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Protection Criteria of Cathodically Protected Pipelines Under AC Interference

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Abstract: Carbon steel structures employed to convey hydrocarbons and other dangerous fluids, such as oil or flammable liquids, are equipped with degradation prevention systems, which typically consist of a cathodic protection (CP) system combined with an external insulating coating, both designed to reduce the corrosion rate below 10 µm/year. The presence of electrical interference, both AC and DC, can cause significant corrosion damage to metallic structures, even when CP is applied. DC interference is determined by the presence of a third-party CP system or public transportation system. AC interference may occur through conduction or induction mechanisms, caused by high-voltage powerlines or high-speed trains, powered by AC. Both interferences may lead to localized corrosion at coating defects, despite compliance with the −0.850 V saturated Cu/CuSO$_4$ reference electrode (CSE) protection criterion. Considering AC-induced corrosion, both field failures and laboratory investigations have demonstrated that corrosion can occur at industrial frequencies, and when CP is applied following the standards. Even though AC-induced degradation is generally not as severe as DC interference, uncertainties remain regarding the protection potential range necessary to achieve acceptable corrosion prevention under AC interference. To formulate a CP criterion under AC interference, weight loss measurements were conducted on carbon steel samples under cathodic protection in solutions that simulate real soil conditions. Carbon steel coupons protected by CP were interfered with AC densities ranging from 1 A/m^2 to 800 A/m^2 for four months. During this time interval, polarization potential, protection current density and AC density were monitored. Based on the experimental data gathered during this study, a proposal for a risk map is also suggested. The results indicate that overprotection (potentials < −1.2 V CSE) represents the most dangerous scenario when AC interference is involved.

Keywords: cathodic protection; alternating current; protection criteria; AC interference

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Academic Editor: Y. Frank Cheng

Received: 30 December 2024
Revised: 5 February 2025
Accepted: 6 February 2025
Published: 8 February 2025

Citation: Paterlini, L.; Marinelli, A.; Brenna, A.; Ormellese, M. Protection Criteria of Cathodically Protected Pipelines Under AC Interference. *Corros. Mater. Degrad.* **2025**, *6*, 7. https://doi.org/10.3390/cmd6010007

1. Introduction

Buried carbon steel structures employed to convey hydrocarbons and other dangerous fluids are often protected by external corrosion with a polymeric coating and a cathodic protection (CP) system. These preventive measures aim to reduce the corrosion rate below 10 µm/y, the maximum accepted threshold value to consider a buried steel structure in safe working conditions according to EN ISO 15589-1 [1].

AC interference is considered a significant threat for cathodically protected pipelines, regarding electrical human safety and pipeline corrosion integrity. When metallic pipelines run parallel to AC sources, such as high-voltage transmission lines (HVTL) or AC high-speed rail traction systems, AC interference can occur through resistive (conductive) and inductive (electromagnetic) mechanisms, causing corrosion in correspondence to coating defects or holidays, even if the −0.850 V (CSE) criterion is respected along the pipe [2,3]. Thus, it is crucial to establish an appropriate CP criterion that accounts for the impacts of AC interference. Currently, there is broad consensus about two key points:

1. Corrosion may occur even under a proper CP level at industrial AC frequencies;
2. AC-induced corrosion is less severe than DC-induced corrosion at the same level of current density, as confirmed by a previous work [4].

Over the last 50 years, different approaches and criteria have been proposed based on laboratory and field tests [5–25], leading to the formation of an ISO standard specifically dedicated to AC interference-induced corrosion, ISO 18086 [26], which provides guidelines to identify, measure and mitigate long-term AC interference. In 2017, the ISO 18086 standard was replaced by the EN 15280 standard [27], which previously covered the topic.

However, certain aspects of the phenomenon are not yet fully understood, such as the impact of CP levels on AC-induced degradation. For example, Carpentiers et al. [5] suggest that steel is protected by AC interference only if its potential lies within the immunity domain according to the Pourbaix diagram. Off-potentials below −1.200 V CSE are recommended since a local increase in pH occurs due the cathodic processes occurring in the presence of CP. Similarly, Panossian et al. [6] report that AC corrosion does not occur when the peak of the IR-free potential waveform remains below the equilibrium potential of the iron corrosion reaction.

More recently, Xu et al. [7] found that carbon steel is properly protected when the protection potential is sufficiently negative, such as −1 V SCE, even in the presence of an AC density close to 400 A/m^2.

On the other hand, Hosokawa et al. [8] and, more recently, Kajiyama et al. [9] proposed a criterion based on AC and DC densities that does not explicitly consider the protection potential of the metal. They stated that the AC-induced corrosion might be mitigated if the following conditions are verified:

- $0.1\ A/m^2 \leq i_{CP} \leq 1.0\ A/m^2$ and $i_{AC} < 25\ i_{CP}$, and
- $1.0\ A/m^2 \leq i_{CP} \leq 20\ A/m^2$ and $i_{AC} < 70\ A/m^2$,

where i_{CP} and i_{AC} are CP and AC current densities, respectively. This approach highlights the beneficial effect of CP in increasing the maximum permissible AC density on the pipe, from a few A/m^2 at a low CP level to 70 A/m^2 at a higher CP level.

Conversely, Nielsen et al. [10,11] introduced the “corrosion alkalization theory”, stating that the combined effects of high pH (when high protection currents are applied) and potential variation produced by AC interference could be identified as the causes of the high corrosion rate. Accordingly, field test results showed that high i_{CP} increases the AC corrosion rate up to 10 mm/y and should be avoided.

