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INDUCED CORROSION**

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DETECTION AND ASSESSMENT OF AC INDUCED CORROSION

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1. INTRODUCTION

AC induced corrosion is of concern in a number of situations such as :

- when high voltage transmission lines run parallel to buried pipelines on long distance,
- when catenary systems are close to concrete rebars, in railway tunnels,
- concentric neutral copper wires of urban district buried electrical cables,
- when AC stray currents are present.

Leaks that occurred in Bavaria and in the canton of Valais, Switzerland on gas lines were attributed to the influence of AC induced currents, although the lines were correctly protected cathodically (1,2,3).

For pipelines parallel to AC conductors, the induced voltage is given by

$$V_{\text{induced}} = -j\omega MI$$

where I is the AC current and M is the mutual induction and depends on the geometry and of the permeability and conductivity of the environment.

AC induced currents are influenced by this induced voltage and by the electrical resistance of the structure and of the coating.

2. LITERATURE, AIM OF THE WORK

Until the year seventies, most literature references indicate that AC induced corrosion is much less severe than corrosion due to DC stray currents. According to the literature, the AC induced corrosion at 50 Hz would be only 0.1 % of the corrosion that would be caused by DC current of the same value as the rms AC value, for buried steel structures (4). Other sources indicate larger ratios of 1 to 5% for steel in soils (5,6,7) and for lead in soil (8).

These numbers are meaningless and they seem to indicate an insufficient understanding and approach of AC induced corrosion.

Measurements made with an AC voltmeter between a reference electrode on the ground surface and a buried pipe sometimes indicate potentials as high as 100 V rms, in the case of long parallelism (2). AC current measurements were made on a probe connected to the structure, as an attempt to define a criterion for AC induced corrosion. Following one proposed criterion (9) there would be no AC corrosion when the rms AC current density is less than 2 mA/cm², between 2 and 10 mA/cm², corrosion would depend on the nature of the soil and AC induced corrosion would be highly suspected above 10 mA/cm².

It is felt that such criteria are incomplete and even wrong. AC induced corrosion much likely largely depends on the characteristic of the metal-environment interface, on the surface condition, on the nature of the soil and on the exact polarisation conditions both in DC and AC.

Some literature mentions possible shifts of the DC electrode potential when the structure is or has been exposed for a prolonged time to AC induced currents (10,11,12). This seems more reasonable because of different overpotentials and kinetics for some anodic and cathodic reactions that may occur along an AC period. Such effects are expected to be more pronounced at lower frequency (16.6 compared to 50 Hz) and they would be especially marked in passive systems such as steel in concrete (10) or stainless steel in sulphuric acid (11). A detection method for AC induced corrosion based on the shift of the electrode potential is used for monitoring the corrosion of the reinforced concrete linings in the Channel Tunnel since 1994 (12).

This work is aimed at developing a more rational approach to predict, identify and assess the true importance of AC induced corrosion. The first efforts were aimed at measuring correctly the maximum and minimum peak values of the electrode potential, so that the risk of corrosion could be evaluate more rigorously. In particular, it is important to determine if the potential of buried pipelines is maintained inside or outside the domain of cathodic protection.

We then studied methods to determine the importance of AC induced corrosion when the potential are sometimes higher than the critical potential for cathodic protection, even during part of the period.

Other specific aspects of AC induced corrosion were also investigated, such as the concept of passivation, the rate of initiation of electrochemical corrosion reactions, the role of the frequency (16.6 or 50 Hz) etc.

3. EXPERIMENTAL METHODS

3.1 Classical on-site potential measurements

AC measurements as commonly done up to now generally use an AC voltmeter and/or an oscilloscope, connected between the structure and a reference electrode. In some cases, the measurements are made on a probe connected to the structure and it is the possible to measure DC and AC current densities.

On site measurements soon indicated that this method is not suitable because ohmic drop errors due to AC current are often very important (see 4.1 and 4.2).

