} + R_z} \qquad (14)$$

Data required to evaluate equ. (14) are obtained as follows:

- $U_{m/t,off}$ to be measured according fig. 1
- U_f to be measured as $U_{t,off}$ if $R_z \ll R_{mi}+R_{ma}$
- U_{ma} to be measured using intensive measurement technique [1] on the casing
- R_{ma}, R_{mi}, R_z to be calculated according to chapter 2.3

3 Discussion of practical examples

In the following some results from measurements at casing/pipeline constructions are reported and interpreted using the procedures described in 2.3 and 2.4.

3.1 Estimation of electrical characteristics of casing/pipeline constructions according to chapter 2.3

Measurements (see table 1) had been carried out on casing/pipeline constructions (constructed 1962, pipeline diameter 400mm).

results from measurements							**calculated results**		
test post No.	$U_{t,on}$ (V)	$U_{t,off}$ (V)	$U_{ma,on}$ (V)	$U_{ma,off}$ (V)	$R_{m/t}$ (Ω)	**location**	A	R_{mi} (Ω)	R_{ma} (Ω)
20	-1,49	-1,17	-1,33	-1,04	1,22	Drakestr.	9,67	1,3	13,0
27	-1,41	-1,11	-1,03	-0,83	0,57	Grothusstr.	2,00	0,9	1,7
28	-1,39	-1,08	-1,19	-0,93	10,97	Lehrhovebruch	5,20	13,1	68,0
assumption: R_z=0,1Ω									

Table 1: Results from measurements at three casing/pipeline constructions; $R_{m/t}$ had been measured using a hand-held megger; values for A, R_{mi} and R_{ma} have been calculated according to equ. (4), (6) and (4) respectively.

$U_{t,on}$, $U_{t,off}$, $U_{ma,on}$ and $U_{ma,off}$ had been measured against remote earth. The differences between casing on- and off-potentials indicate cp-current entering the casing due to any coating faults on the carrier pipe in the casing. Values measured for $R_{m/t}$ do not imply a metallic contact between pipeline and casing.

From equ. (4) the factor A describing the ratio between spread resistance of the casing R_{ma} and the resistance in the annular space of the casing R_{mi} (see fig. 1) is calculated. At test post no. 20, 27, 28 R_{ma} exceeds R_{mi} by a factor of app. 10, 2 and 5 respectively.

From equ. (6) R_{mi} is calculated using R_z=0,1Ω as terminating resistance of the pipeline because the average coating resistance r_u of the pipeline is between 1 and 2 kΩm^2 (as calculated from cathodic protection supervision measurements, see fig. 2a). Results for R_{mi} suggest large coating faults on the carrier pipe in the casing at test posts 20 and 27 and it may be assumed that effective cathodic protection is virtually not possible. At test post 28 $R_{mi} \approx 13\Omega$ has been estimated; from fig. 3 it is concluded that a driving cp-voltage of app. 1.5V is required if R_{mi} is caused by one circular coating fault (see also comments at the end of chapter 2.4.1). Spread resistances of casings (R_{ma}) are calculated from equ. (4).

For a second set of measurements (table 2) the casings from table 1 had been connected to other grounded structures (steel piling, crash barrier etc., spread resistance measured as $R_{pipe/grounding}$) thus lowering the spread resistance of the casing from R_{ma} to R_{ma}'.

results from measurements								calculated results			
test post No.	$U_{t,on}$ (V)	$U_{t,off}$ (V)	$U_{ma,on}$ (V)	$U_{ma,off}$ (V)	**$R_{m/t}$ with gounding (Ω)**	**$R_{pipe/grounding}$ (Ω)**	**cp-current via grounding (mA)**	A	R_{mi} (Ω)	R_{ma}' (Ω)	**$R_{pipe/gounding}$ (Ω) calculated**
20	-1,49	-1,17	-0,72	-0,55	**0,81**	1,47	**310**	1,13	1,5	1,7	1,9
27	-1,41	-1,11	-0,72	-0,63	**0,51**	1,27	**320**	0,43	1,5	0,7	1,1
28	-1,39	-1,08	-0,5	-0,49	**1,22**	1,32	**24**	0,03	34,9	1,2	1,2
assumption: R_z=0,1Ω											

Table 2: Results from measurements at the casing/pipeline constructions from table 1 after establishing a connection between the casing and another grounded structure; $R_{m/t}$ and $R_{pipe/grounding}$ had been measured using a hand-held megger; values for A, R_{mi} and R_{ma}' have been calculated according to equ. (4), (6) and (4) respectively.

