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AC Corrosion at Other Frequencies

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Abstract

AC corrosion on cathodically protected pipelines is commonly experienced due to interference from high voltage transmission lines at a frequency of 50 or 60 Hz. In some cases, the source of interference may be low frequency AC transit systems (1/3 of the fundamental frequency) and in other cases higher harmonics of the fundamental frequency can be detected on pipelines. In this paper AC corrosion of cathodically protected steel is investigated using electrical resistance (ER) probes at various frequencies (16.6-360 Hz) and different CP levels in an artificial soil solution. The effect of frequency on basic aspects and understanding of AC corrosion, specifically in terms of alkalization mechanisms and related time constants for involved processes, is discussed.

Key words: Alternating current, AC interference, Cathodic protection, Electrical Resistance Probes, AC corrosion, AC frequency

Introduction

The existing NACE¹ SP21424-2018 standard on AC corrosion addresses typical power frequencies up to 60 Hz, and the studies undertaken to sustain criteria for risk assessment, mitigation and monitoring have been based on 50 or 60 Hz¹. Other frequencies such as 16 2/3 Hz, and 2nd and 3rd harmonics of the 60 Hz (i.e. 120 and 180Hz) may interfere with the CP system on buried pipelines as well, and it is necessary to address this. Already, some research has been performed on the effect of frequency on AC corrosion²⁻⁵, the earliest dating back to the beginning of the 20th century, where it was concluded that low frequency AC had the highest impact on corrosion rates². Zhu and Du explain this by a negative shift of the corrosion potential with lower AC frequencies, and the damaging impact of AC on the stability, compactness and uniformity of the passive film on steel⁴. Several authors also point out another important effect from varying the frequency: At high AC frequencies, the impedance of the electrochemical double layer capacitance is low, and most of the alternating current will pass via charging/discharging of the double layer, whereas for lower frequencies, a larger portion of the AC current will pass via the polarization resistance, i.e. as electrode reactions such as corrosion⁵⁻⁸. Using this rationale, AC corrosion can essentially be understood as DC interference corrosion (at least during the anodic cycle), if the frequency is low enough. However, if AC corrosion could simply be treated as a periodical DC corrosion phenomenon, where the fraction of current running via electrode reactions and not the double layer capacitance is increasing with lower frequencies, then a simple mitigation measure could be to increase the level of CP as it is sometimes done in DC interference cases. This conclusion is wrong, since it is well documented that increasing the CP level will in fact accelerate corrosion rates in the presence of AC interference⁹⁻¹². AC corrosion is, in other words, far more complex than just considering anodic dissolution during the positive half-cycle of an alternating voltage signal.

¹ National Association of Corrosion Engineers (NACE), 15835 Park Ten Place Houston, Texas 77084, USA. (Now AMPP – Association for Materials Protection and Performance)

To illustrate how important it is to remember the role of the cathodic protection level on AC corrosion, this paper will be investigating the effect of three parameters; AC interference, AC frequency and CP level.

Experimental Procedure

Laboratory experiments were conducted in 50 L soil-box setups with separate AC (frequency generator and signal amplifier) and DC (potentiostat) circuits to simulate cathodic protection and induced AC interference of varying frequency on two ER probes buried in the same environment. Separation of the two circuits was done by implementation of a capacitor and a low resistance inductor in each of the two circuits (see *Figure 1*). Two working electrodes (WE) were used for double verification of the corrosion rate measurements. The exposed area of each of the ER probes was 1 cm² (3.16 x 31.6 mm). AC and DC counter electrodes (CE) were inert mixed metal oxide (MMO) coated titanium meshes of >20 cm². An interference corrosion logger (ICL) recorded the corrosion rate (v_{corr}), ON and IR-free potentials (E_{ON} and $E_{IR-free}$), AC voltage (U_{AC}), the resulting AC and DC current densities (J_{AC} , J_{DC}) and the spread resistance (R_s) with 20 minute intervals and uploaded the data to a web-based monitoring service every hour via a cellular modem. The reference electrode (RE) used in the setup was a saturated copper/copper-sulphate standard electrode (CSE) and all potentials are reported with respect to this.

The chemical environment was an inert sand (0.4-0.8 mm) fully wetted with a non-scaling artificial soil solution containing 5 mM Na₂SO₄, 2.5 mM NaHCO₃ and 10 mM NaCl in deionized water, having an initial pH = 8.2 and initial resistivity, $\rho_0 = 17.3 \Omega m$. The setup is described in further detail elsewhere¹³.

