Challenges in developing coupon DC current density-controlled impressed current cathodic protection system on buried steel pipelines

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Abstract

The point of a natural gas transmission pipeline beneath a railway crossing with low track-to-earth resistance goes into exposure of stray current corrosion and overprotection as DC trains operated by regenerative braking system pass through the railway crossing. In such a case, coupons are useful to assess the effectiveness of cathodic protection (CP). It is extremely important not to make coupon leaving current occur. To ensure complete CP, the author has developed coupon DC current density-controlled impressed current cathodic protection (ICCP) system. The developed system has proved to be an excellent long-term CP performance. The enhanced characteristics of this system include a faster, more accurate alternative to conventional methods, with respect to control over a DC power source i.e. transformer rectifier using pulse width modulation (PWM) circuit.

1 Introduction

When a segment of the buried pipeline runs beneath a railway crossing, a casing pipe is typically installed that surrounds and protects the carrier pipeline from third party damage (damage to the coating and pipeline) and dynamic load. The carrier pipelines are installed in inaccessible areas where it is not typically feasible to repair the carrier pipelines. Therefore, it is imperative that an effectual corrosion management method must be utilised to ensure the carrier pipelines are as safe as possible particularly in high consequence areas. The entire carrier pipe is usually coated for corrosion protection. In addition to the coating, CP is typically applied to the entire carrier pipeline. The space between the carrier pipe and the casing is filled with electrolyte to provide CP current to the carrier pipeline. The point of the carrier pipeline beneath a railway crossing with low track-to-earth resistance goes into exposure of stray current corrosion and overprotection as DC trains operated by regenerative braking system pass through the railway crossing. Recently the use of a regenerative braking system on the railway locomotives has increased in many countries, due to efficient operation. Special care over cathodically protected natural gas transmission pipelines should be taken. Proper ICCP system is needed to ensure complete CP at all times because it is not possible to control stray current at source. To accomplish pipeline integrity management, the author has developed coupon DC current density-controlled ICCP system. This paper offers the developed ICCP system based on DC current density measurement and consequent control on the coupon installed at a crucial point.

2 Corrosion and overprotection of a cathodically protected pipeline induced by the earth potential gradients surrounding a railway crossing

2.1 Cathodically protected pipeline

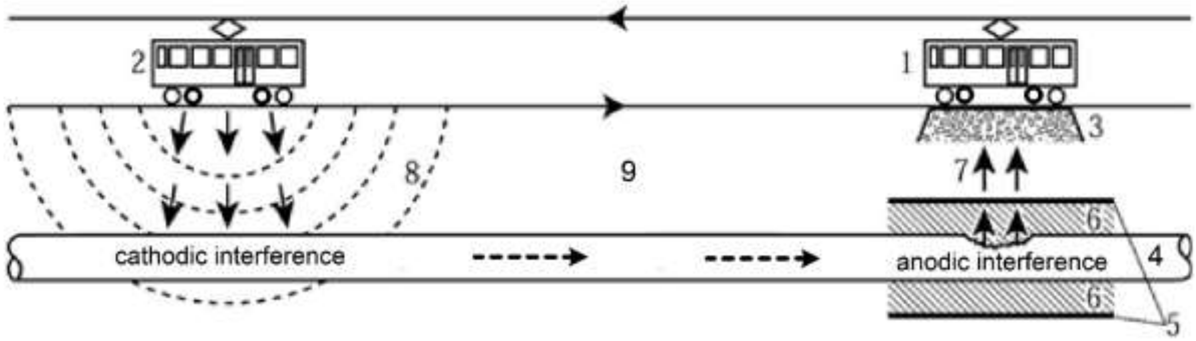
CP of pipelines forces currents to enter the pipelines through the metal surface in contact with electrolyte where the coating is damaged. This current prevents corrosion from taking place by removing oxygen from electrolyte. Moreover, the cathodic current results in the increase of the alkalinity on the steel surface.