Results for $U_{t,on}$ and $U_{t,off}$ do not differ from those in table 1 indicating that the modifications of the electrical characteristics of the casings do not significantly interfere the overall electrical characteristic of the pipeline. Results for $U_{ma,on}$ and $U_{ma,off}$, however, are considerably more positive compared to table 1. This is predominantly due to the reduced voltage drop across the reduced spread resistance R_{ma}'.

$R_{m/t}$-values are lower compared to table 1 due to grounding of casings. For information the cp-current entering the grounded structure, measured at the bond to the casing is also given in table 2.

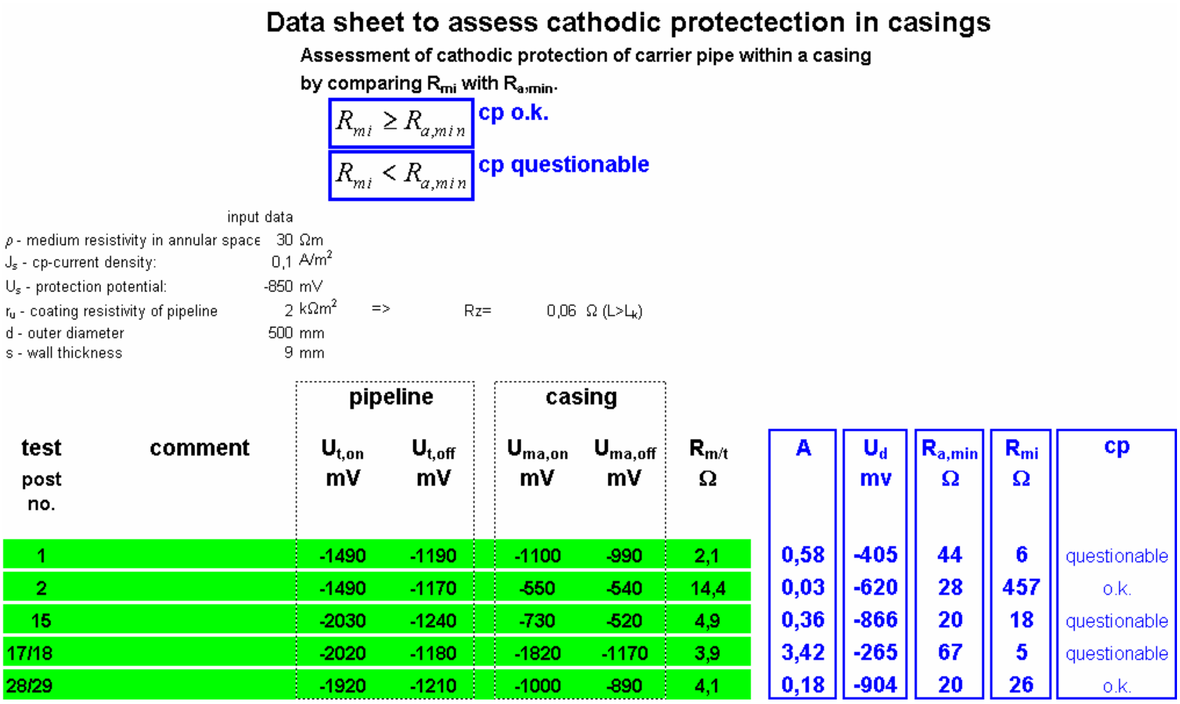
Values for A have been calculated as described before; they are significantly smaller compared to table 1 due to the low spread resistance of the grounded structure parallel arranged to the casing.

Values calculated for R_{mi} should not differ from those presented in table 1 because the situation of the carrier pipe in the casing and in the annular space is not changed. The comparison, however, shows deviations by a factor up to app. 3. This should be accepted as the accuracy of this method.

