Alternating Current Corrosion Likelihood of Cathodically Protected Steel Pipelines by Analyzing Coupon Current for a Single Period

Dr. Fumio Kajiyama
Tokyo Gas Co., Ltd., 5-20, Kaigan, 1-Chome, Minato-ku, Tokyo, 105-8527, Japan

Abstract

Over the last three decades, coupons have been used to determine the cathodic protection level of a pipeline affected by a.c. interference. Coupon a.c. current density with commercial frequency as well as coupon instant off-potential is the primary determining factor in evaluating the a.c. corrosion risk of cathodically protected steel pipelines. Regarding coupon current for a single period, polarity, the difference in appearance time between the maximum and the minimum values, and distortion factor for a wave form should be taken into account when ascertaining the consistency with the coupon a.c. current with commercial frequency.

In this paper, particular emphasis is placed on the evaluation method of the a.c. corrosion likelihood of cathodically protected steel pipelines by analyzing coupon current for a single period measured at intervals of 0,1 ms with 16 bits.

Beurteilung der Wahrscheinlichkeit von Wechselstromkorrosion an kathodisch geschützten Stahlrohren durch die Analyse des Stroms in einem Coupon für einen bestimmten Zeitraum

Dr. Fumio Kajiyama
Tokyo Gas Co., Ltd., 5-20, Kaigan, 1-Chome, Minato-ku, Tokio, 105-8527, Japan

Zusammenfassung

In den letzten drei Jahzehnten wurden Coupons verwendet, um den kathodischen Schutzumfang einer Pipeline zu bestimmten, die einer Wechselstrominteferenz unterliegt. Die Wechselstrom-Stromdichte in Coupons bei üblichen kommerziellen

Frequenzen sowie das “Instant Off Potential” von Coupons sind die wichtigsten Bestimmungsfaktoren bei der Beurteilung des Wechselstromkorrosionsriskos bei kathodisch geschützten Stahlrohren. Was den Coupon-Strom in einem bestimmten Zeitaum betrifft, sollten die Polarität, der Unterschied des Erscheinungszeitpunkts zwischen höchstem und niedrigstem Wert sowie der Verzerrungsfaktor für eine Wellenform berücksichtigt werden, wenn man prüft, ob der Wechselstrom in einem Coupon mit den üblichen kommerziellen Frequenzen konsistent ist.

In dieser Arbeit geht es insbesondere um die Beurteilungsmethode für die Wahrscheinlichkeit von Wechselstromkorrosion bei kathodisch geschützten Stahlrohren, wenn der Strom in einem Coupon für einen bestimmten Zeitraum in Abständen von 0,1 ms mit 16 Bits gemessen wird.

Probabilité de corrosion par courant alternatif sur les canalisations en acier dotées d’un système de protection cathodique en analysant le courant du coupon pour une seule période

Dr. Fumio Kajiyama
Tokyo Gas Co., Ltd., 5-20, Kaigan, 1-Chome, Minato-ku, Tokyo, 105-8527, Japon

Résumé

Ces trente dernières années, les coupons ont été utilisés pour déterminer le niveau de protection cathodique d’une canalisation affectée par des interférences CA. La densité du courant alternatif du coupon avec fréquence commerciale ainsi que le potentiel hors charge ponctuel constituent le principal facteur déterminant dans l’évaluation du risque de corrosion par courant alternatif de canalisations en acier dotées d’une protection cathodique. En ce qui concerne le courant du coupon pour une seule période, la polarité, la différence au niveau du temps d’apparition entre la valeur maximale et minimale et le facteur de distorsion pour une forme d’onde doivent être pris en compte lors de la vérification de la concordance entre le courant alternatif du coupon et la fréquence commerciale.

Dans le présent document, une attention particulière a été accordée à la méthode d’évaluation de la probabilité de corrosion par CA de canalisations en acier dotées d’une protection cathodique en analysant le courant des coupons pour une seule période, mesuré à des intervalles de 0,1 ms avec 16 bits.

1 Current status of a.c. corrosion

It is widely recognized that at prevailing commercial current frequencies (such as 16-2/3, 50 or 60 Hz) a.c. corrosion is possible, even though cathodic protection level satisfies the ISO standard based on polarized potential. At present, however, there is no consensus about the a.c. corrosion mechanism and a.c. corrosion protection criterion for cathodically protected steel pipelines. Although there is a controversy about the opinion that the a.c. current density is the primary factor in determining the a.c. corrosion likelihood [1-2], d.c. and a.c. current densities as well as polarized potential are responsible for the corrosion process [3-4]. Over the last three decades, coupons have been used to evaluate the a.c. corrosion likelihood of cathodically protected steel pipelines. If coupon a.c. current density is used for evaluation, it is very important to ascertain that the coupon a.c. current density is that affects a.c. corrosion.

2 Terms and definitions

The terms and definitions used in this paper are given as described below.
This paper deals with the a.c. corrosion likelihood of cathodically protected steel pipelines at frequency of 50 Hz.

Coupon potential, $E_{on}(t)$ or $E_{off}(t)$: The coupon-to-electrolyte potential measured regardless of an electric on or off-status between the coupon and the pipe.

Coupon on-potential, E_{on}: The coupon potential measured while the coupon is being connected to the pipe with the cathodic protection applied.