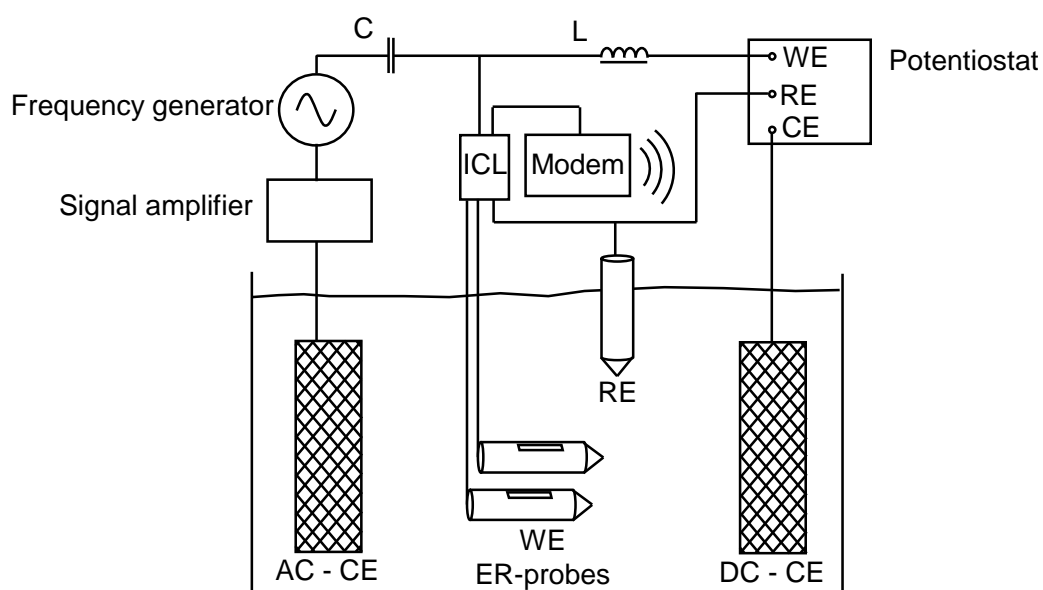


Figure 1: Schematic illustration of the experimental setup with a separate AC and DC circuit for investigation of AC corrosion under CP condition.

Using the experimental setup illustrated in *Figure 1*, different parameters were varied. Investigated frequencies are 16 2/3 Hz, 50 Hz, 60 Hz, 120 Hz, 180 Hz and 360 Hz. At each of these frequencies the AC interference level was varied through 0.5, 2, 5, 10 and 20 V_{rms} with >24 hrs. at each setting to be able to measure a corrosion rate on the ER probes. (For the 50 Hz investigation, data from a previous study in an identical setup was used where the AC interference levels were 0.5, 5, 10, 15 and 20 V_{rms} instead). This scan through AC frequencies and AC levels was done both at an intermediate/low level of CP ($E_{ON} = -1100 \text{ mV}_{CSE}$) and a high level of CP ($E_{ON} = -1500 \text{ mV}_{CSE}$) to assess the effect of the protection potential on AC corrosion as well.

For the 120 Hz frequency, which is of particular interest due to reported observations of high levels of interference from faulty transformer rectifiers¹⁴, a wider range of CP potentials was investigated ($E_{ON} = -900, -1000, -1100, -1200, -1300, -1400, -1500$ and -1600 mV_{CSE}) and this was compared to results from the 50 Hz study that similarly had data from this CP range.

Finally, a simple experiment was performed on the described setup in which the AC interference (60 Hz) was set for the maximum output level (34.2 V) of the frequency generator and amplifier (without cutting the peaks of the AC signal, measured with an oscilloscope), and the CP level was set at $E_{ON} = -1000$ mV_{CSE}. This was done in order to test the theory that AC corrosion can be mitigated, even at very high AC interference levels, simply by adjusting the DC settings of the CP system.