Similarly, Yunovich and Thompson measured high corrosion rates under conditions of both elevated AC and CP current densities [12]. Based on empirical data, Büchler et al. [13,14] stated that high i_{CP} in combination with $i_{AC} > 30\ A/m^2$ can lead to AC-induced corrosion, which is also to be expected if the ratio i_{AC}/i_{CP} exceeds 3 when high CP currents are applied. They also proposed an additional criterion based on the use of AC voltage combined with on-potential to assess corrosion risk, although doubts about the meaning of the on-potential measurement exist and are described below. Fu and Cheng [15] reported that at low AC density, i.e., 20 A/m^2, a protection potential of −0.950 V CSE is sufficient to ensure the safety of the steel structure. Furthermore, they also suggested that whenever AC density exceeds 20 A/m^2, lower protection potentials are required to effectively prevent severe steel corrosion.

Recently, Chen et al. [18] studied through in situ Raman spectroscopy the surface film evolution of a CP X65 carbon steel in different AC interference conditions, measuring corrosion rates up to 0.29 mm/y in the presence of an AC density interference of 500 A/m^2 and an IR-free potential equal to -1.16 V CSE. According to the authors, when the metal surface is subjected to strong CP and AC interference, cyclical oxidation and reduction lead to the formation of a magnetite and rust layer, which offers weak resistance to delamination when intense hydrogen recombination occurs at the steel/layer interface during the cathodic wave phase. The progressive peeling of the outer product layer cycle after cycle is then the suggested cause of the unexpectedly high corrosion rates, despite the correct CP application.

This brief overview shows that a protection criterion for carbon steel buried structures suffering AC interference is far from being accepted by everyone. However, in the last decade, an extensive effort has been made in Europe to define acceptable criteria to assess the risk of AC-induced corrosion.

CP Criteria Provided by ISO 18086 [26]

ISO 18086 (Corrosion of metals and alloys—Determination of AC corrosion—Protection criteria) [26] reports that when AC interference is involved, the safety thresholds proposed by EN ISO 15589-1 [1] are not enough to guarantee corrosion protection, and provides new safety limitations, measurements and mitigation procedures, as well as information to properly handle AC-induced corrosion.

According to ISO 18086, the primary factors to consider are AC voltage, AC density and CP current density. Nevertheless, the standard also highlights some other relevant parameters to evaluate AC-induced corrosion, such as AC/DC densities ratio, IR-free pipeline potential and soil resistivity. The AC voltage on the pipeline is measured as the remote earth voltage. While this parameter is relatively easy to detect, it is considered less reliable for assessing AC interference because the value depends significantly on the resistivity on the soil. Consequently, it is not possible to define any threshold only according to this parameter. Furthermore, ISO 18086 suggests that the average AC voltage measured over a 24 h period should never exceed 15 V.

Regarding electrical safety and system protection, the NACE SP0177 standard (Mitigation of alternating current and lightning effects on metallic structures and corrosion control systems) [28] also indicates 15 V as the upper limit for AC voltage to remote earth.

Furthermore, ISO 18086 proposes a safety criterion based on CP current densities, AC density and the ratio i_{AC}/i_{DC}; to avoid severe corrosion conditions, the average interfering AC density should never exceed 30 A/m^2, while if the AC density is higher than 30 A/m^2, CP current density should always be lower than 1 A/m^2 (Figure 1). According to ISO 18086, ISO 15589-1 and EN 12954 [1,3,26], the buried structure is to be considered in safe conditions when there is a 90% probability of $CR < 10$ µm/y, while it should be considered unsafe when there is a 90% probability of $CR > 10$ µm/y.

The average CP and AC densities should be measured over a representative period of time according to ISO 18086, i.e., 24 h. The pipeline, always according to the standard, is also to be considered efficiently protected if the ratio i_{AC}/i_{DC} does not exceed 3 (the region visible in the right part of the graphical visualization displayed in Figure 1).

Just to gauge the current densities involved, a stray current of 3 mA exchanged by a coating defect of about 1 cm^2 results in a local AC density of 30 A/m^2.

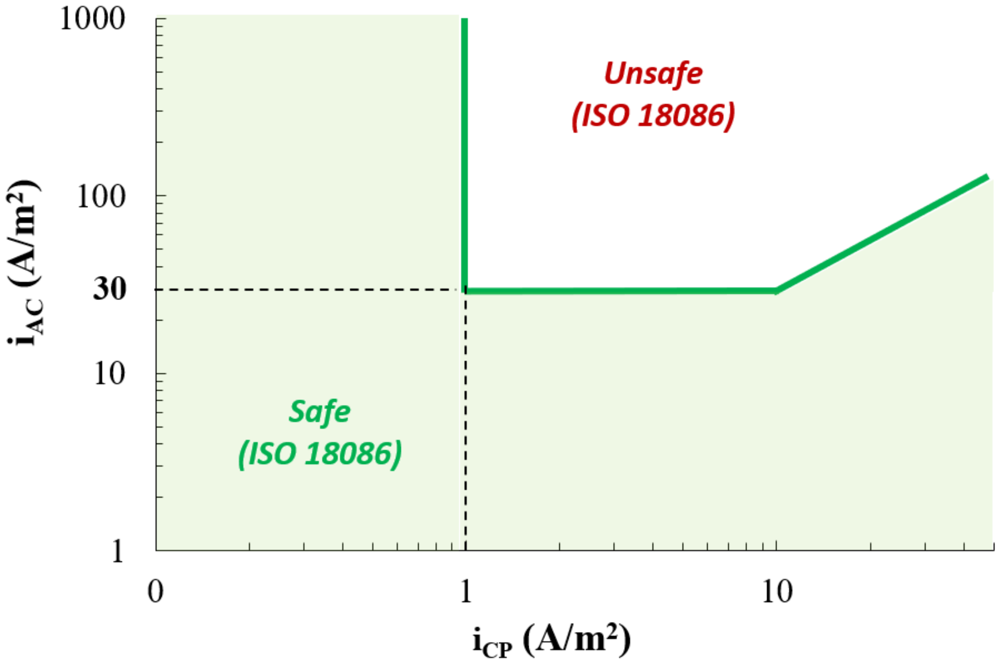

Figure 1. Safe and unsafe areas for cathodically protected structures in the presence of AC interference, according to ISO 18086 (modified from [26]).