Coupon instant-off potential, E_{off}: The coupon potential measured immediately after the coupon is disconnected from the pipe, which closely approximates the potential without IR drop from the protection current and any other current such as a.c. interference current (i.e., the polarized potential).

Coupon current, $I(t)$: The current obtained at intervals of 0,1 ms which flows between the coupon and the pipe while the cathodic protection system is continuously operating. Positive values in coupon current indicate the current flowing through electrolyte to the coupon (i.e., cathodic current flowing).

Coupon d.c. current density, $I_{d.c.}$: Using coupon current $I(t)$ for a single period of 50 Hz (i.e., each subunit), the coupon d.c. current density $I_{d.c.}$ is obtained by calculating eq. (3).

Coupon a.c. current density, $I_{a.c.}$: Using coupon current $I(t)$ and coupon d.c. current density $I_{d.c.}$, the coupon a.c. current density $I_{a.c.}$ is obtained by calculating eq. (4).

$$E_{on} = \frac{1}{200}\sum_{t=1}^{200} E_{on}(t) \tag{1}$$

$$E_{off} = \frac{1}{200}\sum_{t=800}^{1000} E_{off}(t) \tag{2}$$

$$I_{d.c.} = \frac{1}{A}\cdot\frac{1}{200}\sum_{t=1}^{200} I(t) \tag{3}$$

$$I_{a.c.} = \frac{1}{A}\cdot\sqrt{\frac{1}{200}\sum_{t=1}^{200}\{I(t) - A\cdot I_{d.c}\}^2} \tag{4}$$

where:

$E_{on}(t)$ = coupon potential at t ms in each subunit while the coupon is being connected to the pipe
$E_{off}(t)$ = coupon potential after disconnecting the coupon from the pipe in each subunit
A = surface area of a coupon
$I(t)$ = coupon current at t ms in each subunit

Distortion factor: The degree of the distortion of the obtained wave form compared to sine wave for a period of commercial frequency

| [(coupon d.c. current density) — {(the maximum coupon current density) — (the minimum coupon current density)}/2]/{(the maximum coupon current density) — (the minimum coupon current density)} |

3 ISO/DIS 18086 Determination of AC corrosion — Protection criteria

Draft international standard ISO/DIS 18086 offers the acceptable interference levels as below:

– As a first step, the a.c. voltage on the pipeline should be decreased to a target value, which should be 15 V rms or less. This value is measured as an average over a representative period of time (e.g. 24h).

and

– As a second step, effective a.c. corrosion mitigation can be achieved by meeting the cathodic protection potentials in ISO 15589-1, Table 1 [5],

and

– maintaining the a.c. current density (rms) over a representative period of time (e.g. 24h) to be lower than 30 A/m^2 on a 1 cm^2 coupon or probe

or

– maintaining the ratio between a.c. current density ($J_{a.c.}$) and d.c. current density ($J_{d.c.}$) less than 5 over a representative period of time (e.g. 24h).

4 Procedure for the acquisition of the parameters

The evaluation of a.c. corrosion likelihood of a cathodically protected steel pipeline was performed by evaluation of the following parameters:

– coupon on-potential,
– coupon instant-off potential,
– coupon d.c. current density,
– coupon a.c. current density.

Figure 1 shows measuring system for coupon potential and coupon current. Measurements were made by using a developed instrumentation by the authors [6]. Coupon potentials and coupon currents were measured with resolution of 16 bits at intervals of 0,1 ms. A low pass filter with a cut-off frequency of 73 Hz was used to avoid abnormal electrical spike and harmonic components. Coupon currents were measured by the voltage drop across a shunt resistor with 0,1 ohm so that significant disturbance of the system could be avoided. On or off-status between the coupon and the pipe was created by operating a solid state relay.

Table 2 shows the schematic representation of measurement on coupon on-potential E_{on}, coupon instant-off potential E_{off}, coupon d.c. current density $I_{d.c.}$, and coupon. a.c.

current density $I_{a.c.}$ at frequency of 50 Hz for a period of 24 hours.
A steel coupon was installed with a saturated copper/copper sulfate reference electrode (CSE) in a monitoring station. Therefore, as the distance from the pipeline to the reference electrode was not long, the reference electrode location might not be considered as remote earth. However, coupon on potential E_{on} is approximate the a.c. voltage on the pipeline.

The detailed description of the acquisition of the parameters is given in [7].