A system was therefore developed to measure « true » AC potentials, without ohmic drop errors.

3.2 Method of measurement of « true » potentials and of current densities, using the improved CORREAL system

The principle is similar to the measurement of the « true » DC potential (13,14,15): the potential is measured just after a switch-off of a probe that is normally connected to the structure (figure 1). In AC, the switch-off is made à many instants of an AC period. Figure 1 shows the arrangement used to compare the apparent potentials and the true potentials.

In a preliminary version, the CORREAL system¹ was modified to switch the connection off at a frequency slightly different from the network frequency. The measure is made 1 ms after the switch-off. With this method, the true peak potentials, without ohmic drop error, can be identified over a few periods. The raw data delivered by the modified CORREAL system appear as in figure 2:

¹ CORREAL, ABI Data, Brussels

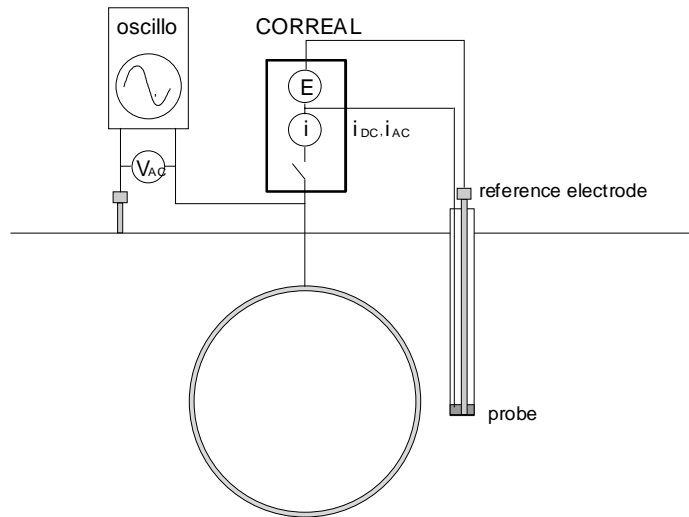


Figure 1: Measuring systems for the apparent potentials and true potentials

the extreme values of the potential correspond to the « true » peak potentials, and the other values correspond to measurements made at other instants, throughout a period.

In a second improved version, about twenty switch-offs are made along a same period. The current density is measured just before the switch-off and the potential is measured 200 μ s after the switch-off. This method allows measuring also the phase angle. The set of values of the true potential, the current density and the phase angle is used to assess the importance of AC induced corrosion (see 5).

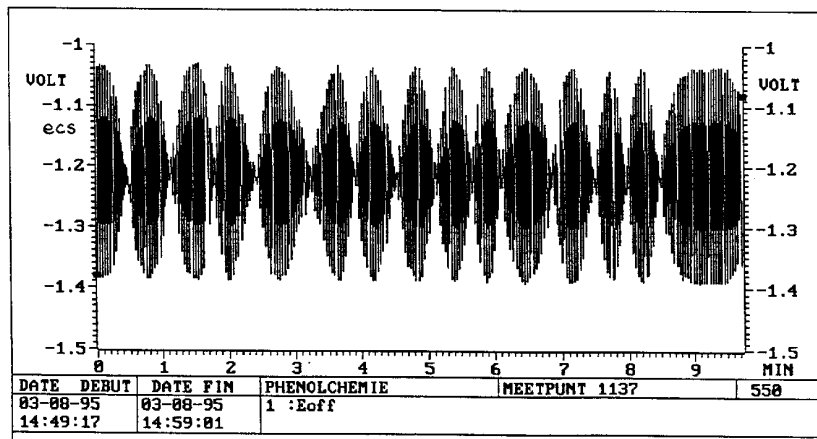


Figure 2: Raw data collected by the CORREAL system modified for AC currents

3.3 Measurement of corrosion rate

Mirror polished coupons were used on site and in the laboratory to assess the importance of corrosion. The aspect and the depth of corrosion attack, compared to a reference surface covered by a coating, are observed. Exposure duration was 1 to 3 months on site and 24 to 48 hours in the laboratory. It was important to ensure a tight contact between the probes and the soil.