Other safety criteria proposed by the standard are reported in the informative Annex (E), the first based on the ON-potential measurement approach (and mainly founded on the results reported by Büchler in 2012 [14]), and the second on IR-free potential measurement. In this regard, the on-potential criterion is considered less accurate, because the measurement includes an ohmic drop contribution related to both soil resistivity and circulating current rather than reflecting the effective electrochemical protection level. Indeed, the on-potential measurement consists of two contributing factors [29]:

$$E_{ON} = E_{IR-free} + IR = E_{IR-free} + i \cdot \rho \cdot d \quad (1)$$

where $E_{\text{IR-free}}$ is the IR-free potential (according to ISO 15589-01) [1] and IR is the ohmic drop contribution, which depends on soil resistivity (ρ), on the distance between the reference electrode and the structure (d) and current density (i). Furthermore, the standard reports additional parameters that can influence AC-induced corrosion, such as local resistivity and its composition (alkali and earth/alkali ions ratio), due to their effect on spread resistance associated with defects in the coating. The authors express some doubts about assessing the risk of AC corrosion based on soil composition, as it strongly depends on the cathodic current provided to the structure. Electric fields induced by CP and processes of ion diffusion can alter the local chemical composition, making it significantly different from that of the surrounding environment.

These considerations suggest that AC density (measured by means of proper corrosion probes or coupons) and CP polarization level (expressed by IR-free potential and protection current density) should be regarded as the primary parameters for quantifying the risk of AC interference degradation.

In this work, cathodic protection criteria under AC interference are proposed. These criteria are derived from weight loss measurements performed on carbon steel samples in soil-simulated conditions under cathodic protection, exposed to AC interference with current densities ranging from 1 to 800 A/m^2.

2. Materials and Methods

API 5L X52 carbon steel specimens [30] were exposed to long-term tests to evaluate the combined effect of AC and DC interference, by means of weight loss measurement.

Carbon steel specimens were firstly cleaned according to ASTM G1 [31], then fixed to a PTFE cylindrical sample holder (Figure 2), exposing a circular area 1 cm^2 wide to the electrolyte. The electrical contact with the specimen inside the PTFE cap was guaranteed by a stainless-steel rod screwed to the sample through a hole on its top. The electrical insulation between the rod and the surrounding electrolyte was guaranteed by a glass tube placed around the screw and pressed on the sample holder, interposing a polymeric gasket.

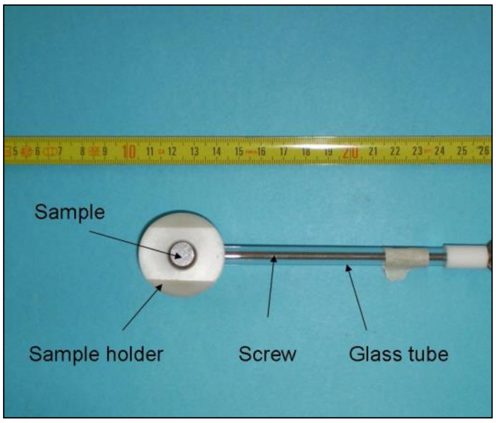

Figure 2. Carbon steel specimen and holder.

Tests were performed in soil-simulating conditions: a 3 L in volume cell was filled with sand, saturated with sulphate and chloride ions containing solution (sulphates 170–1200 mg/L, chloride 0–200 mg/L, pH 7). The temperature was maintained at a constant 20 °C (±1 °C) for the whole duration of the test.

CP was applied by means of a DC feeder (AMEL srl, Milan, Italy), under galvanostatic conditions: protection current density was applied in the range 0.2 A/m^2–10 A/m^2, corresponding to an IR-free potential ranging between −0.85 V and −1.50 V CSE, respectively.

Such high CP current densities (i.e., so negative potentials) can be reached in correspondence to pipe sections near the ground bed or in the presence of polyethylene or polypropylene coatings, at their small porosities or holidays, resulting in high local current density.

AC density (from 1 to 800 A/m^2) was applied to the specimens through an AC feeder (variable transformer) and a two-mesh electrical circuit, properly designed to separate the DC and AC signals (Figure 3).

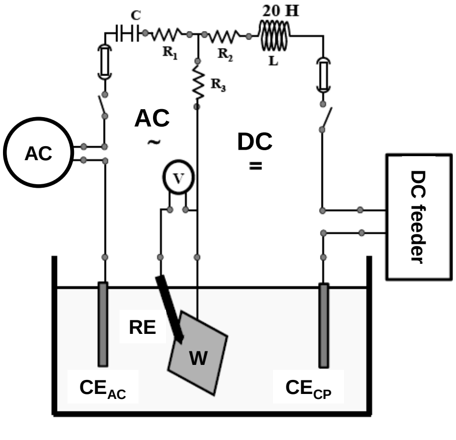

Figure 3. Schematic representation of the electrical circuit [32].

