Risk assessment of fluctuating stray current interference on buried steel pipelines with cathodic protection applied

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Abstract

BS EN 50162:2004 states the usefulness of current probes to assess fluctuating stray current interference on cathodically protected steel structures [1]. This paper provides risk assessment of combined d.c. and a.c. stray current interference on buried steel pipelines with cathodic protection applied using current probes as shown in BS EN 50162:2004. The most significant feature is data acquisition every 2 seconds on average, maximum, and minimum d.c. and a.c. probe current densities along with probe on- and instant-off potentials with data sampling rate of 0,1 ms. Presented measuring technique is extremely effective to assess fluctuating stray current interference due to operation of d.c. traction systems.

1 Sound assessment of the risk of fluctuating stray current interference

BS EN 50162:2004 presents that fluctuating stray current interference on cathodically protected structures arising from operation of d.c. traction systems can be assessed by the analysis of probe current variations with frequent polarity reversals during periods of stray current activity [1]. However, measuring method for probe d.c. current is not described. This paper offers measurement and consequent assessment methods for interference-related parameters, that is, probe d.c. and a.c. currents, probe on-potential, and probe instant-off potential by using a rapid response instrument. This technique offers assessment of fluctuating combined d.c. and a.c. stray current interference on cathodically protected structures simultaneously and continuously.

2 Terms and definitions

The terms and definitions used in this paper are given as described below.
E_{on} (t): Probe potential at t ms in each subunit (20 ms) while the probe is being connected to the pipe.

Probe on-potential, E_{on}: Using E_{on} (t) for a subunit, probe on-potential is obtained as per Equation (1).

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

Probe d.c. current density, $I_{d.c.}$: Using probe current I(t) for a single period of 50 Hz (i.e., each subunit), the probe d.c. current density $I_{d.c.}$ is obtained by calculating Equation (2).

Probe a.c. current density, $I_{a.c.}$: Using probe current I(t) and probe d.c. current density $I_{d.c.}$, the probe a.c. current density $I_{a.c.}$ is obtained by calculating Equation (3).

E_{off} (t): The probe-to-electrolyte potential measured between the probe and the pipe after disconnection of the probe from the pipe.

Probe instant-off potential, E_{off}: The probe potential measured immediately after the probe 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). Probe instant-off potential is obtained from averaging 200 data on E_{off} (t) during 80 to 100 ms after disconnecting the probe from the pipe according to Equation (4).

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

$$I_{d.c.} = \frac{1}{A}\cdot\frac{1}{200}\sum_{t=1}^{200} I(t) \quad (2)$$

$$I_{a.c.} = \frac{1}{A}\cdot\sqrt{\frac{1}{200}\sum_{t=1}^{200}\{I(t) - A\cdot I_{d.c}\}^2} \quad (3)$$

$$E_{off} = \frac{1}{200}\sum_{t=800}^{1000} E_{off}(t) \quad (4)$$

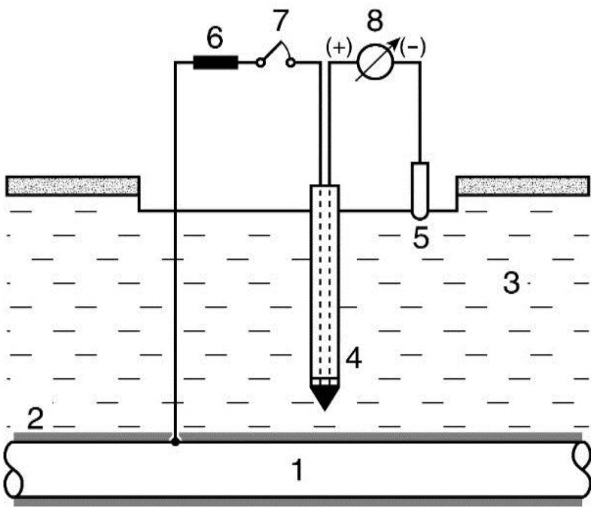
A: surface area of a probe

3 Procedure of measurement and assessment

To assess if the risk of fluctuating stray current interference on cathodically protected pipelines is to be accepted or not, one needs to go through five steps.