Using equ. (4) the reduced casing spread resistance R_{ma}' may be calculated from R_{mi}- and A-values. The spread resistance of the grounded structure (i.e. $R_{pipe/grounding}$ in table 2) may be re-estimated from $R_{pipe/grounding} = \frac{R_{ma} R_{ma}^{'}}{R_{ma} - R_{ma}^{'}}$ by using R_{ma}-values from table 1. Re-estimated values for $R_{pipe/grounding}$ are presented in the last column of table 2 and may be directly compared with measured data given in the sixth column of table 2 whereby reasonable consistency is found.

3.2 Assessment of effectiveness of cathodic protection using the resistance comparison method (chapter 2.4.1)

Table 3 summarizes results from measurements at six casing constructions on a DN 400 pipeline constructed in 1962 and provides the evaluation of data according to the procedures described in chapters 2.3 and 2.4 whereby default values have been used for medium resistivity in the annular space of the casing (30Ωm) and for cp-current density needed to achieve U_s=-850mV (0,1A/m^2).



Data sheet to assess cathodic protectection in casings

Assessment of cathodic protection of carrier pipe within a casing
by comparing R_{mi} with $R_{a,min}$.

$\boxed{R_{mi} \geq R_{a,min}}$ cp o.k.

$\boxed{R_{mi} < R_{a,min}}$ cp questionable

input data

ρ - medium resistivity in annular space	30	Ωm				
J_s - cp-current density:	0,1	A/m^2				
U_s - protection potential:	-850	mV				
r_u - coating resistivity of pipeline	2	kΩm^2	=>	Rz=	0,06	Ω ($L>L_k$)
d - outer diameter	500	mm				
s - wall thickness	9	mm				

test post no.	comment	pipeline $U_{t,on}$ mV	 $U_{t,off}$ mV	casing $U_{ma,on}$ mV	 $U_{ma,off}$ mV	$R_{m/t}$ Ω	A	U_d mv	$R_{a,min}$ Ω	R_{mi} Ω	cp
1		-1490	-1190	-1100	-990	2,1	0,58	-405	44	6	questionable
2		-1490	-1170	-550	-540	14,4	0,03	-620	28	457	o.k.
15		-2030	-1240	-730	-520	4,9	0,36	-866	20	18	questionable
17/18		-2020	-1180	-1820	-1170	3,9	3,42	-265	67	5	questionable
28/29		-1920	-1210	-1000	-890	4,1	0,18	-904	20	26	o.k.

Table 3: Results from measurements at several casing constructions on a DN 400 pipeline constructed 1962 and evaluation of data according to chapter 2.3 and 2.4.

Data have been evaluated to determine the ratio A (equ. (4)), the driving voltage U_d (equ. (13)), $R_{a,min}$ (equ. (12)) and R_{mi} (equ. (6)). Effectiveness of cathodic protection is assessed by comparing R_{mi} with $R_{a,min}$ (see chapter 2.4.1).

Cathodic protection is clearly effective inside the casing at test post no. 2 where R_{mi}=457Ω indicates a good coating quality of the carrier pipe. In case of casing at test post no. 28/29 corrosion likelihood should be low but a possible polarisation of the casing should be taken into account (see comment to equ. (13)). In accordance with these assessments results from an intelligent pig run did not indicate external metal loss on the carrier pipe in these casings.

There is a minor problem with the casing at test post no. 15 where R_{mi} is slightly smaller compared to $R_{a,min}$. The problem could be overcome by constructing an additional ground electrode (spread resistance e.g. 6Ω or less) and electrically connect it with the casing. Results from an intelligent pig run, however, did not indicate external metal loss on the carrier pipe within the casing.

Effectiveness of cathodic protection is clearly questionable in casings at test post n. 1. Results from intelligent pigging however did not indicate external metal loss on the carrier pipe in these casings. Possible reasons might be an arrangement of distributed small coating faults on the carrier pipe rather than one large coating fault and/or a small distance between carrier pipe and casing, e.g. at the bottom where distance is app. 5 cm due to the size of spacers.

Effectiveness of cathodic protection is also questionable inside casing at test post no. 17/18 and results from intelligent pigging did indicate external metal loss on the carrier pipe.

3.3 Assessment of effectiveness of cathodic protection using the potential comparison method (chapter 2.4.2)

This example refers to test post no. 28 from table 1 where additional measurements have been carried out to calculate U_t-U_{mi} according to equ. (14). The following data had been measured:

Potential data of pipeline and casing:
$U_{t,on}$ =-1,42 V
$U_{t,off}$ =-1,16 V
$U_{ma,on}$ =-1,24 V
$U_{ma,off}$ =-1,06 V

Hence A=2,25 is calculated from equ. (4).