2.2 Corrosion and overprotection induced by the earth potential gradients surrounding a railway crossing

In Figure 1, when a DC powered train at a railway crossing (train 1) applies regenerative braking to provide electric power to the other train (train 2) which accelerates, return current from the train 2 divides, part going back to the train 1 along rails, and part leaking off rails onto pipeline which lies within a current path. Such a pipeline will carry the current to a location in the vicinity of the train 1 where it will flow the pipeline through the earth and return to the train 1, causing corrosion of the pipe.

As a result, hemispheric potential gradients with the point of track at the railway crossing as the central figure are caused in the earth. This is illustrated by Figure 1. In Figure 1, the dotted lines indicate equipotential ones. Within the earth potential gradient region, the pipeline tends to become positive with respect to adjacent soil. The point beneath the railway crossing of the steel surface at a holiday is the point of the most intense stray current discharge, which will result in the greatest corrosion damage.

Because running rails at a railway crossing are laid at ground level and are not fully insulated from the earth, generally, the track-to-earth resistance is considerably lower. Therefore, when trains operated by regenerative braking system pass through a railway crossing, larger currents flow to the path of pipeline leading to severe corrosion.

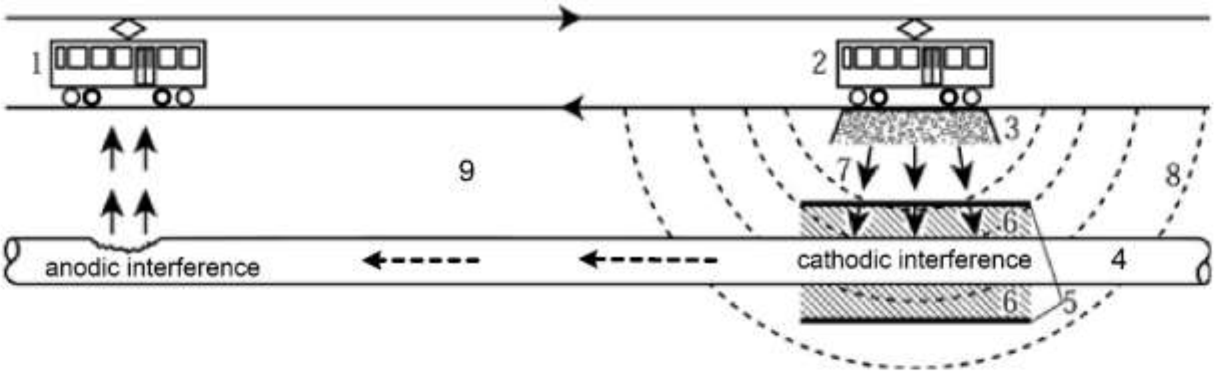


Key

1	train equipped with regenerative braking	6	electrolyte
2	accelerated train	7	discharge current
3	railway crossing	8	equipotential line
4	coated pipeline	9	soil
5	casing pipe		

Figure 1 — Stray current corrosion of a pipeline beneath a railway crossing.

In Figure 2, when a DC powered train at a railway crossing (train 2) receives electric power from a train applying regenerative braking (train 1), the earth potential gradient is caused by current flowing onto the pipeline from rails at the railway crossing and is the reverse of the gradient in Figure 1. The positive earth potentials will force the pipeline to pick up current at points within earth potential gradient region. This current will return to the train 1. Where the current leaves the pipeline in the vicinity of the train 1, corrosion of pipeline occurs. The point beneath the railway crossing of the steel surface at a holiday is the point of the most intense stray current pickup, which will result in overprotection.



Key

1	train equipped with regenerative braking	6	electrolyte
2	accelerated train	7	collecting current
3	railway crossing	8	equipotential line
4	coated pipeline	9	soil
5	casing pipe		

Figure 2 — Stray current corrosion caused by entering the current from the tracks at the railway crossing to the pipeline.