Results

Averaged data for the experiments at different AC frequencies and voltages are displayed in

Table 1 and *Table 2*. The relatively short duration of the experiment at each setting (≥ 24 hrs.) will have an effect on the certainty of the corrosion rate measurement, but still the general picture becomes clear when observing the results. Some deviations from the design values occur, in particular for the AC voltages. Also some difference between the recorded current density values and corrosion rate measurements on the two ER probes is evident, likely due to slight variations in local soil chemistry (i.e. alkalinity, composition and density of formed oxides, etc.) in front of either coupon. Despite the controlled laboratory conditions in this study, this is a valuable reminder that field measurements on coupons are only representative of the coupon itself, and the soil in which the coupon is installed. Coupon readings merely serve as a guide for evaluating the conditions on an actual pipeline and efforts should be made to mimic the pipeline conditions as best as possible when using coupons and probes.

Table 1: Averaged data from the frequency experiments performed at $E_{ON} = -1100 \text{ mV}_{CSE}$. AC and DC readouts and measured corrosion rates.

f (Hz)	Probe 1					Probe 2				
	E_{ON} (V_{CSE})	J_{DC} (A/m^2)	U_{AC} (V)	J_{AC} (A/m^2)	v_{corr} ($\mu\text{m/y}$)	E_{ON} (V_{CSE})	J_{DC} (A/m^2)	U_{AC} (V)	J_{AC} (A/m^2)	v_{corr} ($\mu\text{m/y}$)
16.6	-1.1	-0.3	0.5	6	0	-1.1	-0.2	0.5	6	0
	-1.1	-0.3	2.0	24	0	-1.1	-0.2	2.0	20	2
	-1.1	-0.5	5.1	64	2	-1.1	-0.4	5.1	64	2
	-1.1	-2.0	9.7	199	0	-1.1	-1.9	9.7	196	0
	-1.1	-3.4	20.0	514	68	-1.1	-2.7	20.0	463	98
50*	-1.1	0.03	0.4	6	0	-1.1	0.05	0.4	6	0
	-	-	-	-	-	-	-	-	-	-
	-1.1	-0.1	5.1	65	6	-1.1	-0.1	5.1	72	3
	-1.1	-0.8	8.9	172	0	-1.1	-1.2	8.9	207	0
	-1.1	-2.8	13.9	445	66	-1.1	-3.6	13.9	524	47
60	-1.1	-0.11	0.5	5	0	-1.1	-0.12	0.5	5	0
	-1.1	-0.13	2.0	22	0	-1.1	-0.13	2.0	21	0
	-1.1	-0.17	5.0	57	0	-1.1	-0.18	5.0	54	2
	-1.1	-0.35	10.1	118	2	-1.1	-1.21	10.1	170	0
	-1.1	-3.20	19.3	504	0	-1.1	-3.05	19.3	483	0
120	-1.1	-0.1	0.5	5	0	-1.1	0.04	0.5	5	0
	-1.1	-0.1	2.0	22	5	-1.1	0.04	2.0	18	0
	-1.1	-0.2	5.1	54	0	-1.1	-0.1	5.1	47	0
	-1.1	-1.5	9.8	186	4	-1.1	-0.4	9.8	112	3
	-1.1	-2.9	19.5	484	2	-1.1	-1.9	19.5	392	7
180	-1.1	-0.2	0.5	6	0	-1.1	-0.2	0.5	6	1
	-1.1	-0.1	2.2	24	0	-1.1	-0.1	2.2	22	0
	-1.1	-0.2	5.1	62	0	-1.1	-0.2	5.1	59	1
	-1.1	-0.4	10.4	151	0	-1.1	-0.6	10.4	167	0
	-1.1	-2.8	21.1	574	0	-1.1	-3.1	21.1	621	0
360	-1.1	-0.2	0.5	7	0	-1.1	-0.1	0.5	7	2
	-1.1	-0.2	2.0	26	10	-1.1	-0.1	2.0	22	0
	-1.1	-0.2	5.0	65	3	-1.1	-0.2	5.0	55	0
	-1.1	-0.4	9.9	137	0	-1.1	-0.2	9.9	113	N/A
	-1.1	-1.0	19.4	339	12	-1.1	-0.9	19.4	321	0

* The 50 Hz data are from another study, performed under identical conditions but slightly different AC levels.