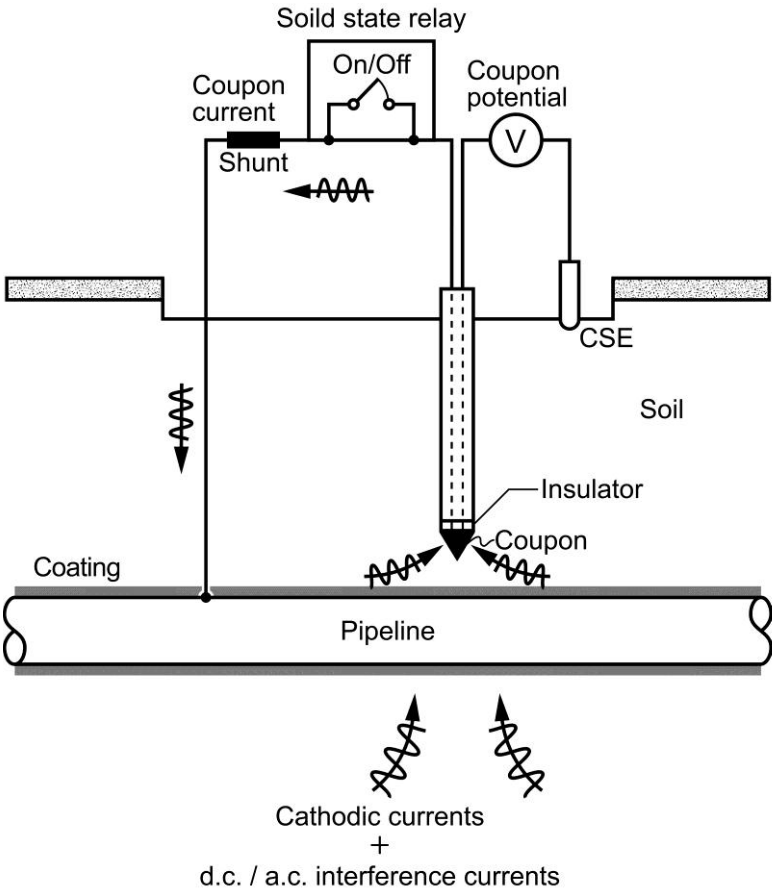

Figure 1 — Measuring system for coupon potential and coupon current

The following should be considered when acquiring the coupon instant-off potential:

- As there may be transient phenomena in the coupon potential reading due to low pass filter effects of an instrumentation immediately after disconnecting the coupon from the pipe, the coupon instant-off potential should be acquired by using coupon potentials after these transient phenomena;
- Time for off-status between the coupon and the pipe shall be as short as possible not to disturb the cathodic protection system;
- If coupon potentials oscillate with commercial frequency even though the coupon is disconnected from the pipe, the mean coupon potential for a single period of commercial current frequency as the coupon instant-off potential should be acquired to eliminate a.c. interference effects on the coupon.

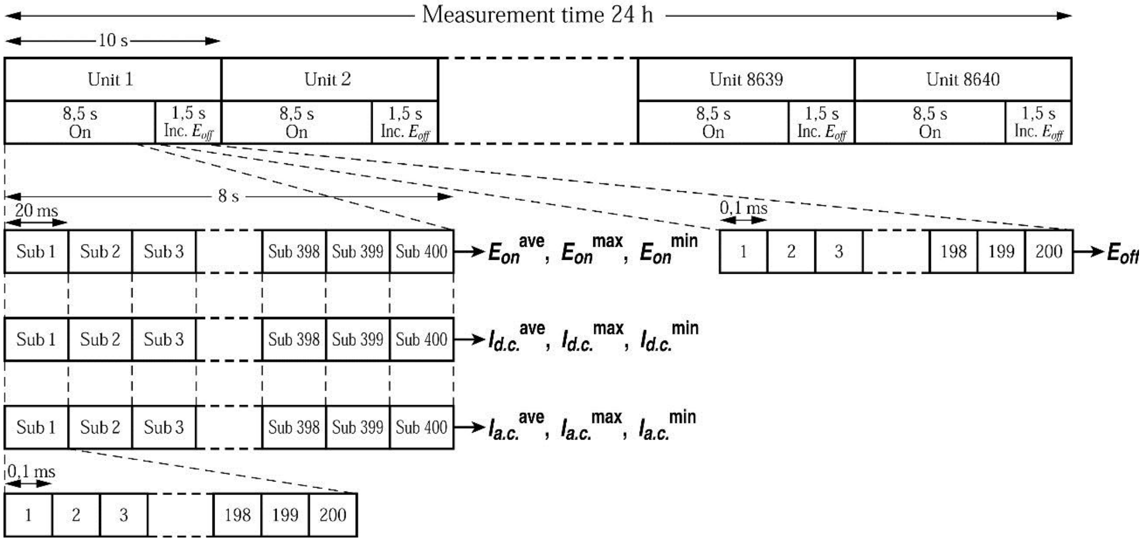

Figure 2 — The schematic representation of measurement on coupon on-potential E_{on}, coupon instant-off potential $E_{off,}$ coupon d.c. current density $I_{d.c.}$, and coupon a.c. current density $I_{a.c.}$ at frequency of 50 Hz

5 Field study on the cathodically protected steel pipeline under a.c. interference

The coupon was connected to the polyethylene coated 400 mm diameter gas pipeline paralleling a 25 kV a.c. traction system which operated at frequency of 50 Hz with great acceleration, high speed and long trains (250 m). The steel coupon was installed in the monitoring station where the a.c. current density reached its maximum. The a.c. transit system did not operate after midnight until early morning (around 0:00 - 6:00). High speed a.c. trains passed the monitoring station every several minutes at the rate of 150 to 200 kilometers per hour. Parameters given in **4** at the coupon were acquired.

6 Results and discussion

6.1 Coupon on-potential and coupon instant-off potential

Figure 3 (above) shows the coupon potential variations in accordance with on or off-status between the coupon and the pipe when the a.c. transit system was in operation (around 12:00). The section between time 0 and 100 ms is magnified as shown in Figure 3 (below).

When the coupon was being connected to the pipe (coupon/pipe on-status), coupon potential, that is, coupon on-potential, with the sinusoidal frequency of 50 Hz consistent with the a.c. transit system frequency was observed.

Immediately after disconnecting the coupon from the pipe at a time 0, there were transient phenomena due to low pass filter effects of the instrumentation followed by cathodic depolarization. After the coupon was connected to the pipe again at a time 100 ms, the coupon potential returned to the value of 1,65 V rms, that is, the a.c.

voltage on the pipeline in coupon/pipe on-status.