In the laboratory, corrosion was also measured by pickling the coupons and by dissolving all the corrosion products in suspension are attached to the walls and by calculating the total amount of metal lost.

3.4 Metal-solutions systems

On site measurements were made on steel pipes in different soils (clay, schist, chalk, sand, polder...).

Literature suggests that AC induced currents may influence differently active systems (corroding systems) and passive systems. For this reason, laboratory tests were conducted in various electrochemical systems:

a) platinum in tap water (resistivity 1600 ohm.cm) under 15 mA/cm² 50 Hz AC current. This system was selected because the potential of platinum is very sensitive to small polarisation currents, contrary to actively corroding steel.

b) mirror polished iron in :

acid (corroding) solutions:

- acetic acid 0.001 N + 500 mg/l Cl⁻ as NaCl, pH 3.92

- H₂SO₄ 0.5 10⁻³ M + 1000 mg/l Cl⁻, pH 2.96

neutral solutions:

- Na₂SO₄ 0.01 M at pH 6.0

- Rhine sand saturated with Na₂SO₄ 0.01 M at pH 6.0

alkaline solutions (passivating solutions):

- NaHCO₃ 0.1 M + Na₃PO₄ 0.01 M, pH 9.15

- Na₂CO₃ 0.1 M, pH 11.2

One test was made on an iron sample packed in a plastic bag and immersed in a conductive solution.

3.5 Measurement programme

On site measurements were made on the Belgian network of high and medium pressure gas pipes, to search for possible situations where AC induced corrosion could be a problem.

The measurements were made during up to 3 months at selected locations where the potentials measured with an AC voltmeter and with a reference electrode on the surface of the ground were particularly high. These locations correspond to the extremities of sections parallel with high voltage electrical lines. The apparent potentials were measured with an oscilloscope and the true potentials were measured with the CORREAL system (figure 1). Corrosion was measured at the same locations on mirror polished coupons, after 1 and 3 months.

Similar comparisons between the apparent potentials and the true potentials were made in the laboratory in controlled DC + AC polarisation conditions. The conditions were selected so that the true potential was either permanently below the cathodic protection potential, either below or above at various instants of a period, or permanently above the cathodic protection potential. The duration of the tests is generally between 24 and 48 hours. The test circuitry is represented in figure 3. Tests were made at 16.6 and 50 Hz.

We investigated first the relationship between the « true » potentials and the absence or occurrence of corrosion. Then, we investigated methods to evaluate the importance of corrosion, under conditions where corrosion could occur.

The concern is particularly on pipes that are cathodically protected, where the true potential is not permanently (i.e. at all instants of a period) below the cathodic protection potential.

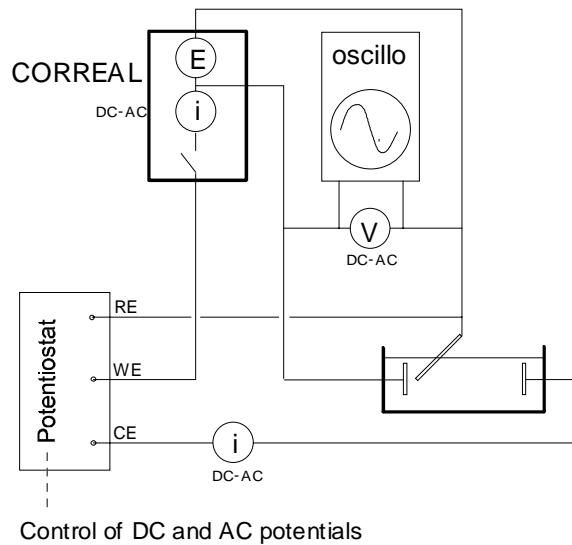


Figure 3: Circuitry for the control of DC + AC polarisation for laboratory tests

4. RESULTS

4.1 On site measurements

Figure 2 shows an example of measurements of the true potential made on site. In the case presented, the true maximum peak potential is $-1.03 V_{s_{ce}}$ and the true minimum peak potential is $-1.39 V_{s_{ce}}$. The true potential varies around an average value of $-1.22 V_{s_{ce}}$.