Step 1: **Measuring probe on- (including IR drop) and instant-off potentials along with currents for a period of 24 h**

Figure 1 shows a typical method for the measurement with a current probe [2]. The dark shading on the probe simulating a coating defect (surface area of 10 cm^2) was insulated from a rod. Current probes are installed in the monitoring stations where stray current interference is suspected.

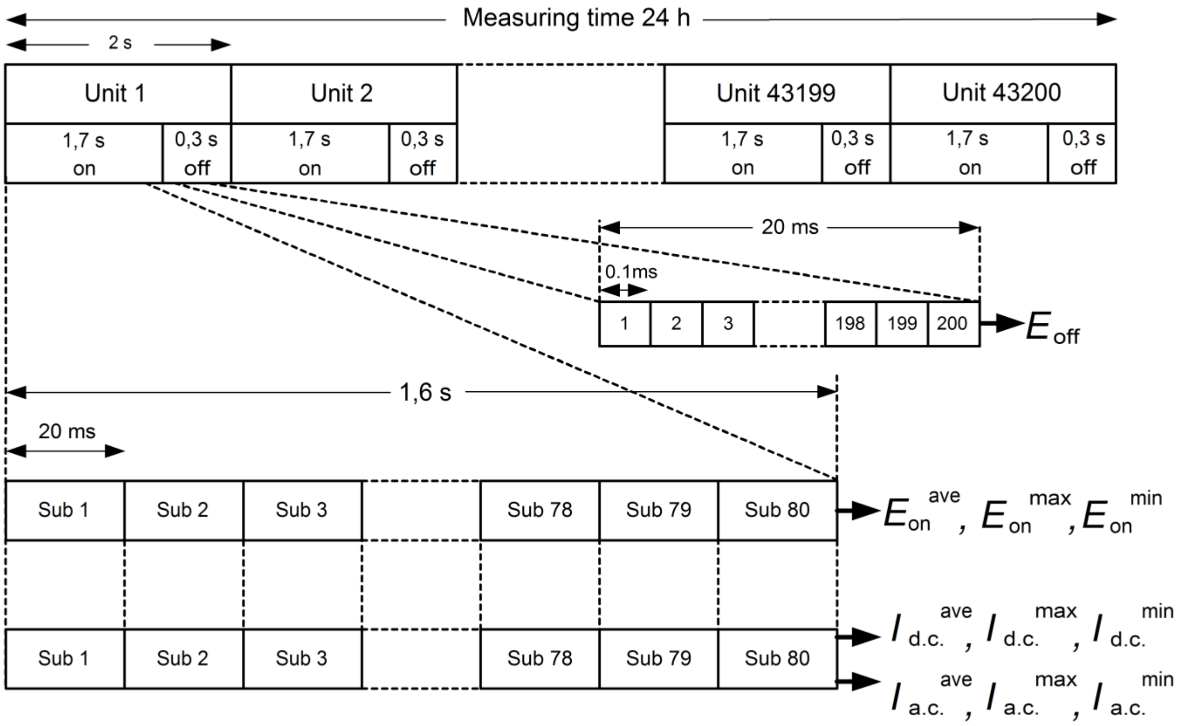


Key

1	pipeline	5	reference electrode
2	coating	6	shunt
3	soil	7	switch (normaly closed)
4	probe	8	voltmeter

Figure 1 — A typical method for the measurement with a current probe.

Figure 2 shows the schematic representation of acquisition of probe on-potentials E_{on}, probe d.c. current densities $I_{d.c.}$, probe a.c. current densities $I_{a.c.}$, and probe instant-off potentials E_{off} over 24 h.