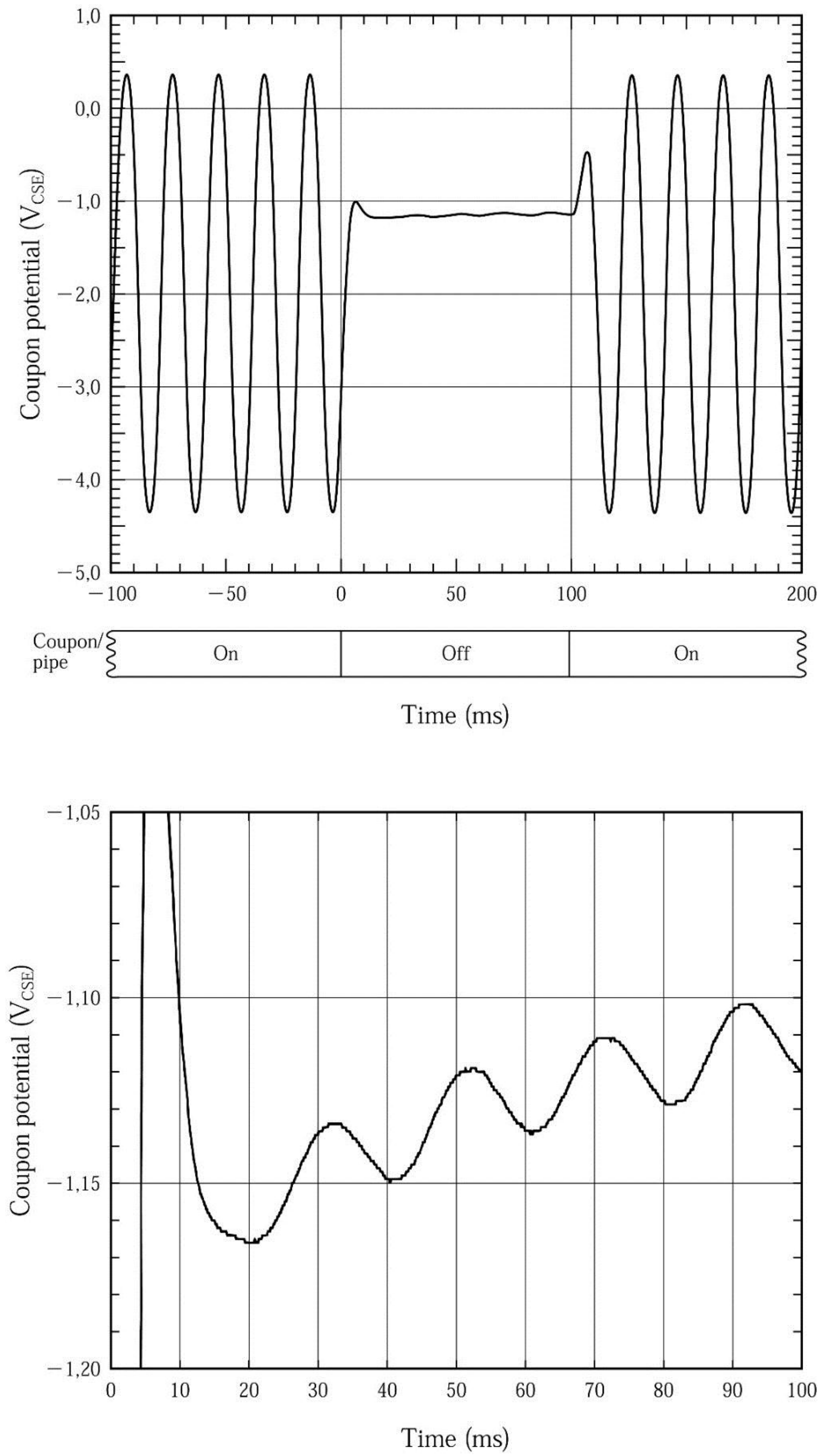

Figure 3 — The coupon potential variations in accordance with on or off-status between the coupon and the pipe when the a.c. transit system was in operation around 12:00 (see chart above) and the magnification of the section between time 0 and 100 ms in the above chart (see chart below)

6.2 Coupon potential and coupon d.c. and a.c. current densities

Figure 4 shows the data on coupon potentials, coupon d.c. current densities, and coupon a.c. current densities over 24 hours in December 2013.