Table 2: Averaged data from the frequency experiments performed at $E_{ON} = -1500 \text{ mV}_{CSE}$. AC and DC readouts and measured corrosion rates.

f (Hz)	Probe 1					Probe 2				
	E_{ON} (V_{CSE})	J_{DC} (A/m^2)	U_{AC} (V)	J_{AC} (A/m^2)	v_{corr} ($\mu m/y$)	E_{ON} (V_{CSE})	J_{DC} (A/m^2)	U_{AC} (V)	J_{AC} (A/m^2)	v_{corr} ($\mu m/y$)
16.6	-1.5	-4.0	0.5	11	0	-1.5	-4.0	0.5	11	6
	-1.5	-9.4	2.1	59	9	-1.5	-9.0	2.1	61	26
	-1.5	-13.7	5.2	165	158	-1.5	-13.0	5.2	163	116
	-1.5	-20.3	10.5	385	1107	-1.5	-18.3	10.5	355	905
	-1.5	-25.6	18.0	734	1670	-1.5	-22.5	18.0	672	1175
50*	-1.5	-6.9	0.3	11	0	-1.5	-6.7	0.3	12	0
	-	-	-	-	-	-	-	-	-	-
	-1.5	-11.3	5.1	225	92	-1.5	-11.7	5.1	244	46
	-1.5	-17.1	10.0	559	461	-1.5	-18.7	10.0	615	578
	-1.5	-24.5	15.3	1009	1030	-1.5	-26.1	15.3	1110	804
60	-1.5	-5.6	0.5	13	0	-1.5	-5.1	0.5	12	2
	-1.5	-6.1	2.0	54	1	-1.5	-5.5	2.0	51	3
	-1.5	-8.2	5.0	144	0	-1.5	-8.3	5.0	140	0
	-1.5	-13.6	9.8	333	55	-1.5	-12.9	9.8	322	51
	-1.5	-22.9	20.2	816	857	-1.5	-20.9	20.2	788	739
120	-1.5	-5.3	0.5	12	0	-1.5	-6.1	0.5	13	0
	-1.5	-5.7	2.0	46	0	-1.5	-6.7	2.0	50	5
	-1.5	-6.9	5.0	123	11	-1.5	-7.2	5.0	128	0
	-1.5	-10.2	10.4	298	7	-1.5	-9.7	10.4	307	1
	-1.5	-13.9	19.6	627	137	-1.5	-13.1	19.6	630	141
180	-1.5	-6.8	0.5	14	1	-1.5	-6.3	0.5	15	0
	-1.5	-7.0	2.0	56	0	-1.5	-6.6	2.0	59	0
	-1.5	-7.6	5.0	147	15	-1.5	-7.1	5.0	150	0
	-1.5	-8.6	10.0	315	0	-1.5	-8.9	10.0	328	5
	-1.5	-15.0	19.8	761	82	-1.5	-18.6	19.8	847	197
360	-1.5	-5.8	0.5	13	0	-1.5	-5.9	0.5	12	0
	-1.5	-6.6	2.0	57	18	-1.5	-6.4	2.0	54	36
	-1.5	-6.9	5.0	146	0	-1.5	-6.5	5.0	139	13
	-1.5	-7.3	9.9	299	0	-1.5	-6.9	9.9	284	43
	-1.5	-11.5	19.6	711	0	-1.5	-9.5	19.6	655	30

* The 50 Hz data are from another study, performed under identical conditions but slightly different AC levels.

The data from

Table 1 and Table 2 is displayed in Figure 2 as a function of the induced AC current density at high CP ($E_{ON} = -1500 \text{ mV}_{CSE}$) in a) and low/intermediate CP ($E_{ON} = -1100 \text{ mV}_{CSE}$) in b). The two plots clearly show that the corrosion rate is highly influenced by both AC current density and frequency, showing the highest corrosion rates at low frequencies and high AC current densities.