This AC density range (1–800 A/m^2) can be encountered in the field on buried pipelines running parallel to railways and/or high-power transmission lines. In particular, very high AC densities may be found at small defects in pipelines with high-insulation coatings, such as three-layer polyethylene (3LPE). Unlike bituminous coatings, these high-insulation coatings can have small defects (in the order of a few mm^2). The AC density at the coating defect can be estimated using the following equation [17]:

$$i_{AC} = \frac{8 \cdot V_{AC}}{\rho \cdot \pi \cdot \varnothing} \tag{2}$$

where V_{AC} is AC voltage (V), ρ is soil resistance (Ω·m) and $\varnothing$ is the diameter of a circular coating defect (m).

Assuming a 3LPE coating with a small defect size (Ø = 2 mm), a maximum AC voltage of 15 V and a resistivity of soil close to 30 Ω·m (high corrosivity soil), the AC density is about 650 A/m^2.

As extensively described in a previous paper [32], a dedicated electric circuit was realized to impose and measure DC and AC signals separately without causing interference (Figure 3). The circuit is divided into two meshes: one for the AC signal and the other for the DC signal. Within the AC mesh, the AC supplied by a variac flows between the sample (working electrode, W) and a carbon steel counter electrode (CE_{AC}), connected through a 10 Ω, 250 W shunt. Two 1000 µF capacitors in series were introduced into the AC mesh, providing a total capacitance of 500 µF (capacitive reactance of about 6 Ω), to prevent DC circulation.

In the DC mesh, the DC current was supplied by a galvanostat, flowing between the W and a Ti-MMO counter electrode (CE_{CP}), connected through a 10 Ω, 10 W shunt. To avoid interference with the AC supply system, a 20 H inductor (with an inductive reactance of about 6300 Ω) was introduced into the DC mesh, dimensioned to limit AC circulation to <1% of the total value. The testing procedure was carried out as follows:

- Immersion of the specimens;
- CP application for 15 days (galvanostatic, until a steady stable potential was achieved);
- AC interference (fixed AC density, through a proper set of shunts in series with the specimen) for about 100 days of exposure;
- Weight loss measurements, according to ASTM G1 [31].

Corrosion rate (CR, µm/y) by mass loss measurement was estimated as follows:

$$\mathrm{CR} = \frac{8.76 \cdot 10^7 \cdot \mathrm{W}}{\mathrm{A} \cdot \mathrm{t} \cdot \rho} \tag{3}$$

where W is the mass loss (g), A is the specimen's surface (cm^2), t is the duration of the test (hours) and ρ is the density of the metal (g/cm^3). The rate of corrosion was considered stable throughout the whole duration of the test. Both mechanical and chemical methods were employed to eliminate the corrosion products from the surface. Chemical cleaning was performed by immersing the sample in a picking solution containing 500 mL hydrochloric acid, 3.5 g hexamethylene tetramine and reagent-grade water up to a volume of 1000 mL. The immersion was carried out for 10 min at room temperature [31]. Hexamethylene tetramine minimizes the possible corrosion of the metal substrate during the cleaning process. Heavily encrusted corrosion products were removed by means of ultrasonic mechanical cleaning.

Corrosion rates estimated by mass loss can be misleading in the case of localized corrosion, as for AC-induced corrosion. Nevertheless, this value gives information about AC corrosion likelihood in different CP and AC conditions.

The potential of carbon steel specimens was measured with a CSE reference electrode combined with a Luggin capillary to reduce to the minimum the ohmic drop contribution. Thus, the measured values are the real level of polarization of the steel samples, and are reported in this paper as IR-free potentials (Equation (1)).

3. Results and Discussion

Experimental tests were carried out simulating AC-induced interference on buried coated pipelines under CP in the presence of coating defects. The results are analyzed and discussed to identify the key parameters influencing AC corrosion risk and to assess the cathodic protection (CP) criteria under conditions of AC interference.

Corrosion rates evaluated by means of weight loss tests are reported in Figure 4 for varying AC density; data are gathered based on the CP current density supplied to the metal: lower than 0.5 A/m^2, ranging between 0.5 and 1 A/m^2, and higher than 1 A/m^2. In the absence of AC, corrosion is absent or negligible (corrosion rate is lower than 10 µm/y, according to EN ISO 15589-1 [1]), i.e., steel operates in the protection condition, as expected. The dotted line in Figure 4 shows the critical corrosion threshold. Under AC interference, the higher the AC density, the higher the corrosion rate, even if cathodic protection is supplied to the metal.