As previously described, generally, as track-to-earth resistance at a railway crossing is very low structurally, the point of track at a railway crossing can discharge or collect so much stray current that substantial voltage drops can be induced in the earth around its point. The closer to the track at a railway crossing, the steeper the earth potential gradient. If a pipeline passes through the gradient, as above mentioned, the most intense corrosion damage and overprotection can take place on the steel surface at the holiday beneath a railway crossing

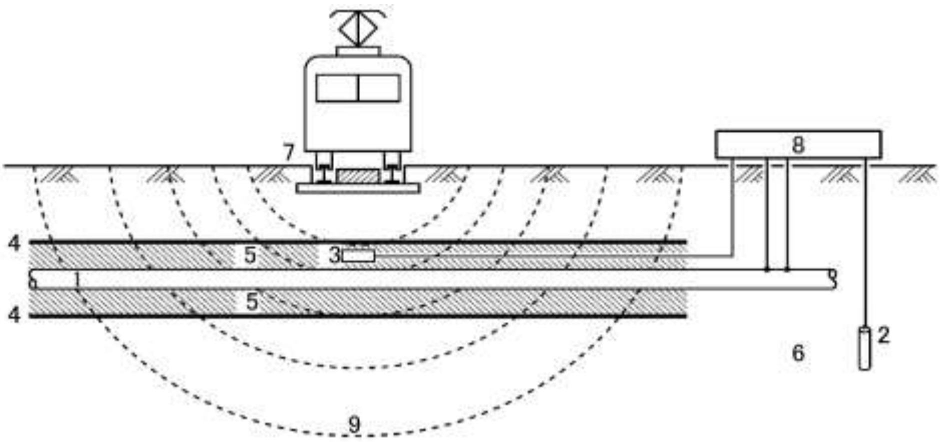
If the pipeline had a perfect coating, there could be no current discharge and no current pickup, that is, no corrosion damage and no overprotection, despite the existence of earth potential gradients where it passed through the zone of influence around the railroad crossing. For this case, however, it is prerequisite to place a coupon at a crucial point, then acquire DC current density on the coupon to evaluate the risks of stray current corrosion and overprotection.

3 Significance to consider current density on coupons

Coupon current is extremely sensitive to identification of stray current and a potential AC corrosion risk of buried steel pipelines as described in EN 50162 [1] and ISO 18086 [2], respectively. It is not possible to control stray current at source. By taking the above mentioned into consideration, there is a strong possibility that, after confirming acceptable AC interference level, coupon DC current density-controlled ICCP system will be effective to control over DC stray current interference.

When a pipeline runs beneath a railway crossing, the installation of a coupon shall be implemented at the stage of pipeline construction in the casing pipe. The location of the coupon is very important, particularly when used to control the system. The coupon shall be placed beneath a railway crossing where the most intense risks of corrosion and overprotection are possible. Because the area of influence surrounding the track at the railway crossing is limited, it is applicable for the installation of shallow impressed current anodes and smaller cathodic protection currents, which can result in minimization of the interference effect on foreign metallic structures and AC corrosion risk.

Coupon instant-off potential i.e. polarized potential is used as a criterion for CP [3]. In this system, a permanent reference electrode is not placed in the vicinity of the coupon to avoid contamination effects caused by chlorides from waters or deicing salts. When effectiveness of CP for the pipeline is assessed, a copper-copper sulphate (saturated) reference electrode is placed outside the casing. And then, measurement on coupon instant-off potential is performed during no stray current activity (ex. at midnight).



Key

1	pipeline	6	soil
2	Impressed current anode	7	train operated by regenerative braking system
3	coupon	8	DC power source
4	casing pipe	9	equipotential line
5	electrolyte		

Figure 3 — Coupon DC current density-controlled ICCP system.

4 Developed block diagram for coupon DC current density-controlled ICCP system

Figure 4 shows the developed block diagram for coupon DC current density-controlled ICCP system.

Decreasing DC current flowing into the coupon installed at a crucial point can reap significant benefits, including reduced likelihood of AC corrosion, hydrogen embrittlement, and coating damage to a natural gas transmission pipeline, and a reduced amount of calcareous deposits on the surface of the coupon having a surface area of 10 cm^2.