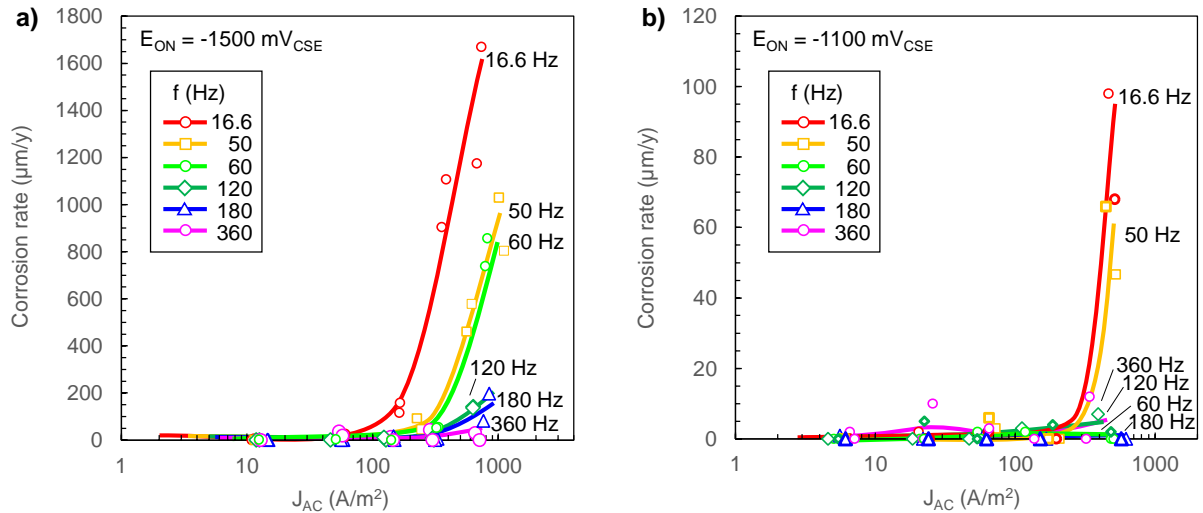


Figure 2: AC corrosion rates at different frequencies as a function of the AC current density. a) at high CP and b) at low/intermediate CP. Notice the similarity of the two plots but with a difference in corrosion rate of more than an order of magnitude.

When comparing a) and b) the recorded corrosion rates are generally more than an order of magnitude higher at the more negative on-potential (a), which underlines the importance of the CP level when analyzing AC corrosion data.

Another important observation from

Table 1 and Figure 2b is that only very limited corrosion ($< 1\text{ mpa} / 25\ \mu\text{m/y}$) occurs at a moderate/low CP level ($-J_{\text{DC}} < 1\ \text{A/m}^2$), even at AC levels well above $J_{\text{AC}} < 100\ \text{A/m}^2$.^{1,15} For frequencies of 60 Hz and higher, no upper limit of AC current interference is detected within the investigated AC range, when the CP level is moderate/low.

Increasing the CP level to $E_{\text{ON}} = -1500\ \text{mV}_{\text{CSE}}$ (Table 2 and Figure 2a) causes the DC current densities to be markedly higher. This affects the AC current density levels, due to enhanced alkalization of the steel/soil interface and lowered spread resistance. Corrosion $> 1\text{ mpa}$ ($25\ \mu\text{m/y}$) is observed at an AC current density that appears to be very dependent on the AC frequency.

Figure 3 displays the same corrosion rate data as a function of the frequency. Each line corresponds to an AC interference level. This representation of data makes the effect of frequency on the AC corrosion rate very clear. Less corrosion is observed at higher frequencies. Still the effect of the cathodic protection level is important to notice.

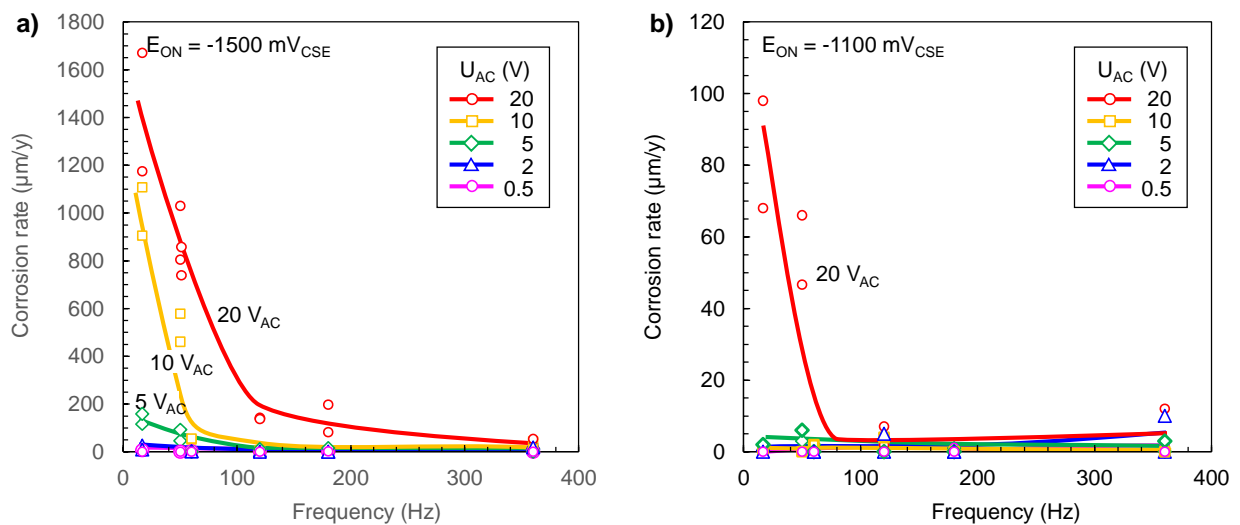


Figure 3: AC corrosion at different AC voltages as a function of AC frequency. a) at high CP and b) at low/intermediate CP. Notice the similarity of the two plots but with a difference in corrosion rate of more than an order of magnitude.