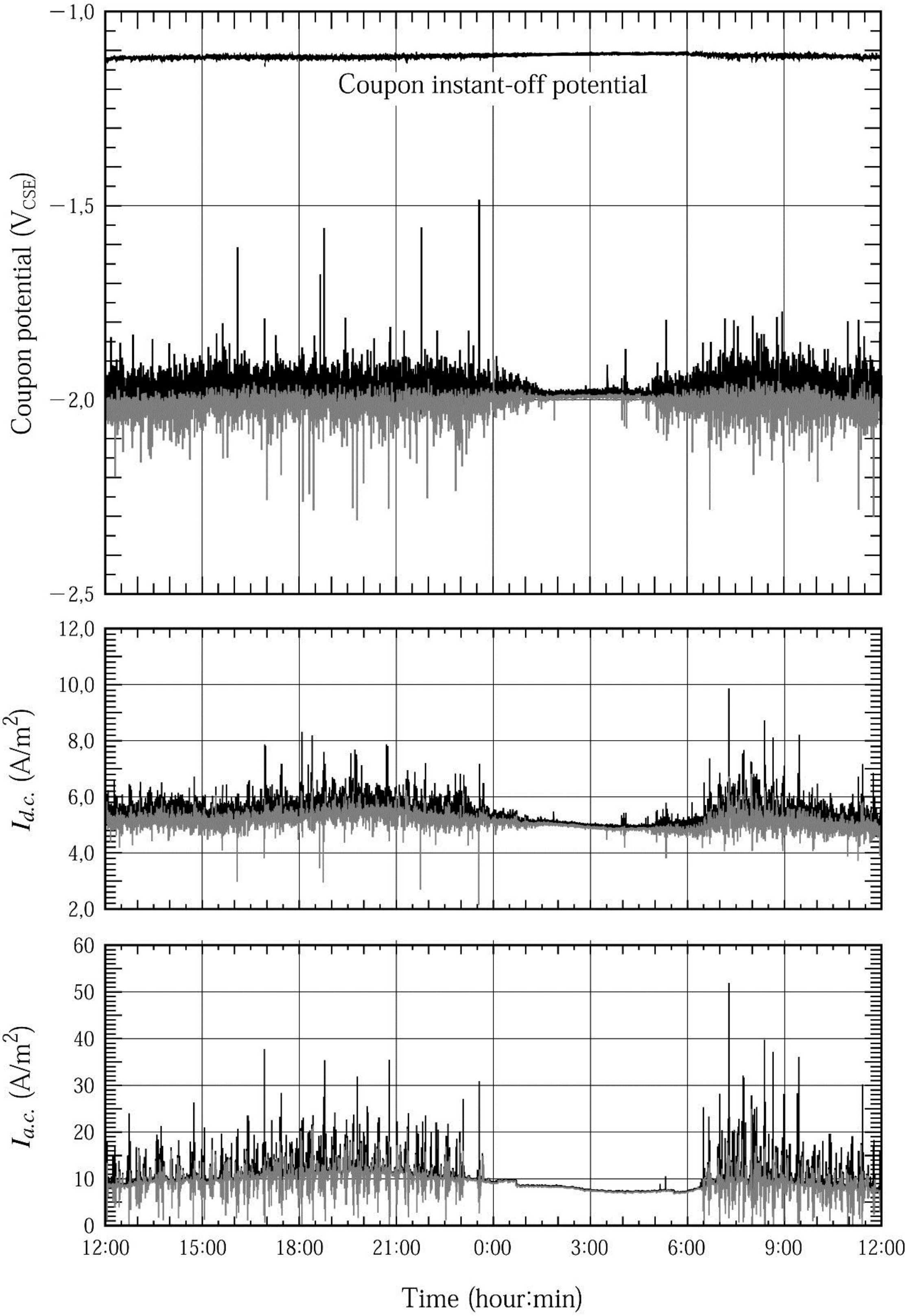

Figure 4 — The data on coupon potentials, coupon d.c. current densities and coupon a.c. current densities over 24 hours

Summary data are shown in Table 1.

Table 1 – Results of on-potential E_{on}, instant-off potential E_{off}, d.c. current density $I_{d.c.}$, and a.c. current density $I_{a.c.}$ at a coupon over 24 hours in December 2013

Coupon on-potential E_{on} (V_{CSE})	Average	Average	−1,984
		Maximum	−1,912
		Minimum	−2,083
	Maximum	Average	−1,962
		Maximum	−1,482
		Minimum	−2,069
	Minimum	Average	−2,008
		Maximum	−1,933
		Minimum	−2,307
Coupon instant-off potential E_{off} (V_{CSE})		Average	−1.111
		Maximum	−1.095
		Minimum	−1.140
Coupon d.c. current density $I_{d.c.}$ (A/m^2)	Average	Average	5.35
		Maximum	8.75
		Minimum	4.76
	Maximum	Average	5.52
		Maximum	9.98
		Minimum	4.86
	Minimum	Average	5.20
		Maximum	6.95
		Minimum	2.25
Coupon a.c. current density $I_{a.c.}$ (A/m^2)	Average	Average	9.90
		Maximum	37.51
		Minimum	1.47
	Maximum	Average	10.52
		Maximum	52.42
		Minimum	1.80
	Minimum	Average	9.32
		Maximum	25.63
		Minimum	0.09

The evaluation of a.c. corrosion likelihood was done on the basis of ISO/DIS 18086.

The results obtained from the measurement as follows:

1) Coupon on-potential exhibited marked variations between –2,307 and –1.482 V_{CSE}. As mentioned in **6.1**, the a.c. voltage on the pipeline was 1,65 V rms.
2) Coupon instant-of potential, meanwhile, maintained stable values of –1,140 to –1,095 V_{CSE} with very small standard deviation of 0,006 over a period of 24 hours. Average coupon instant-off potential of –1,111 V_{CSE} met ISO 15589-1.
3) Very marked and quick coupon a.c. current density variations between 0,09 and 52,42 A/m^2 were observed over 24 hours. Average coupon a.c. current density was 9,90 A/m^2 lower than 30 A/m^2 satisfying ISO/DIS 18086.