Sub: subunit (20 ms)

Figure 2 — The schematic representation of acquisition of E_{on}, $I_{d.c.}$, $I_{a.c.}$, and E_{off} over 24 h.

The measurement is typically carried out during a period of 24 h. Measuring period of 24 h is comprised of 43200 units that have all the same 2 s with the probe/pipe on-state being 1,7 s and the probe/pipe off-state being 0,3 s. One unit has 80 subunits. Probe potentials and currents are measured with resolution of 16-bit at intervals of 0,1 ms. Measurements should be made by using a rapid response instrument. It is crucial to measure probe instant-off potential and current at very frequent intervals as shown in Figure 2.

Step 2: **Assessing the cathodic protection level by comparing probe instant-off potentials with ISO 15589-1:2015**

Regarding d.c. interference, ISO 15589-1:2015 states that, for cathodically protected pipelines, anodic shifts are acceptable provided that the cathodic protection criteria range is maintained [3]. Therefore, ensuring that satisfaction of cathodic protection criterion of polarized potential during periods of stray current activity is crucial.

Step 3: Identifying leaving currents

The third step is fairly straightforward; the leaving currents to be assessed are identified. The waveforms of the most positive probe on-potential and the minimum probe d.c. current density for the same subunit are stored.

Step 4: Calculating corrosion rate by Faraday's Law

All collected data on leaving currents should be used to calculate corrosion rate. Corrosion reaction is assumed to take place when leaving current is observed. It is a safe approach that applies Faraday's Law to calculation of corrosion rate. In the case where $I_{d.c.}^{min}$ is negative value denoted by $I_{d.c.}^{min}$(negative) and $I_{d.c.}^{ave}$ is positive in a unit, corrosion rate is obtained from the following Equations.

$$W = \{55,85 \times \Sigma(|I_{d.c.}^{min}(\text{negative})| \times 20 \times 10^{-3}) \times 365\} / (2 \times 96500) \quad (g)$$

$$d = (W/7,86) \times 10 \quad (\text{mm per year})$$

where

W	:	weight loss of steel per year (g)
55,85	:	atomic weight of iron
7,86	:	density of iron (g/cm^3)
96500	:	1 coulomb (1 A × s)

Step 5: Assessing the risk of fluctuating stray current interference

If the calculated corrosion rate is less than 0,01 mm per year according to ISO 15589-1:2015 [3], the risk of fluctuating stray current interference is negligible.

4 Field study on the cathodically protected steel pipeline under d.c. interference

In December 2016, field study was carried out on a polyethylene coated natural gas pipeline that crossed a 1,5 kV d.c. transit double-track line. Impressed cathodic protection system was applied to the pipeline. The probe was connected to the pipeline that was manufactured according to API 5L X60. The d.c.-electrified railway system did not operate after midnight until early morning (around 1:00 - 5:00 a.m.). The probe was installed in a monitoring station located close to the d.c. transit line. d.c.

trains transversed the buried pipeline every several minutes at a speed of 80 to 100 kilometers per hour.

5 Results and discussion

5.1 E_{on} and E_{off} along with $I_{d.c.}$ and $I_{a.c.}$

Figures 3 and 4 show the record of E_{on} and E_{off}, and $I_{d.c.}$ and $I_{a.c.}$, respectively.

From Figures 3 and 4, it is worthwhile to note that:

1) Probe instant-off potential was very stable between −1,336 and −1,229 V_{CSE} which satisfied ISO 155898-1:2015. The probe instant-off potential can have an adverse effect on the coating due to disbondment and/or blistering. To reduce this risk, periodic alternating current voltage gradient (ACVG) test is being implemented. In corrosion management program, mitigation of the leaving current level is a top priority.
2) The maximum $I_{a.c.}^{max}$ was 4,325 A/m^2, suggesting the a.c. interference level was acceptable.
3) There were significant variations between −2,728 and −0,896 V_{CSE} in E_{on} and −4,200 and 13,117 A/m^2 in $I_{d.c.}$, respectively that were the results of d.c.-electrified railway system loading changes. The pipeline was not interfered by fluctuating stray current at midnight.
4) Over 70 percent of the reference level (5,679 A/m^2) of $I_{d.c.}^{min}$, 3.975 A/m^2, was 96,5 percent as against 43200 units. (Regarding reference level, see 5.2.)