The results of measurements made on the Belgian gas pipe network are given in table 1. The apparent potentials (measured with an oscilloscope, without correction of the AC ohmic drop) show large excursions above the critical cathodic protection potential ($-800 mV_{s_{ce}}$). On the contrary, the true potentials (measured with the CORREAL system) are all below the cathodic protection potential, and corrosion after 3 months is negligible.

These measurements indicated the correct protection of the gas pipes of the Belgian network, even at locations most exposed to AC induction effects.

AC induced currents are often much more important than the DC currents for cathodic protection. For example, DC cathodic current densities of 0.18 , 0.33 and 0.72 mA/cm^2 were measured in the field, while AC induced currents of respectively 0.95 , 1.81 and 3.15 mA/cm^2 at the same locations and at the same time. The ohmic drop error is often more important in AC than in pure DC, and it is thus important to measure the true potentials when AC currents are present.

It must be noticed that the true minimum peak potentials are indicative of an overprotection lower than that suggested by the apparent potentials

Table 1
Comparison of the apparent peak potentials and of the true peak potentials on a cathodically protected gas line, parallel to a 380 kV transmission line (50 Hz).

Resistivity	Apparent peak potentials		True peak potentials		Corrosion depth after 3 months
	min	max	min	max	
ohm.cm	V _{sce}				µm
clay + schist 54 475	-8.00	+1.48	-0.95	-0.86	2 to 6
clay + schist 49 738	-10.61	+3.95	-1.27	-1.21	2 to 6
clay 2 450	-10.15	+5.01	-1.48	-1.15	2 to 4
clay + sand 2 450	-11.83	+9.39	-1.26	-1.02	3 to 5

4.2 Measurements in the laboratory. Comparison between the apparent potentials and the true potentials, and relationship with corrosion.

Iron in a corrosive solution:

Iron was polarised in CH₃COOH 0.001 N + NaCl 500 mg/l Cl⁻ at pH 3.92 with a cathodic DC current of 26 mA/cm², with an added AC current of 30 mA/cm² rms. The peak values of the apparent potential (measured with an oscilloscope) are +1.28 and -8.05 V_{sce}. The peak values of the true potential measured with the CORREAL system are -0.88 and -1.38 V_{sce}. A slight hydrogen evolution is observed during the test. After 20 hours, the coupon is still mirror polished, without any trace of corrosion. A blank coupon immersed in the same solution without polarisation showed an important general corrosion.

In this case, in spite of an apparent maximum peak potential that suggests corrosion and a minimum peak apparent potential that suggests a large overprotection, the true peak potentials indicate that cathodic protection is achieved at all time and that overprotection is limited.

Iron in passivating solutions:

Iron was polarised around its free potential in NaHCO₃ 0.1 M + Na₃PO₄ 0.01 M at pH 9.15 during 4 days, with an AC current of 40 mA/cm² rms. There was neither corrosion nor any gas evolution. But in another test in the same passivating solution, where iron was polarised by a DC current to -700 mV_{sce} and by an AC current such that the true potential oscillated between -1150 and -470 mV_{sce}, a corrosion of 2.08 mm/year was measured.

Subsequently, apparent potentials are no more considered. The interpretation of the test results will be based solely on the true potentials.

Table 2 summarises a series of results obtained in other systems, in various polarisation conditions. Columns 2 and 3 give the test solutions and frequencies. Columns 4 and 5 indicate the true peak

potentials maintained throughout the 24-hours tests. Column 6 gives the AC current densities and the last column shows the corrosion rates.