4) The ratio between average coupon a.c. current density $I_{a.c.}$ and average coupon d.c. current density $I_{d.c.}$, $I_{a.c.}/I_{d.c.}$ was 1,9(=9,90/5,35) less than 3, thus met ISO/DIS 18086.

The above-mentioned results indicated that the pipeline had low risk of a.c. corrosion.

6.3 Coupon current density for a single period of 50 Hz

Figure 5 shows two wave forms for the maximum $I_{a.c.}^{max}$ of 52,42 A/m^2 and the minimum $I_{d.c.}^{min}$ of 2,25 A/m^2 ($I_{a.c.}$ 8,27 A/m^2) in measurement time, respectively. The data regarding the two wave forms are shown in Table 2.

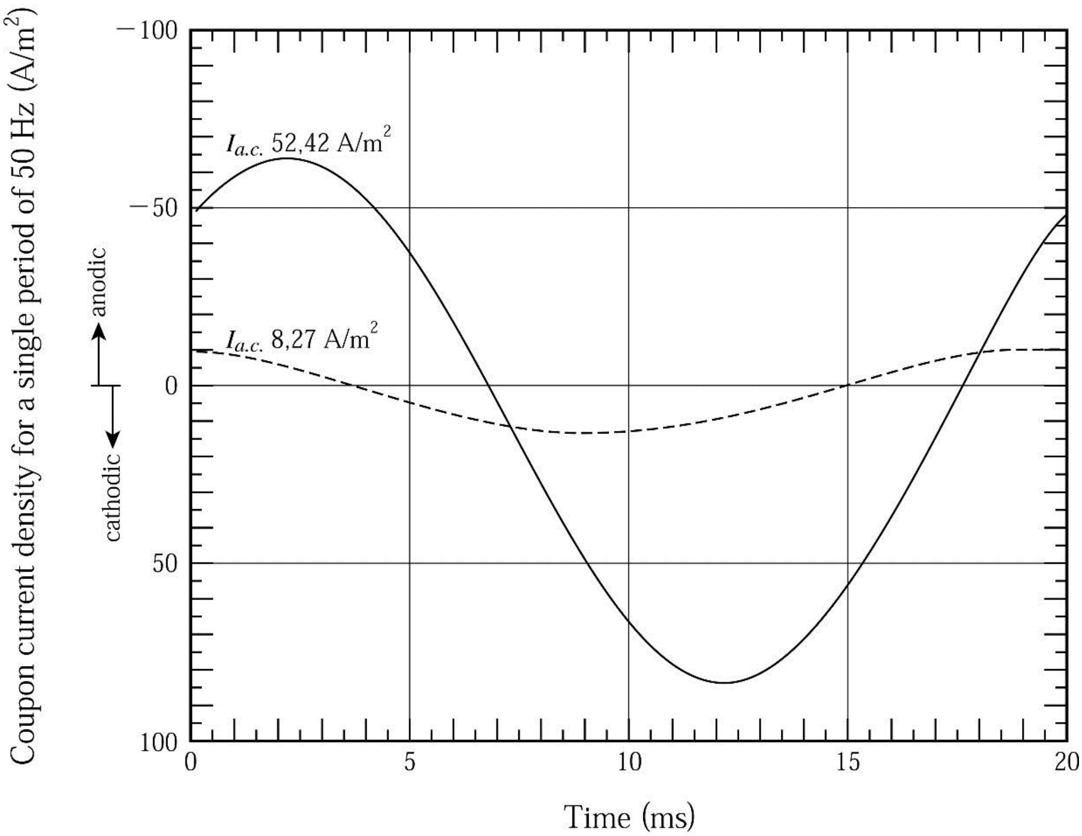

Figure 5 — The two wave forms for the maximum coupon a.c. current density (a solid line) and the minimum coupon d.c. current density (a dotted line) for a single period of 50 Hz

Table 2 – Data on the maximum of $I_{a.c.}^{max}$ and the minimum of $I_{d.c.}^{min}$ for a single period of 50 Hz over 24 hours in December 2013

	Maximum of $I_{a.c.}^{max}$	Minimum of $I_{d.c.}^{min}$
$I_{d.c.}$ (A/m^2)	9,85	2,25
$I_{a.c.}$ (A/m^2)	52,42	8,27
Average of anodic current density（A/m^2）	41,06	6,31
Average of cathodic current density（A/m^2）	53,22	8,72
Anodic current periods of time（ms）	92	86
Cathodic current periods of time (ms）	108	114
Difference in appearance time between the maximum and the minimum values for a single period of 50 Hz (ms)	10,1	10,0
Distortion factor	0,03	0,24

The following results were drawn from Figure 5 and Table 2.

1) The wave forms were asymmetry for the positive (cathodic) and negative (anodic) half-cycle, indicating that the extent of polarization in the cathodic direction was larger than in the anodic.
2) A time period of cathodic currents was slightly longer than that of anodic currents.
3) The difference in appearance time between the maximum and the minimum for a single period of 50 Hz was within 10,0 ± 1,0 ms for the two wave form.
4) Larger the coupon a.c. current density, smaller the distortion factor was observed. Distortion factor of the wave form with coupon a.c. current density of 52,42 A/m^2 was 0,03, suggesting that the wave form was sine wave without distortion.