When comparing 50 and 120 Hz AC interference over a wider CP range from $E_{\text{ON}} = -900$ to $-1600\ \text{mV}_{\text{CSE}}$, a better understanding of the effect of cathodic protection on AC corrosion is obtained. The corrosion rates measured by ER probes are presented in the AC/DC current density plots in Figure 4 and Figure 5 and the SP 21424 and ISO 18086 current density criteria lines are drawn in the same plots.

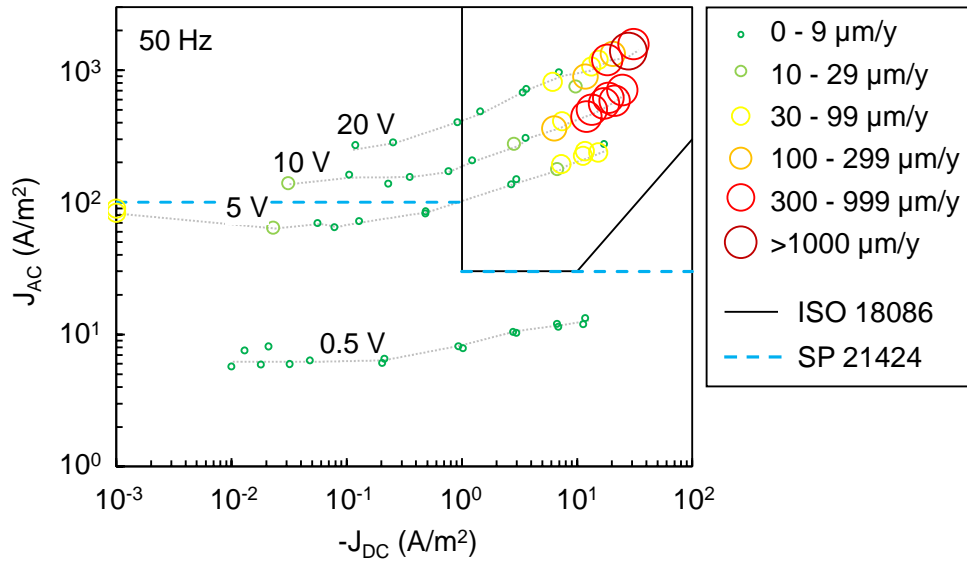


Figure 4: AC/DC current density plot with corrosion rates at 50 Hz AC interference. The investigated AC and DC levels were $U_{AC} = 0.5 - 20 \text{ V}$ and $E_{ON} = -900 - -1600 \text{ mV}_{CSE}$.

A corrosion domain is found at high AC and DC current densities, but for 120 Hz the domain is shifted towards higher AC current densities and the corrosion rates are lower. The horizontal lines in the plots indicate data of the same U_{AC} level. The obtained AC current density is very dependent on the CP level, i.e. the datapoints shift up towards the right side of the plot due to alkalization and reduced spread resistance, underlining the difficulty of attempting to use AC voltage as a practical protection criterion without also addressing the CP level.