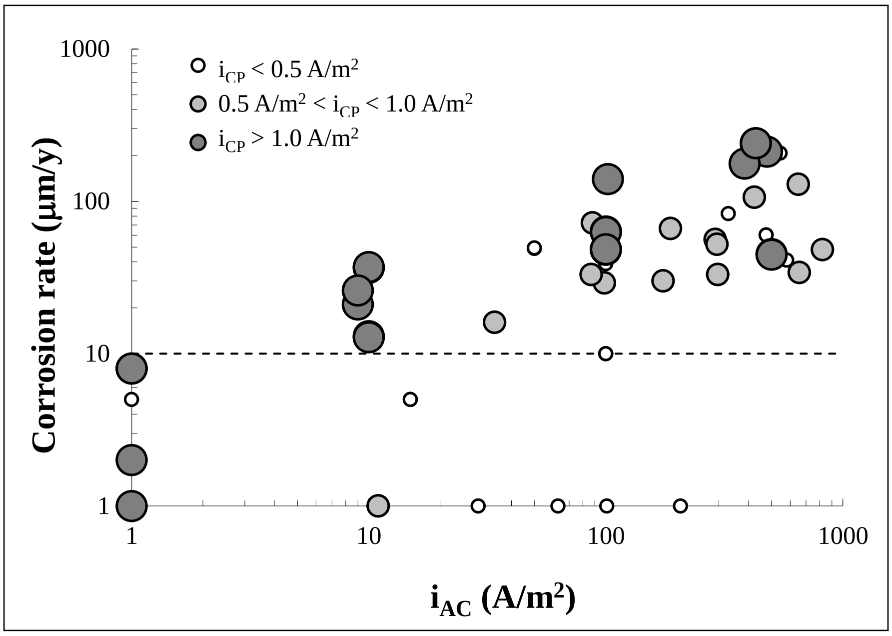

Figure 4. Corrosion rate vs. AC density (i_{AC}) at different CP current densities (i_{CP}).

At a constant AC density, the higher the applied cathodic current density, the higher the corrosion rate. When the AC density is higher than 30 A/m^2, corrosion rates ranging between 30 and 200 µm/y are measured regardless of the applied CP current density.

When AC interfering density is in the order of 100 A/m^2, corrosion rate increases of about one order of magnitude are observed with respect to the critical threshold (10 µm/y). Moreover, corrosion is not negligible, even for a low level of AC density (10 A/m^2) when a high value of CP current density is applied (>1 A/m^2).

Corrosion rates as a function of the i_{AC}/i_{CP} ratio are reported in Figure 5. An i_{AC}/i_{CP} ratio equal to 3 is highlighted in bold: at lower values, no remarkable corrosion risk should arise, according to ISO 18086 [26]. Data are divided into two sets, depending on the IR-free potential (average value):

- IR-free potential in the range between −0.85 V and −1.20 V CSE, simulating ordinary CP levels of buried pipes;
- IR-free potential lower (i.e., more negative) than −1.20 V CSE, simulating high CP levels (overprotection condition). This value is the limiting critical value below which detrimental effects on coatings could occur due to hydrogen evolution, such as blistering or gradual cathodic disbonding close to defects of the polymeric coating.

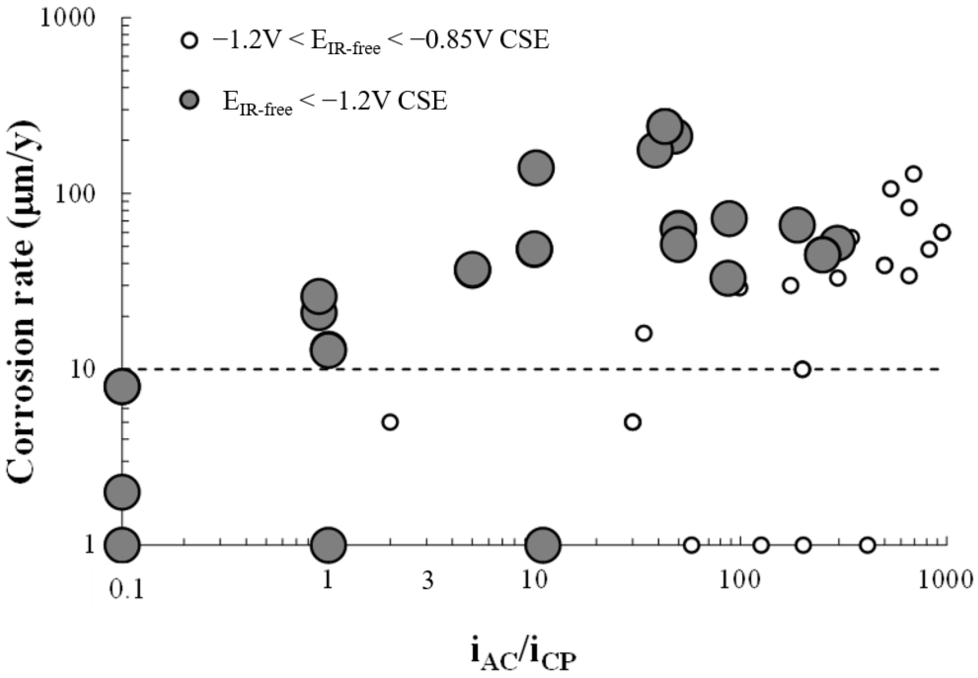

Figure 5. Corrosion rate vs. i_{AC}/i_{CP} with varying IR-free protection potential ($E_{IR\text{-}free}$).

The i_{AC}/i_{CP} ratio does not depend on the metal surface exposed to the electrolyte and it gives additional information to define the risk of AC-induced corrosion. Overprotection seems to be the most dangerous condition: if the i_{AC}/i_{CP} ratio is higher than 10, the corrosion rate is higher than 10 μm/y when the protection potential is more negative than −1.2 V CSE.

The authors do not recommend using only the i_{AC}/i_{DC} ratio to assess the risk of AC-induced corrosion, due to the misleading interpretations that could be associated with it. For instance, an i_{AC}/i_{CP} ratio equal to 10 can result in different protection and interference levels, e.g., 40 A/m^2 AC in the presence of 4 A/m^2 CP rather than 3 A/m^2 AC with 0.3 A/m^2 protection current density. Despite the same i_{AC}/i_{CP} ratio, the interference and the risk of corrosion is different, i.e., a 3 A/m^2 AC density is not considered as a critical value, unlike 40 A/m^2.