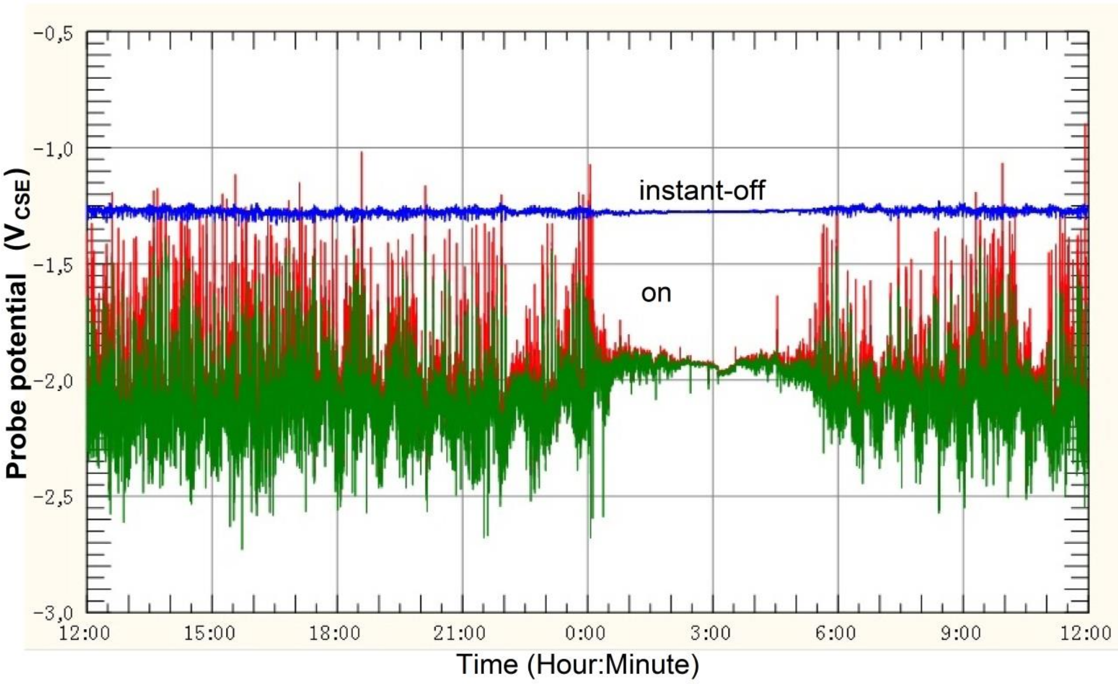


Figure 3 — Record of E_{on} and E_{off} during a period of 24h.