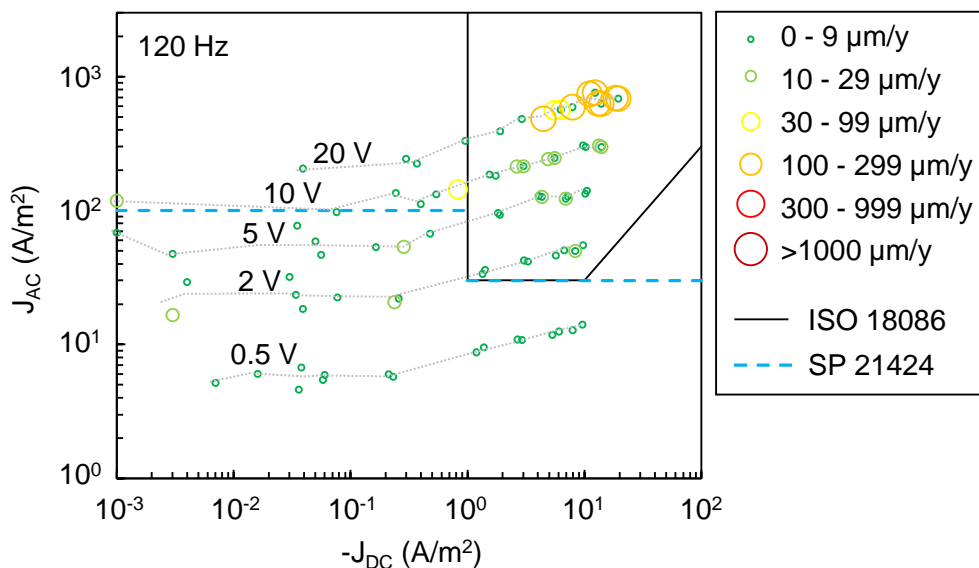


Figure 5: AC/DC current density plot with corrosion rates at 120 Hz AC interference. The investigated AC and DC levels were $U_{AC} = 0.5 - 20 \text{ V}$ and $E_{ON} = -900 - -1600 \text{ mV}_{CSE}$.

The result of the simple experiment, in which the AC interference level was set as high as 34.2 V (60 Hz), is shown in Figure 6. Despite an AC current density of $J_{AC} = 400 \text{ A/m}^2$, only 1.6 $\mu\text{m/y}$ corrosion is recorded by doing a linear regression of the measured thickness data. The explanation for this lies in the moderate CP level applied. The ON-potential was set at -1 V_{CSE} and the IR-free potential was measured continuously at -960 mV_{CSE} . This CP setting yielded a DC current density of -0.36 A/m^2 on average, well below the -1 A/m^2 limit.^{1,15} The experimental period in the experiment was two weeks. This longer duration of the test was

done to minimize the error on the linear regression as well as to rule out the possibility that any effects of polarization could affect the corrosion rate measurement.