3.1. AC Corrosion Risk Diagram

Figure 6 reports a corrosion risk map which combines IR-free potential and the current densities ratio (i_{AC}/i_{CP}).

The green line divides the graph into two regions; the low risk of corrosion is the top left area. High corrosion risk corresponds to a corrosion rate (CR) greater than 10 μm/y. The higher the i_{AC}/i_{CP} ratio, the higher the risk of corrosion, according to Figure 5. Protection is achieved up to a critical value of the i_{AC}/i_{CP} ratio, which depends on the protection potential of the metal, i.e., it decreases as the protection potential becomes more negative. Under the overprotection condition, a very small AC density (5–20 A/m^2, depending on the true potential) may induce corrosion of carbon steel.

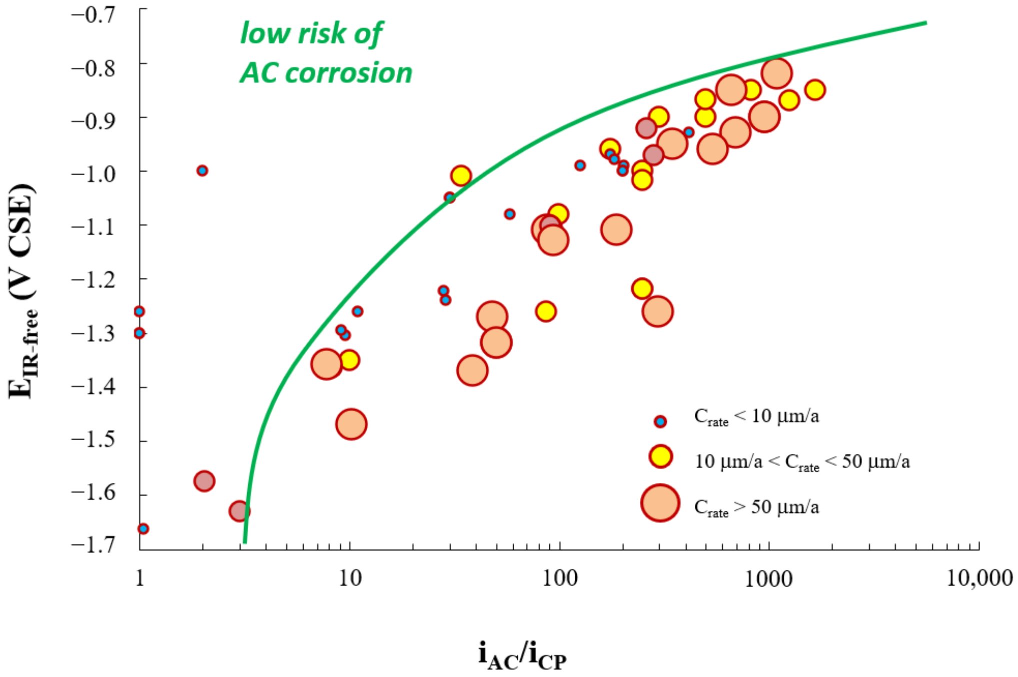

Figure 6. AC corrosion risk diagram: IR-free potential vs. i_{AC}/i_{CP}.

These considerations agree with the alkalization theory proposed by Nielsen et al. [10,11]; based on laboratory and field tests, the authors reported that AC-induced corrosion is not controlled by increasing the CP current density, as happens in the case of DC stray current, with a detrimental effect on the corrosion rate.

It follows that to consider only AC density and CP current density is not sufficient to establish the risk of AC-indued corrosion, since also the protection potential of the metal must be taken into account. At −0.85 V CSE (suggested protection potential according to EN ISO 15589-1 [1]), CP is not effective if the i_{AC}/i_{CP} ratio is higher than 400.

In conclusion, based on laboratory tests, the risk of AC corrosion is not influenced only by the AC interference level, as expected, but it is fundamental to consider the protection condition, namely, the protection potential and the protection current density. Moreover, being the CP criteria reported in international standards based on protection potential measurement, it is more practical to relate the risk of AC corrosion to the protection potential rather than to the protection current density.

3.2. CP Criterion in the Presence of AC Interference

Figure 7 compares corrosion rate data with CP criteria provided by ISO 18086 [26] (Figure 1) in the presence of AC interference. As mentioned in the Introduction, according to the standard, AC corrosion mitigation is achieved by reducing the AC density below 30 A/m^2 and maintaining the CP current density below 1 A/m^2 if the AC density is higher than 30 A/m^2, or if the maximum ratio i_{AC}/i_{DC} = 3 is respected. It follows that for a “low” CP level, there are no practical limitations to the maximum AC density values: in other words, no corrosion is expected, regardless of the value of AC density. On the other hand, the simultaneous presence of protection current densities higher than 1 A/m^2 and AC densities higher than 30 A/m^2 represent an “unsafe corrosion condition”.