Predetermined coupon DC current density was 1,0 A/m^2.
Current can be obtained by measuring voltage across the shunt. The shunt rating of 10 mA/10 mV was determined to implement an accurate control over coupon DC current density.

A DC power source should be able to deliver sufficient electrical current instantly coupon DC current density becomes below the predetermined value. By taking the rating of the equipped DC power source into account, the adequate shunt rating shall be determined for measuring output current accurately.

This type of DC power source should also be able to deliver no electric current instantly coupon DC current density becomes above the predetermined value.

A DC power source shall be equipped with smoothing circuit (filters) which limits the magnitude of ripple to a value as low as possible.

The purpose of a diode is to block the flow of current in one direction. As impressed current anode (groundbed) -to-earth resistance is low to provide effective CP current, cathode of a diode is connected to the groundbed to block the flow of stray current in the direction of ammeter shunt for output current as shown in Figure 4. Thereby pipeline corrosion will be prevented.

The 12-bit high speed successive approximation register (SAR) was used as analog-to-digital converter (AD converter). Conversion rate was 244 μs intervals.

As depicted in Figure 4, by comparing the delivered output voltage to a predetermined reference voltage, an error signal is generated. This error signal is applied to a Pulse Width Modulator (PWM) circuit, which can maintain constant output voltage by adjusting switching current on-time/off-time ratio in a period of 488 μs, regardless of a variation in input voltage caused by stray current. Thereby a DC power source can maintain predetermined constant coupon DC current density very accurately.

In 2015, Mulcahy presented a paper with the title *Successfully Adapting High Frequency Switch Mode Power Supply Technology to Impressed Current Cathodic Protection*. Advantage of PWM circuit is described, however, data for validating this technology are not shown [4].

A DC power source with output current limitation circuits has an effective shut-down in the event of an external short circuit.

Pipeline operators must check whether the CP system is always operating properly. Because of this necessity, there has been significant interest within the pipeline community in the application of remote monitoring and control, thus detecting malfunction of ICCP systems during operation. As depicted in Figure 4, a remote monitoring device is used. The result of remote monitoring is given below.