The process of a.c. corrosion may involve anodic and cathodic reactions. The existence of anodic and cathodic currents is proof that the oxidation and reduction reactions occurred by their currents on the same surface. During the anodic half-cycle the steel surface is oxidized by the anodic current according to reaction (5), resulting in the formation of the passive film Fe_3O_4. Subsequently during the cathodic half-cycle the passive film is cathodically polarized presumably by reaction (6), leading to the destruction of passivity by the reduction of the passive film.

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 8H^+ + 8e^- \quad (5)$$

$$Fe_3O_4 + 8H^+ + 2e^- \rightarrow 3Fe^{2+} + 4H_2O \quad (6)$$

As mentioned earlier, the extent of polarization in the cathodic direction is larger than in the anodic, indicating that the steel surface does not have sufficient time to reform passivity. The Fe^{2+} ions produced by the reduction of the passive film Fe_3O_4 tend to form $Fe(OH)_2$ as pH value increases.

Feller and Rückert studied the influence of alternating current on the electrochemical behavior of nickel in 1 n-H_2SO_4. A 1967 report by Feller and Rückert point out that the passivating film is reduced in the cathodic half period of the alternating current and that the metal dissolves actively in the following anodic half period before the surface is covered by a passivating layer [8].

At all events the steel surface gradually roughens. If Fe on the steel surface locally appears at very alkaline pH, the dissolved $HFeO_2^-$ is formed according to the anodic reaction (7), leading to cause corrosion of steel.

$$Fe + 2H_2O \rightarrow HFeO_2^- + 3H^+ + 2e^- \qquad (7)$$

Figure 6 shows the Pourbaix diagram for iron [9]. It should be noted that the coupon instant-off potential of –1,1 V_{CSE} obtained by this field study is at a potential below the equilibrium potential for the hydrogen evolution reaction at pH's below about 13.

From the thermodynamic point of view, potential oscillations between immunity (Fe) and passivity (Fe_3O_4) domains at very alkaline pH of Pourbaix diagram (Figure 6, ③ line) may cause corrosion as the result of the destruction of passivity by the cathodic reaction (6) and the formation of dissolved $HFeO_2^-$ by the anodic reaction (7).

Taking the process into account, polarity reversal in coupon current for a single period can be linked with the a.c. corrosion likelihood. From the results and speculation, coupon a.c. current density obtained from this field work can be regarded as that affecting a.c. corrosion.

Based on the above-mentioned speculation, the requirements to regard the coupon a.c. current density for a single period of commercial frequency as that affecting a.c. corrosion are:

i) polarity reversal;
ii) consistency with commercial current frequency;
iii) small distortion factor.