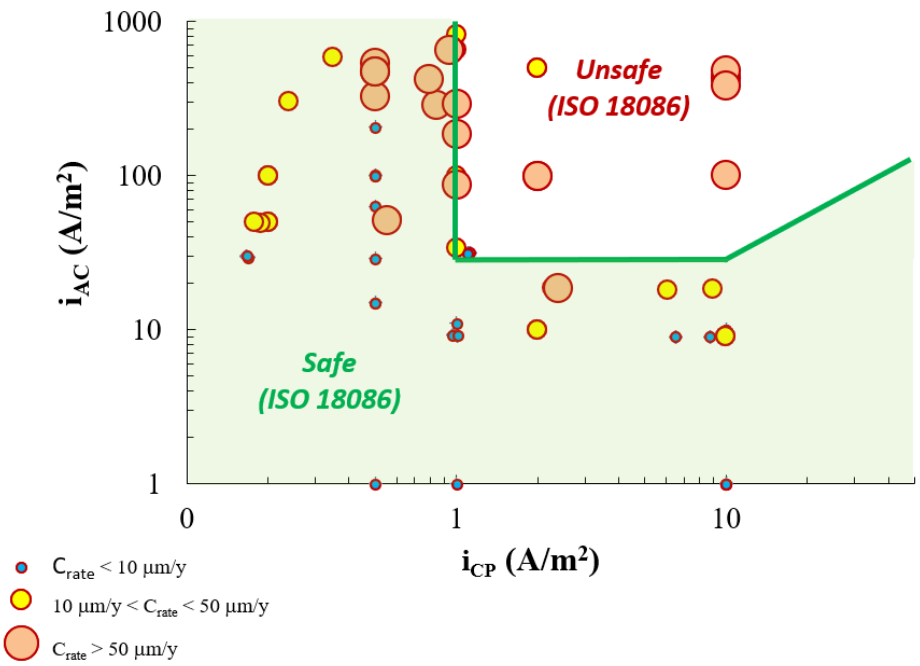

Figure 7. Experimental corrosion rate in the $_{\mathrm{AC}}/i_{\mathrm{CP}}$ diagram. Safe and unsafe regions refer to the CP criterion as reported in ISO 18086 [26].

Based on CP current density values, two CP conditions can be defined:

- A "low" CP level, corresponding to a CP current density lower than 1 A/m^2;
- A "high" CP level, corresponding to a CP current density higher than 1 A/m^2 (for the sake of completeness, this value corresponds to the overprotection condition if the IR-free potential is more negative than −1.2 V CSE).

The alignment between the experimental data and the CP criterion is poor: 15 out of 56 (27%) data points fall outside the current densities' criterion suggested by the standard. At "low" CP current density, a corrosion rate of up to 0.2 mm/y has been measured corresponding to CP current densities in the range from 0.2 to 1 A/m^2 and an AC density higher than 30 A/m^2. For an AC density higher than 30 A/m^2, the corrosion rate is not acceptable regardless of the value of CP current density supplied to the metal.

Figure 8 reports the proposed AC and CP current density threshold based on experimental corrosion rates: the threshold AC density value which may promote corrosion on a specimen under CP decreases from 30 A/m^2 to 10 A/m^2 as the overprotection condition is established (CP current density higher than 1 A/m^2). Therefore, in the presence of AC interference, increasing the CP level can be counterproductive, further aggravating the corrosion rate rather than preserving the pipeline integrity.

Based on the available data, the following can be concluded:

- A low CP current density (<1 A/m^2) in combination with a high AC density (>30 A/m^2) leads to AC-induced corrosion;
- A high CP current density (>1 A/m^2) in combination with an AC density higher than 10 A/m^2 leads to AC-induced corrosion;
- IR-free protection potential must be considered to evaluate the risk of AC corrosion;
- The "−0.85 V CSE criterion" is not always a safe condition in the presence of AC interference;
- Overprotection (potential < −1.20 V CSE) is the most dangerous condition and must be avoided.

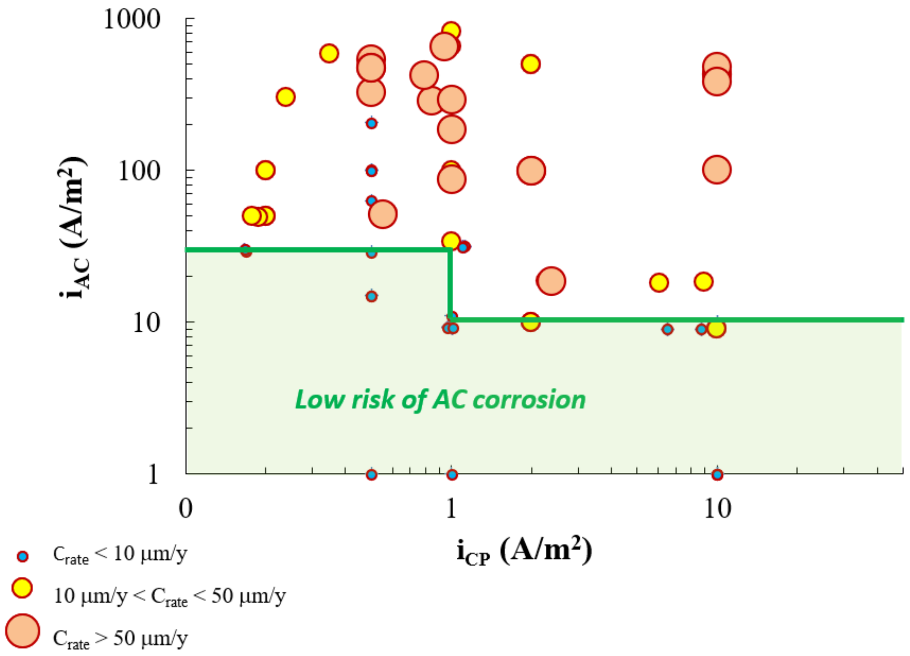

Figure 8. CP criterion based on experimental corrosion rate data.