Table 2

Laboratory tests results under various cathodic polarisation conditions and various induced currents at 16.6 and 50 Hz

n°	Solution	f	True peak potentials		i _{AC}	Potential excursion		corrosion rate
			min	max		abs.	rel.	
		Hz	mV _{sce}		mAcmm ⁻²	mV	%	mm/y
<u>Corroding solutions</u>								
1	Acetic acid 0.001N + 500 mg/l Cl ⁻	50	-1380	-885	30,0	-	-	0,0
2	H ₂ SO ₄ 5.10 ⁻⁴ M + 1000 mg/l Cl ⁻	16	-900	-725	44,5	75	43	25,59
3	idem	16	-1225	-600	44,8	140	25	3,97
4	idem	16	-1489	-815	47,5	-15	-2	0,18
5	idem	50	-935	-620	45,6	180	57	19,11
6	idem	50	-1455	-825	45,6	-25	-4	0,2
<u>Neutral solutions</u>								
7	Na ₂ SO ₄ 0.01 M	50	-1200	-600	40,0	200	33	0,36
8	idem	50	-1390	-840	40,0	-40	-7	0,06
<u>Passivating solutions</u>								
9	NaHCO ₃ 0.1 M + Na ₃ PO ₄ 0.01 M	16	-1150	-470	68,6	330	48	2,08
10	idem	16	-1475	-725	88,5	75	10	0,26
11	idem	50	-1435	-655	77,6	145	18	1,81
12	idem	50	-1470	-860	85,4	-60	-10	0,16
13	Na ₂ CO ₃ 0.1 M	50	-1095	-710	40,0	90	23	0,05
14	idem	50	-1425	-975	40,0	-175	-39	0,04

It is immediately seen that corrosion is significant only when the maximum peak true potential is higher than the critical potential for cathodic protection (-800 V_{sce} or -850 mV_{Cu/CuSO4}) (tests 2,3,5,7,9). There is no corrosion when the true potential is permanently (throughout a period) below this potential (tests 1,4,6,8,12,14).

Other aspects (importance of AC induced corrosion, passive systems, criterion based on current density) are discussed below (see 5).

4.3 Study of the importance of AC induced corrosion

This study concentrated also on an electrochemical method that could immediately indicate the corrosion rate induced by AC currents at any location and at any instant, in cases where corrosion is possible. The concern is particularly on cathodically protected pipes for which the true potentials are not permanently inferior to the critical potential or cathodic protection, because of AC induced currents.

One observation can clearly be derived from the many experimental results: there is a relationship between the rate of corrosion and the excursions of the true potential above the critical potential for cathodic protection. These excursions are given in table 2, column 7 (absolute values, in mV) and in column 8 (relative excursions, expressed in % as shown in figure 4). The relationships between the