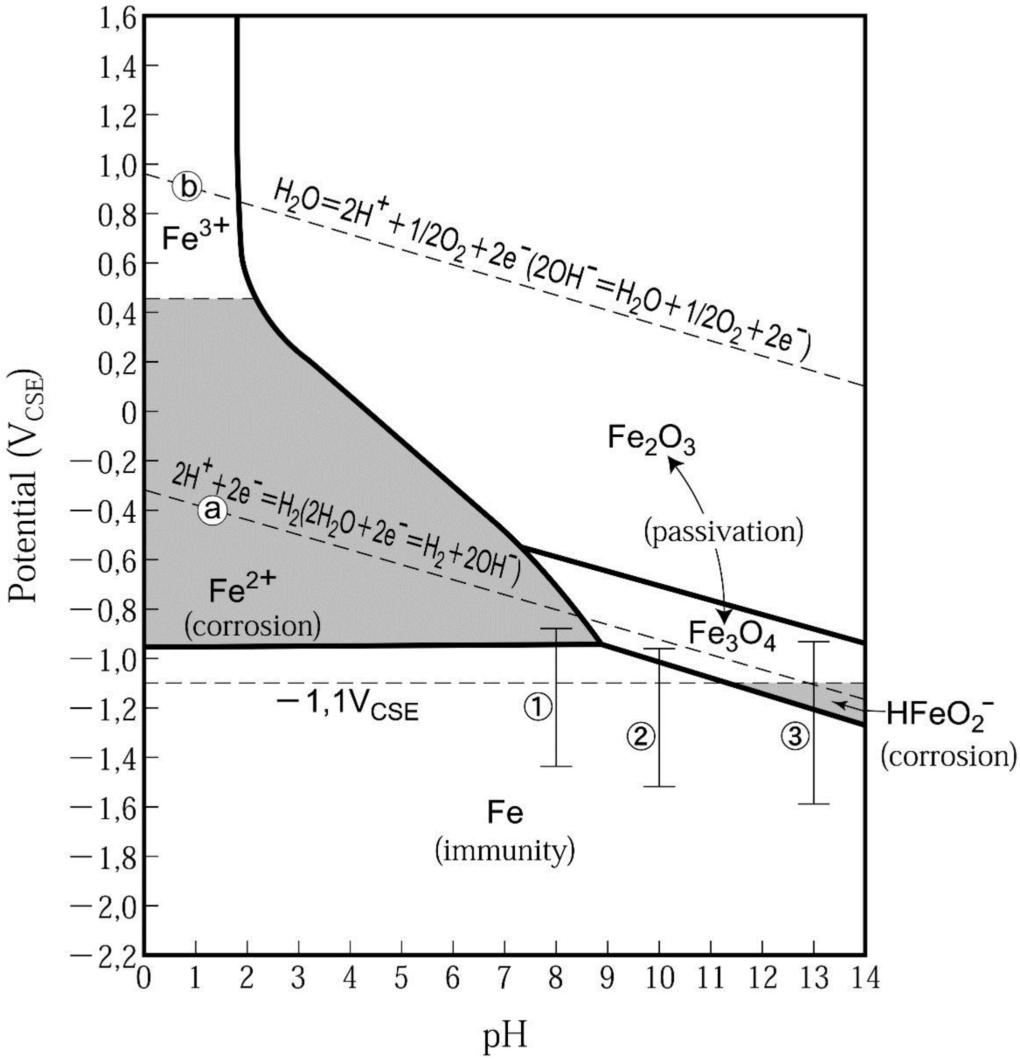

Figure 6 — Pourbaix diagram for iron

6.4 Correlation between d.c. current density and a.c. current density at a coupon

The plot in Figure 7 illustrates correlation between the calculated average coupon d.c. current density $I_{d.c.}^{ave}$ and the actual observed maximum coupon a.c. current density $I_{a.c.}^{max}$. The correlation has been made throughout 8640 units. The maximum coupon a.c. current density increased proportionately with increased the average coupon d.c. current density as found by Büchler [10]. In the case of cathodically protected natural gas transmission pipelines, the steel pipes are under a sustained tensile stress in the circumferential directions by the internal gas pressure, and atomic hydrogen is continuously deposited on the steel surface from the cathodic protection. Therefore, the hydrogen embrittlement risk occurs as a possible problem. Furthermore, a natural gas transmission pipeline is under induced high a.c. voltage at a substantial cathodic protection current, a.c. corrosion can occur in addition to hydrogen embrittlement by the formation of hydrogen and $HFeO_2^-$ due to enhanced cathodic reaction ($2H_2O$ + $2e^-$ → 2H (H_2) + $2OH^-$).

Nielsen indicates that excessive CP increases the AC corrosion rate and should therefore be avoided [11]. The author advocates Nielsen’s report.

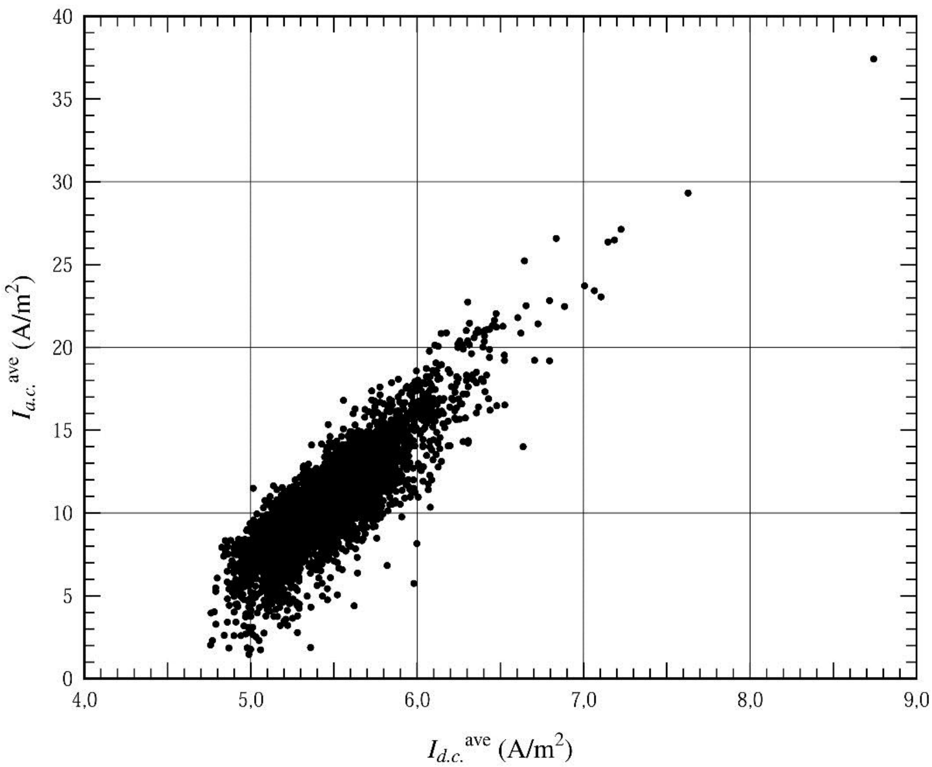

Figure 7 — Correlation between the calculated average coupon d.c. current density $I_{d.c.}^{ave}$ and the actual observed maximum coupon a.c. current density $I_{a.c.}^{max}$

7 Conclusions

Based on the analyses of field work data obtained by coupon technology with high data sampling rate of 0,1 ms, the following conclusions are made.

— If coupon a.c. current density is used to evaluate the a.c. corrosion likelihood, it is very important to ascertain that the coupon a.c. current density is that affects a.c. corrosion at commercial frequency.
The requirements to regard the coupon a.c. current density for a single period of commercial current frequency as affecting a.c. corrosion are:
i) polarity reversal;
ii) consistency with commercial current frequency;
iii) small distortion factor of a wave form.

— The maximum coupon a.c. current density increased proportionately with increased the average coupon d.c. current density. This suggests that high a.c. current density, together with high d.c. current density, at holidays on cathodically protected natural gas transmission pipelines increases the risks of hydrogen embrittlement and a.c. corrosion by the formation of hydrogen and $HFeO_2^-$ due to enhanced cathodic reaction ($2H_2O + 2e^- \rightarrow 2H\ (H_2) + 2OH^-$).

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