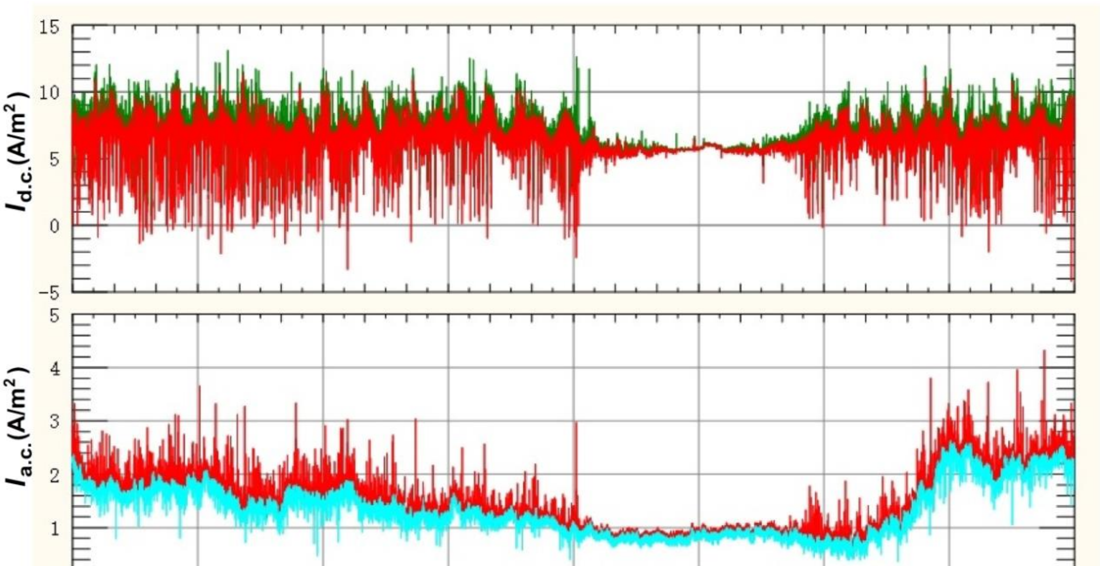


Figure 4 — Record of $I_{d.c.}$ and $I_{a.c.}$ during a period of 24 h.

5.2 E_{on}, E_{off}, and $I_{d.c.}$ during periods of no stray current activity

Table 1 shows E_{on}, E_{off}, and $I_{d.c.}$ during periods of no stray current activity (2:00 through 3:00 a. m.) Because of acceptable level of a.c. interference, Table 1 does not describe probe a.c. current densities. Three values of E_{on}, E_{off}, and $I_{d.c.}$ exhibited small standard deviation of 0,00134 to 0,0129, indicating there was no fluctuating stray current interference. When the pipeline was not interfered by stray current, the average $I_{d.c.}^{ave}$ of 5,679 A/m^2 (E_{off}: −1,276 V_{CSE}) was defined as 100 % (reference value) as shown in BS EN 50162:2004 [1].

Table 1 — E_{on}, E_{off}, and $I_{d.c.}$ during periods of no stray current activity.

Parameter	Measured value		
E_{on} (V_{CSE})	Average	Average	−1,929
		Maximum	−1,899
		Minimum	−2,010
		S.D.*	0,0122
	Maximum	Average	−1,927
		Maximum	−1,859
		Minimum	−2,009
		S.D. *	0,0124
	Minimum	Average	−1,933
		Maximum	−1,903
		Minimum	−2,055
		S.D. *	0,0129
E_{off} (V_{CSE})	Average	Average	−1,276
		Maximum	−1,268
		Minimum	−1,279
		S.D. *	0,00134
$I_{d.c.}$ (A/m^2)	Average	Average	5,679
		Maximum	6,483
		Minimum	5,383
		S.D. *	0,0121
	Maximum	Average	5,722
		Maximum	6,883
		Minimum	5,417
		S.D. *	0,0127
	Minimum	Average	5,654
		Maximum	6,467
		Minimum	5,067
		S.D. *	0,0122

*S.D. stands for standard deviation.

5.3 Relation between anodic shifts and leaving currents

Needless to say, it is impossible to measure E_{off} and $I_{d.c.}$ simultaneously. Despite having a cathodic protection system satisfying the protection criterion of probe instant-off potential (polarized potential), the pipeline might show signs of stray current interference when the probe on-potential shifted in the positive direction. Where the pipeline potential becomes more positive during periods of stray current activity, current discharge is indicated [4].