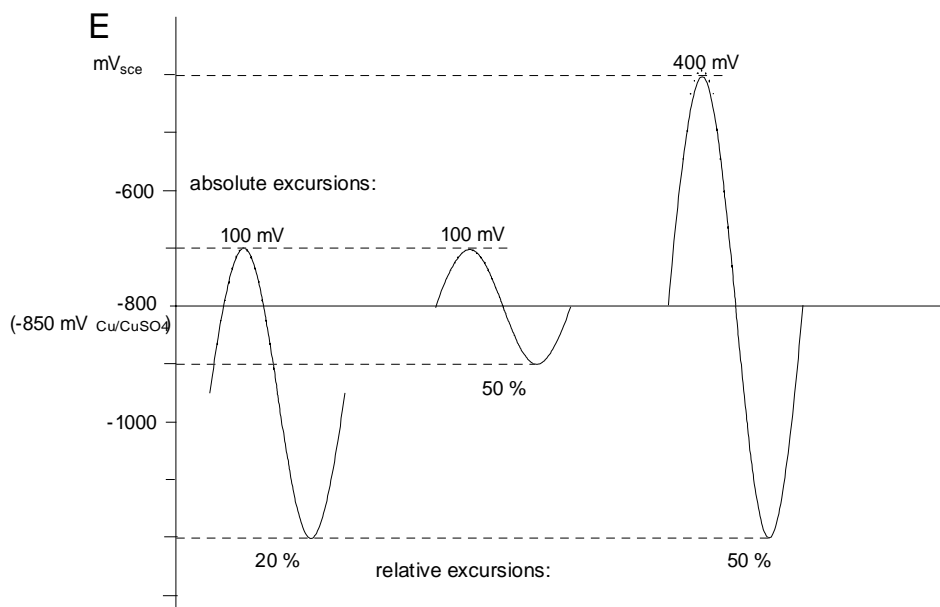


Figure 4: Relative and absolute excursions of the true potential above the cathodic protection potential.

corrosion rate and the potential excursions are shown in figures 5a (absolute values) and 5b (relative excursions). The relationship is better for the relative values than for the absolute excursions, and for corroding systems (dotted lines) than for passivating systems (figures 5a and 5b).

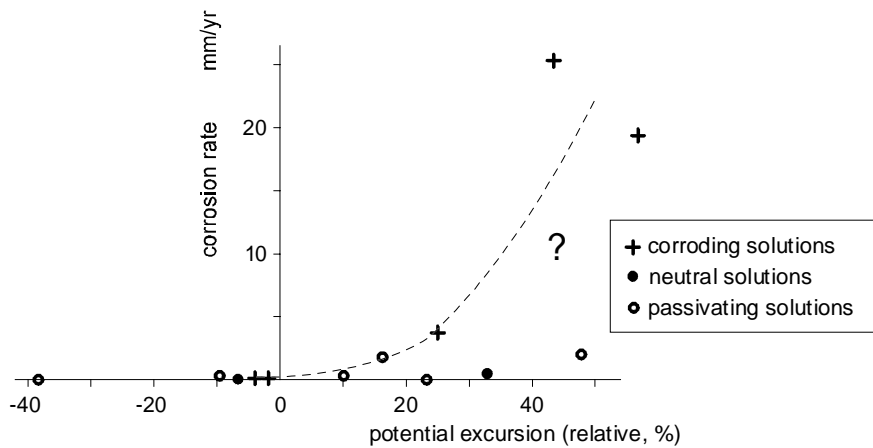
The relationship between the corrosion rate and the relative excursions of the true peak potential is currently considered as reasonably correct. Nevertheless, this point is discussed further in section 5.

5. DISCUSSION

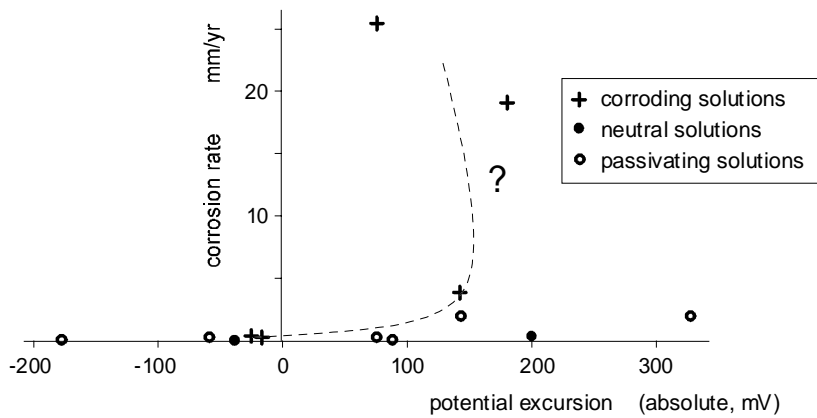
The results indicate that the electrochemical reactions are very rapid and can initiate and come to a stop in a fraction of a second. The results indicate that the 50 Hz Ac currents are not less harmless than the 16.6 Hz currents.

In corrosive environments (such as acid or neutral), any excursion of the true potential above the critical potential for cathodic protection ($-800 mV_{sce}$) corresponds to some corrosion. Conversely, there is no corrosion when the true potential remains below this potential throughout the whole AC period.