Intensive measurements have been carried out along the casing and maximum potential gradients (indicated with symbol "δ") were:

- $\delta U_{ma,on}$=27mV
- $\delta U_{ma,off}$=14mV

Hence the potential at the steel/medium interface, which is considered to represent the mean (IR-free) potential of the casing is [1]:

$$U_{ma} = U_{ma,off} - \frac{\delta U_{ma,off}}{\delta U_{ma,on} - \delta U_{ma,off}}(U_{ma,on} - U_{ma,off}) = -0{,}87\text{V} \qquad (15).$$

Resistance data of pipeline and casing

A current pulse injection test had been carried out, injecting ΔI=1.38A between pipeline and casing. The following data were measured:

$\Delta U_{t,on}$ =-0,13V
$\Delta U_{ma,on}$ =+9,87V

Hence $R_{m/t}=(\Delta U_{ma,on}-\Delta U_{t,on})/\Delta I=7.3\Omega$, B=0.013 (equ. (8)) and

- $R_{mi}=11\Omega$ (equ. (9)),
- $R_{ma}=24\Omega$ (equ. (4))
- $R_z=0,3\Omega$ (equ. (8).

Evaluation of these data according to equ. (14) yields $U_t-U_{mi}=-0,02V$ indicating a mean cathodic polarisation of the carrier pipe (in the casing) compared to the (rest-) potential at the internal steel surface of the casing. This result suggests non effective cathodic protection for the pipeline in the casing and supports the conclusion from the assessment by comparing $R_{mi}=13\Omega$ and $R_{a,min}=203\Omega$ as evaluated from data given in chapter 3.1 for the casing at test post no. 28.

Conclusion

A simplified electrical model of a casing/pipeline construction has been established that takes into account mean (IR-free) potential of that section of the carrier pipe that is laid in the casing, of the casing itself and of the pipeline outside the casing as well as the spread resistance that has to be attributed to the coating faults on pipeline in the casing, outside the casing and the casing itself. Based on this model the following data/statements may be evaluated with reasonable accuracy from the results of cathodic protection supervision measurements:

- resistance in the annular space of the casing
- spread resistance of the casing
- terminating resistance of the pipeline
- pragmatic assessment of effectiveness of cathodic protection for coating faults on the carrier pipe within the casing

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Annex: Frequently used symbols

U_t	average (IR-free) potential at holidays on the pipe section within the casing
U_f	average (IR-free) potential at holidays on pipeline outside the casing
U_{ma}	average (IR-free) potential of holidays on the casing
U_{mi}	average (IR-free) potential at the internal steel surface of the casing (is generally assumed to be at rest potential)
R_{mi}	coating resistance of the carrier pipe in the casing, i.e. spread resistance of coating faults in groundwater or soil particles being present in the annular space of the casing (this resistance also contains the resistance of the organic protective layer if the casing is internally coated, if present)
R_{ma}	average coating resistance (i.e. spread resistance of coating faults) of the casing

R_z	characteristic impedance of pipeline outside casing
$R_{m/t}$	resistance measured between pipeline and casing
$R_{a,min}$	minimum spread resistance of a holiday that can be cathodically protected at a given adjustment of the cathodic protection system, i.e. on-potential U_{on}
U_s	cp protection potential (e.g. according to EN 12954)
$U_{t,on}$	on-potential of pipeline, measured against remote earth
$U_{t,off}$	off-potential of pipeline, measured against remote earth
$U_{ma,on}$	on-potential of casing, measured against remote earth
$U_{ma,off}$	off-potential of pipeline, measured against remote earth
$U_{m/t,on}$	voltage measured between casing and pipeline (cp-rectifier is switched on)
$U_{m/t,off}$	voltage measured between casing and pipeline (cp-rectifier is switched off)
ρ	resistivity of the medium in the annular space of the casing
J_s	minimum current density to achieve cathodic protection, i.e. U_s
U_s	protection potential for cathodic protection to be achieved at steel/medium interface
r_u	average coating resistance (expressed in Ωm^2)
cp	cathodic protection

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