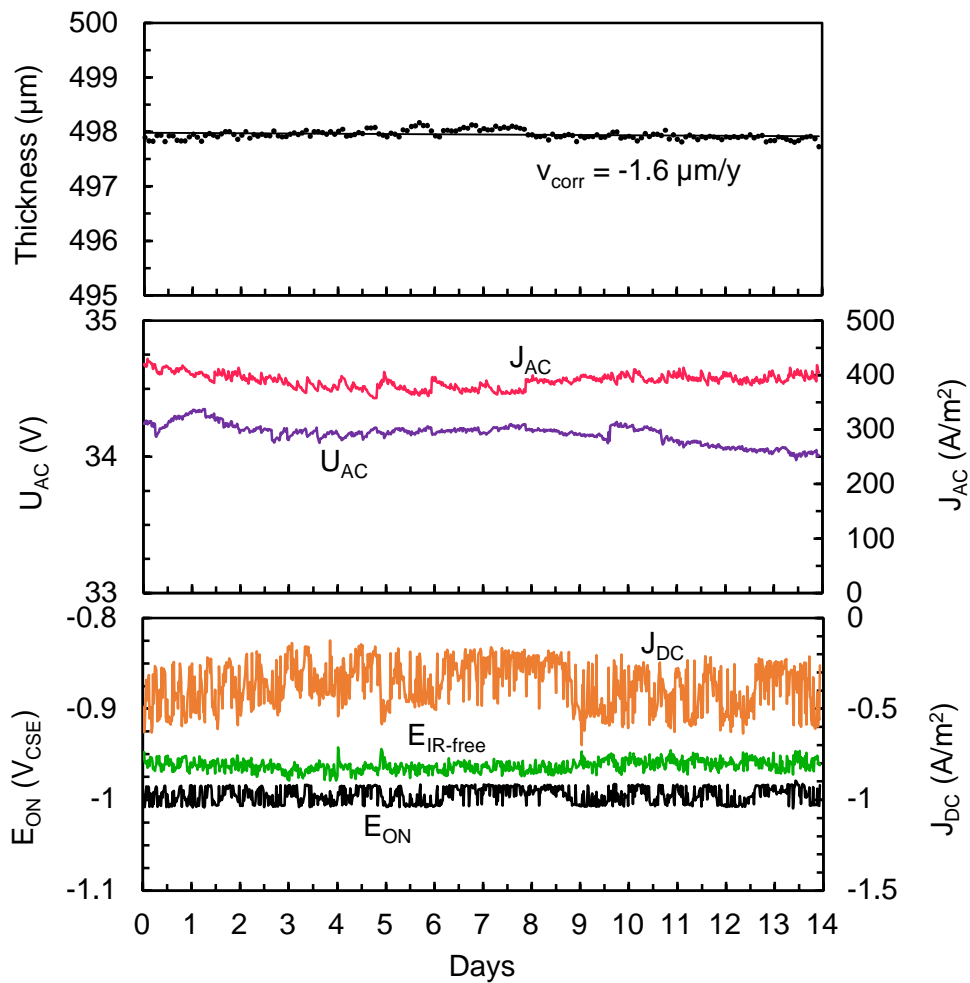


Figure 6: Measurements of thickness and corrosion rate, as well as AC and DC parameters on an ER probe subject to 34.2 V AC (60 Hz) and moderate cathodic protection. Even with a high AC level, corrosion is negligible due to the controlled CP current density.

Discussion

With the presented results in this paper, the strong dependency of frequency on AC corrosion has been confirmed by simple corrosion experiments. Moreover, it has been confirmed that the cathodic protection level has a large influence on AC corrosion under cathodic protection – also at other frequencies. The explanation for this is linked to (at least) two factors:

1. As others have also suggested, the impedance of the electrochemical double layer capacitance increases with lower frequencies, forcing a larger fraction of the alternating charge to pass via charge transfer reactions (electrochemical) at the steel/electrolyte interface, i.e. as iron dissolution during the anodic half-wave of the alternating current.
2. According to the Pourbaix diagram for steel, corrosion is thermodynamically possible in a narrow potential range around the hydrogen line at high pH. The cyclic oscillation of the steel in and out of this range causes the steel to corrode in a continuous manner.^{8,16,17} At lower frequencies the cyclic movement will be slower, and the steel will spend more continuous time in the corrosive region which will allow for some

reactions to occur that would have otherwise been limited by the kinetics, and vice versa for higher frequencies.

It has been demonstrated in several of the experiments herein, that AC corrosion can be mitigated by moderating the CP level (*Figure 3-Figure 6*). The reason for the effectiveness of this strategy is, that the corrosive potential range only exists at a high pH level (> 12) which roughly corresponds to a DC current density of $-J_{DC} > 1 \text{ A/m}^2$.¹⁸ By moderating the CP level, the pH is not allowed to elevate beyond 12 and the steel will not reach the corrosive domain in the Pourbaix diagram. The fact that moderate CP can be used to mitigate low frequency AC corrosion supports the explanation in point 2 above, since corrosion caused exclusively by the mechanism described in point 1 would be possible independently of the pH (perhaps except for the effect of lowering the solution spread resistance and increasing the AC current density). Oppositely, if the mechanism described in point 1 was the only mechanism in play, then increasing the cathodic protection current would contribute to mitigation of the corrosion.

Conclusions

The conclusions of this laboratory investigation of AC corrosion at different AC levels, cathodic protection levels and AC frequencies can be summarized as follows:

- AC corrosion is strongly affected by the AC frequency. As expected from a literature review on the topic, it was confirmed that corrosion rates increase with lower frequencies. This is due to a larger fraction of the alternating current being faradaic (charge transfer) and thus associated with corrosion. It is also anticipated that at lower frequencies, the steel is being cycled through the corrosive domain of the Pourbaix diagram at a lower rate, thus allowing for some corrosion processes to take place that would have otherwise been limited by the kinetics of the reactions.
- It is confirmed that the AC current density is an important parameter for AC corrosion, but this parameter cannot be addressed individually without also considering the DC current density acting on a coupon or coating damage from the cathodic protection system.
- It has been demonstrated that AC corrosion can be mitigated by applying moderate cathodic protection where the cathodic current density is limited to $< 1 \text{ A/m}^2$ as described in the ISO 18086 standard. This appears to be true for all investigated frequencies: 16.6-360 Hz.
- Mitigation of AC corrosion at frequencies of 60 Hz and higher has been demonstrated by application of moderate CP for the entire investigated AC interference range (0.5-20 V) (*Figure 3*).
- The effect of frequency on AC corrosion has been discussed in context of recent theories on AC corrosion.

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