This study showed the importance of the true potentials, measured correctly by eliminating the ohmic drop error. These errors can be significant when AC currents are present. The apparent potentials have little or no meaning.



5a: Relative excursions (in %)



5b: Excursions, absolute values (in mV)

Figure 5: Relationship between corrosion rate and the excursion of the true potential above the cathodic protection potential

Environments that would be passivating in the absence of AC currents can become corrosive under certain conditions of AC polarisation: when the true potential varies between a passive range (thus above the cathodic protection potential) during part of the AC period and the immunity range during most of the period, it may reasonably be accepted that passivating films cannot form up to a stage where they become protective, before they are reduced. This creates a situation where iron can corrode under the combined influence of cathodic protection and AC currents, in a passive environment that would not cause any corrosion in the absence of cathodic protection and of AC currents. This case is illustrated by the tests 9 and 11, in table 2. Such a situation may be of importance in the case of rebars in concrete, under AC influence.

AC induced corrosion is by no means related to a critical value of the AC induced current density. It was shown that AC current can flow on an electrode perfectly covered by a dielectric film, in the same way as AC current is not blocked by a capacitor, without producing any corrosion. The case of a passive system polarised under 40 mA/cm² rms AC current during 4 days, without any

corrosion and without any gas evolution, was also demonstrated. This AC current density is 4 times higher than the critical AC current density mentioned in earlier literature (9).

Laboratory and field measurements indicate that the amplitude of the potential changes due to AC current is significantly less than those indicated by measuring the apparent potential on the surface of the ground, without correction for the ohmic drop.

It seems that there is a relationship between the amount of corrosion due to AC induced currents and the importance of the excursions of the true potential above the cathodic protection potential, expressed as a percentage of the amplitude of the true AC potential. This relationship is presently considered as rather correct. Nevertheless, it is still too approximate in some cases, especially in passive systems.

Currently, this study is oriented to measure the phase angle between the true potential and the current, in the field. It is expected that the combination of the true potential the current density and the phase angle will allow a correct assessment of the AC induced corrosion rate. Preliminary results clearly indicate the various electrochemical reactions that can develop throughout an AC period (hydrogen evolution, corrosion, passivation, and oxygen evolution in some cases...). Methods to assess the corrosion rate are being developed.

6. CONCLUSIONS, PROSPECTIVES

The present study introduce an original method to measure « true » potentials on probes connected to structures influenced by AC induced currents. The method allows measuring the maximum and minimum peak values and the mean value of the true potential.

Field and laboratory measurements indicated that the ohmic drop errors due to AC currents are generally important. The apparent potentials measured without correction of the ohmic drop, or the sole AC current density have no meaning.

The true potentials have a meaning: when the instantaneous true potential oversteps the critical $-800 V_{scc}$ potential, corrosion is possible. Conversely, there is no corrosion when the true potential stays permanently below this value. This study showed that the time for initiation of corrosion reactions is generally much shorter than the AC period, as well for 50 Hz than for 16.6 Hz.

The field measurements made during this study indicated that the protection of the gas lines of the Belgian network is correct, even at locations most exposed to AC induction effects.

The method proposed to measure the true potential uses the CORREAL system, which recently introduced significant progress for the measurement of the true potential in DC current (13,14,15). The probes, the instrumentation and the services have been developed for the AC induced corrosion through a co-operation between with Distrigaz and Abi Data and are available now. Through these services, it is possible to identify situations where AC induced corrosion is effectively present and to distinguish cases where AC currents do not create a corrosion risk.

There is a certain relationship between the AC induced corrosion rate and the excursion of the true potential above $-800 mV_{scc}$. That relationship must still be refined for passivating systems.

Our current work concentrates on the use of the instantaneous true potential and current density and on the phase angle to assess the AC corrosion rate. The preliminary results seem promising. Remedies are also under study, for situations where AC induced corrosion is a problem.

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