Figure 9 illustrates the combination of the risk map suggested by ISO 18086 and the one proposed by the authors. The comparison shows that the authors' risk map adopts a more conservative approach. Figure 9 also highlights the limitations of the ISO 18086 standard, which struggles to predict severe corrosion rates (Crate $\geq$ 50 µm/y) in conditions of low CP current densities ($i_{CP} \leq 1$ A/m^2) combined with strong AC interference.

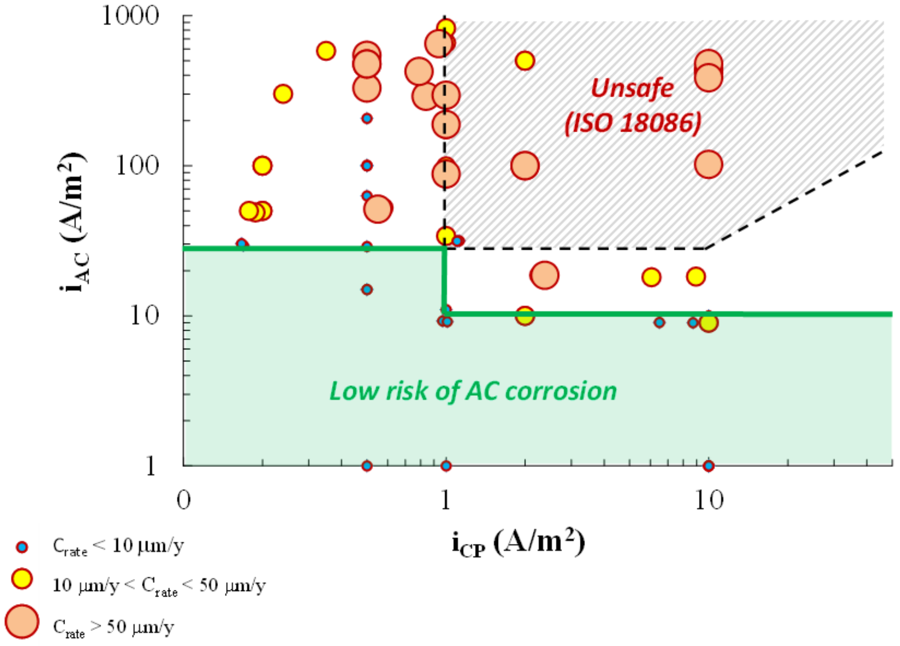

Figure 9. Highlighted in green are the safe regions according to the risk map proposed by the authors; the unsafe regions according to the ISO 18086 risk map are highlighted with a gray line pattern.

3.3. Interpretation and AC Corrosion Mechanism

Surprisingly, at least at first sight, overprotection is the most dangerous condition when AC corrosion of cathodically protected carbon steel pipes is addressed. Based on the experimental results, a two-step AC corrosion mechanism (described in detail in a recent paper [33]) has been proposed.

This model represents a significant innovation in the understanding of the AC corrosion phenomenon. It incorporates previous results on the effects of AC interference on anodic and cathodic polarization curves as well as on the corrosion rate in several electrolytes, including a solution simulating soil and synthetic sea water, for some metals such as carbon steel, galvanized steel, zinc and copper. A "mixed corrosion mechanism" was hypothesized, with a uniform reduction in both the anodic and cathodic overpotentials and an increase in exchange current density [4,32].

AC interference initially causes the rupture of the passive oxide layer present on a carbon steel surface under CP. Electrostriction may be a possible explanation of the film breakdown mechanism: the presence of a high local AC electric field (in the order of about MV/cm) in the passive layer could cause its local cracking. After its breakdown, corrosion starts if at the metal-to-electrolyte interface the pH is very high, close to 14. Such a high pH can be easily reached under the overprotection condition, due to the high level of protection current density. A chemical corrosion not dependent on the metal corrosion potential can be hypothesized.

4. Conclusions

To define cathodic protection criteria under AC interference, weight loss tests on carbon steel specimens under CP were performed in soil-simulated conditions, applying an interfering AC density in the range of 1 to 800 A/m^2, and a corrosion risk map has been proposed. The main findings are as follows:

- IR-free potential, AC and CP current densities (measured by means of corrosion probes or coupons) must be considered in order to evaluate AC corrosion risk;
- The risk of AC-induced corrosion increases with the decrease in the IR-free potential; potential lower than -1.2 V CSE (i.e., in condition) has to be avoided since it is the most dangerous condition;
- A low CP current density (<1 A/m^2) combined with an AC density higher than 30 A/m^2 leads to AC corrosion;
- A high CP current density (higher than 1 A/m^2) in combination with an AC density higher than 10 A/m^2 leads to AC corrosion;
- The i_{AC}/i_{CP} ratio provides a supplementary indication of AC corrosion risk: corrosion protection is achieved up to a critical value of the i_{AC}/i_{CP} ratio, the latter depending on the protection potential of the metal, i.e., the ratio decreases as the protection potential decreases;
- Under the overprotection condition, the corrosion rate is higher than 10 μm/y if the i_{AC}/i_{CP} ratio is higher than 10;
- The on-potential criterion provided by ISO 18086 and ISO 15589-1 is considered less accurate than the IR-free potential criterion, because the on-potential measurement includes an ohmic drop contribution related to both soil resistivity and circulating current, and does not represent an effective protection level.

Author Contributions: Conceptualization, M.O. and A.B.; methodology, L.P. and A.M.; validation, L.P., M.O. and A.B.; investigation, L.P. and A.M.; resources, L.P.; data curation, L.P. and A.M.; writing—original draft preparation, M.O. and A.B.; writing—review and editing, L.P.; supervision, M.O. and A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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