Figure 5 shows the relation between the extent of anodic shift (E_{on}^{max}(activity) – E_{off} (reference)) and $I_{d.c.}^{min}$. E_{on}^{max}(activity) is the most positive probe on-potential including IR drop identified in each unit during periods of stray current activity. Whereas, E_{off} (reference), −1,276 $V_{CSE,}$ is an average of 200 data on probe off-potentials measured during no operation of d.c. traction systems (2:00 to 3:00 a. m.) Figure 5 shows that the extent of anodic shift (E_{on}^{max}(activity) – E_{off} (reference)) increased with increased leaving current density. Very clear linear relationship between them with correlation coefficient of –0,960 was identified. Figure 5 indicates that d.c. stray current corrosion is possible even if anodic shifts are not observed.

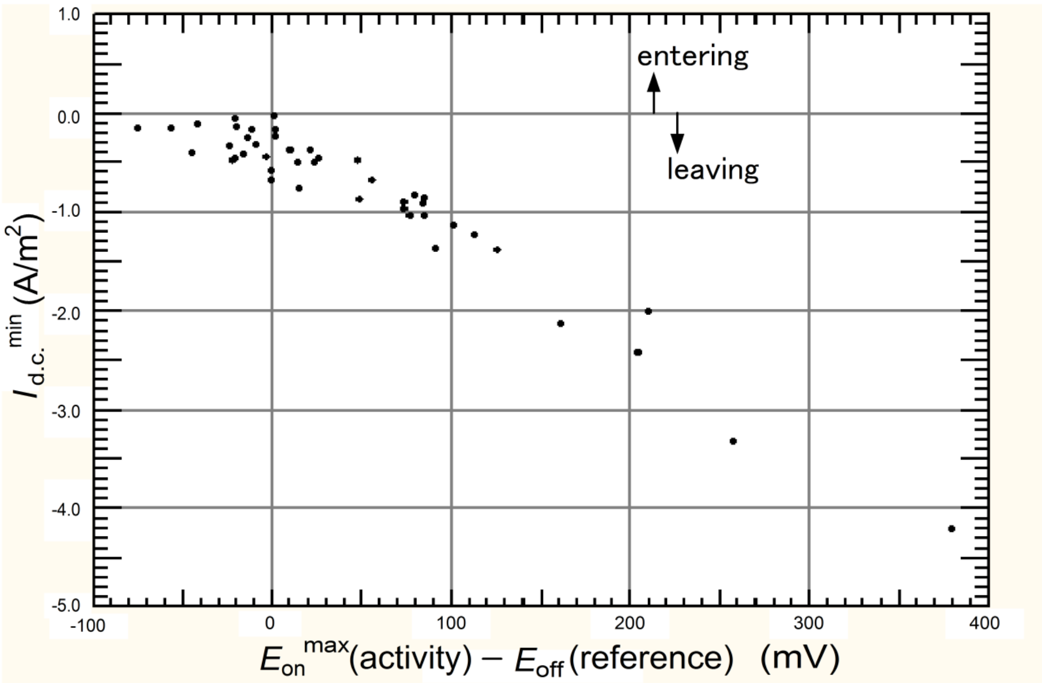


Figure 5 — Relation between anodic shift (E_{on}^{max} (activity) – E_{off} (reference)) and $I_{d.c.}^{min}$.

Figure 6 shows the relation between the most positive probe on-potential including IR drop and the minimum probe current in the same subunit among 43200 units. There is a very good agreement between them with correlation coefficient of −1,000. As shown in Figure 6, probe on-potential shifted for the positive direction, probe current decreased.

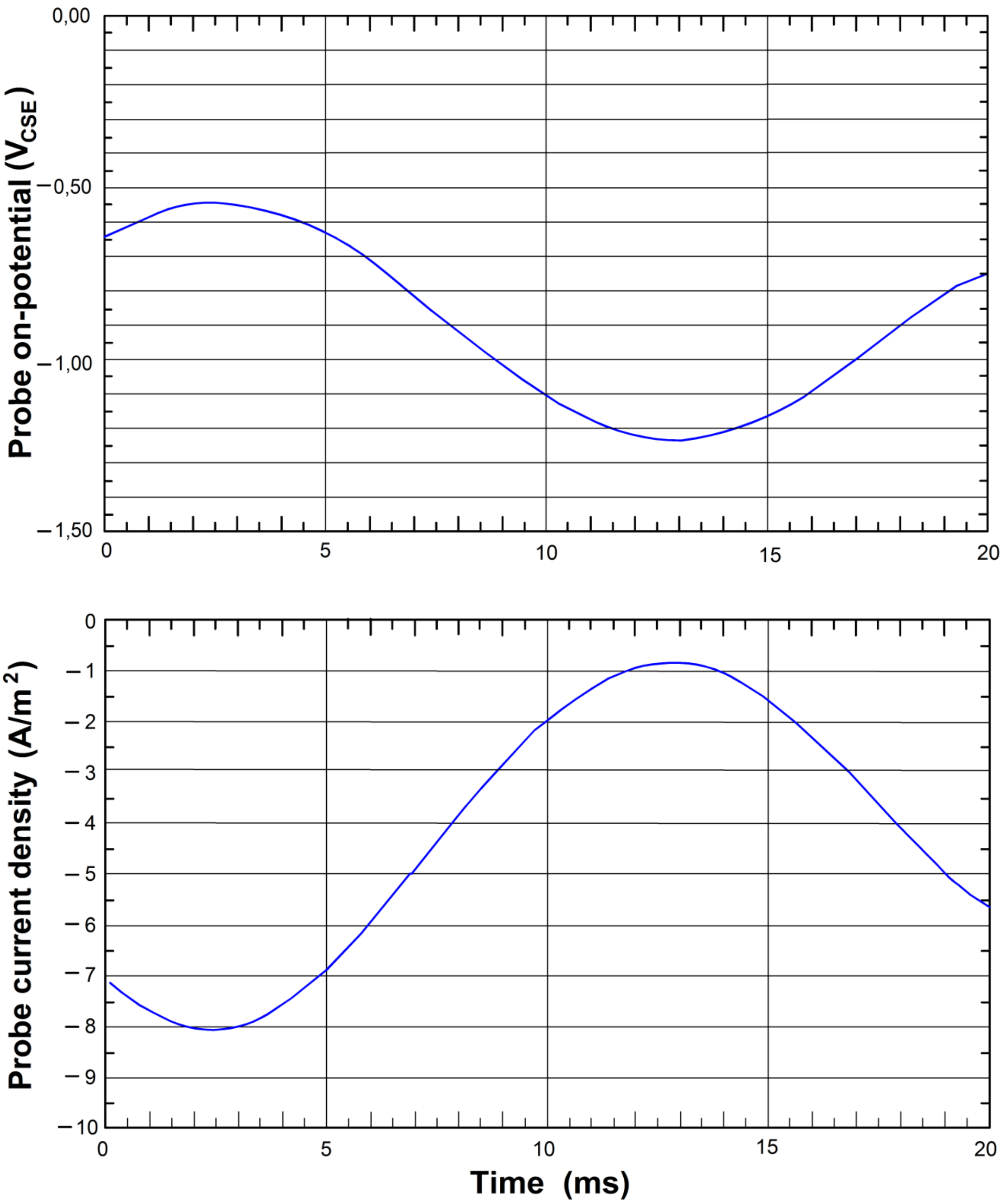


Figure 6 — The most positive probe potential and the minimum probe current in 43200 units.

5.4 Leaving currents leading to corrosion rate

Table 2 summarizes the leaving currents during a period of 24 h. Negative values in probe current indicate the leaving current flowing from the probe to electrolyte. A total of 44 units that showed negative value of $I_{d.c.}^{min}$ were 0,1 percent of 43200 units.

As seen in Table 2, duration showing negative value of $I_{d.c.}^{min}$ was short. Additionally, all of $I_{d.c.}^{ave}$ values were positive indicating entering (cathodic) current.
Based on Table 2, corrosion rate of 0,00975 less than 0,01 mm per year was obtained from **Step 4**. Therefore, it was considered that the risk of fluctuating d.c. and a.c. stray current interference on the cathodically protected pipeline was negligible.

Table 2 — Summary of leaving currents during a period of 24 h.

Unit No.	Time (hour:minute:second)	$I_{d.c.}^{min}$ (A/m^2)	$I_{d.c.}^{ave}$ (A/m^2)	$I_{d.c.}^{max}$ (A/m^2)
1084	12:36:08	–0,917	1,400	6,350
2886	13:36:12	–1.367	1.667	5.400
3043	13:41:26	–1.133	4.167	7.133
3170	13:45:40	–0.133	4.000	6.633
3210	13:47:00	–0.500	1.400	5.217
3409	13:53:38	–0.667	5.483	6.633
3414	13:53:48	–0.483	1.700	5.183
4092	14:16:24	–0.467	1.783	4.833
4329	14:24:18	–0.317	5.267	8.283
4860	14:42:00	–0.167	2.333	3.217
5163	14:52:06	–0.417	5.533	7.283
5516	15:03:52	–0.117	2.683	6.667
5850	15:15:00	–1.033	2.600	4.283
6033	15:21:06	–0.667	3.883	6.250
6401	15:33:22	–2.133	1.333	2.767
6402	15:33:24	–0.150	2.250	5.667
6681	15:42:42	–0.400	4.767	5.950
6853	15:48:26	–0.500	3.767	7.083
6895	15:49:50	–0,250	2,550	6,367
7806	16:20:12	–0,233	3,783	6,750
8707	16:50:14	–0,867	1,100	5,250
9170	17:05:40	–1,383	3,150	6,033
9263	17:08:46	–0,383	5,467	6,600
9267	17:08:54	–0,450	4,150	7,467
9824	17:27:28	–0,750	5,950	7,100
10589	17:52:58	–0,467	5,833	9,150
11515	18:23:50	–0,150	1,733	2,850

11855	18:35:10	–3,317	1,517	3,383
11872	18:35:44	–0,383	4,400	6,633
14598	20:06:36	–1,233	0,800	1,417
17886	21:56:12	–0,967	1,600	3,367
21217	23:47:14	–1,033	2,133	5,967
21410	23:53:40	–0,900	3,350	5,600
21415	23:53:50	–0,333	2,450	6,333
21629	00:00:58	–0,483	4,617	6,267
21713	00:03:46	–2,417	5,167	7,867
21716	00:03:52	–0,833	5,400	6,617
21812	00:07:04	–0,033	3.250	4,367
32338	05:57:56	–0,167	2,233	6,167
38346	09:18:12	–0,850	2,150	5,250
39497	09:56:34	–2,000	1,300	5,650
41981	11:19:22	–0,583	3,950	6,783
42192	11:26:24	–0,050	3,417	6,383
43063	11:55:26	–4,200	6,833	10,867

6 Conclusions

The risk of fluctuating combined d.c. and a.c. stray current interference on buried steel pipelines with cathodic protection applied can be assessed by the analysis of leaving currents provided that probe instant-off potentials satisfy the cathodic protection criterion of polarized potential according to ISO 15589-1:2015.

It is crucial to measure probe instant-off potential and current at very frequent intervals using a rapid response instrument.

References

[1] BS EN 50162:2004 Protection against corrosion by stray current from direct current systems (2004)

[2] ISO 18086 Corrosion of metals and alloys –Determination of AC corrosion – Protection criteria (2015)

[3] ISO 15589-1 Petroleum, petrochemical and natural gas industries – Cathodic protection of pipeline systems – Part 1: On-land pipelines (2015)

[4] A. W. Peabody, Peabody’s control of pipeline corrosion, second edition, Edited by R. L. Bianchetti, NACE International, p.229 (2001)