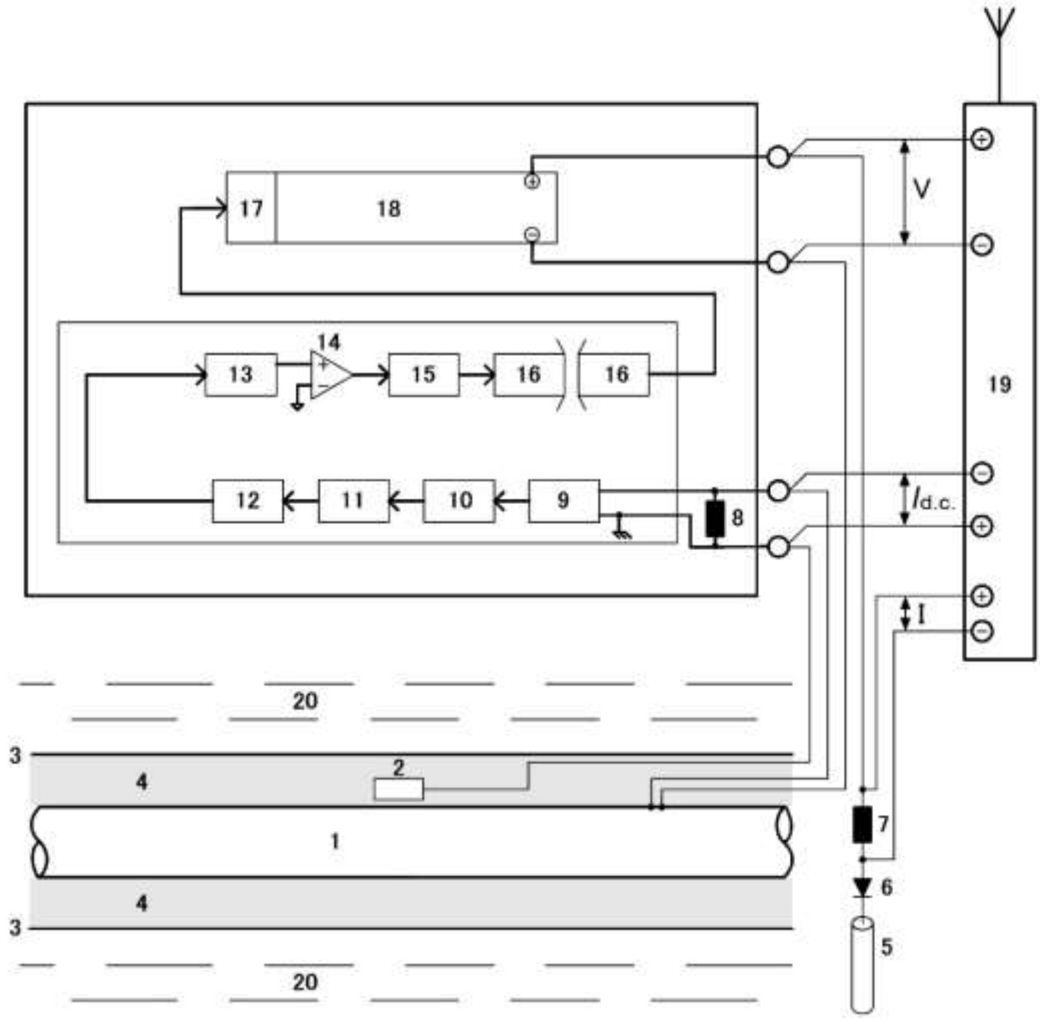


Figure 4 — Developed block diagram for coupon DC current density-controlled impressed current cathodic protection system.

key

1	pipeline	11	switching circuit
2	coupon	12	transforming circuit
3	casing pipe	13	12-bit SAR AD converter
4	electrolyte	14	comparator circuit
5	Impressed current anode	15	pulse width modulation circuit
6	diode	16	isolation amplifier
7	ammeter shunt for output current	17	control of output voltage
8	ammeter shunt for coupon DC current	18	DC power source
9	rectifying circuit	19	remote monitoring device
10	smoothing circuit	20	soil

5 Validation of the developed coupon DC current density-controlled ICCP system

Validation of the developed coupon DC current density-controlled ICCP system was performed based on the results of CP for a polyethylene well-coated 600 mm diameter natural gas transmission pipeline API 5L X65 beneath a railway crossing. The pipeline was installed in 2001. DC trains operated by regenerative braking system passed through the railway crossing. The line is double-tracked. At this location, DC trains of eight or fifteen carriages passed with a speed of approximately 100 kilometers an hour at about 10-minute intervals. The 1.5 kV DC powered railway system did not operate after midnight until early morning.

The rating of a power source was 40 V/27 A. ISO 15589-1 states that generally, voltages higher than 50 V d.c. (rectifier output) should avoided [1]. The equipped DC power source was designed properly for CP service. By taking the rating of the equipped power source 40 V/27 A into account, the shunt rating of 30 A/60 mV was determined for measuring the output current.

Records of remote monitoring of controlled coupon DC current density $I_{d.c.}$, the output voltage V and current I of a DC power source, and total circuit resistance R were checked. The detailed description of the acquisition of the parameters is given in [5].

Figures 5 through 8 show an example of records of $I_{d.c.}$, V, I, and R over 31-day period in November/December, 2017. In these Figures, solid lines show average values.

In Figure 5, positive values in coupon DC current indicate the current flowing through electrolyte to the coupon (i.e. entering (cathodic) current flowing). As shown in Figure 5, no leaving current was observed. The values of coupon DC current density ranged between 0,5 and 14,9 A/m^2 with average of 1,7 A/m^2 compared with the set value of 1,0 A/m^2, indicating that the predetermined coupon DC current density was successfully controlled.

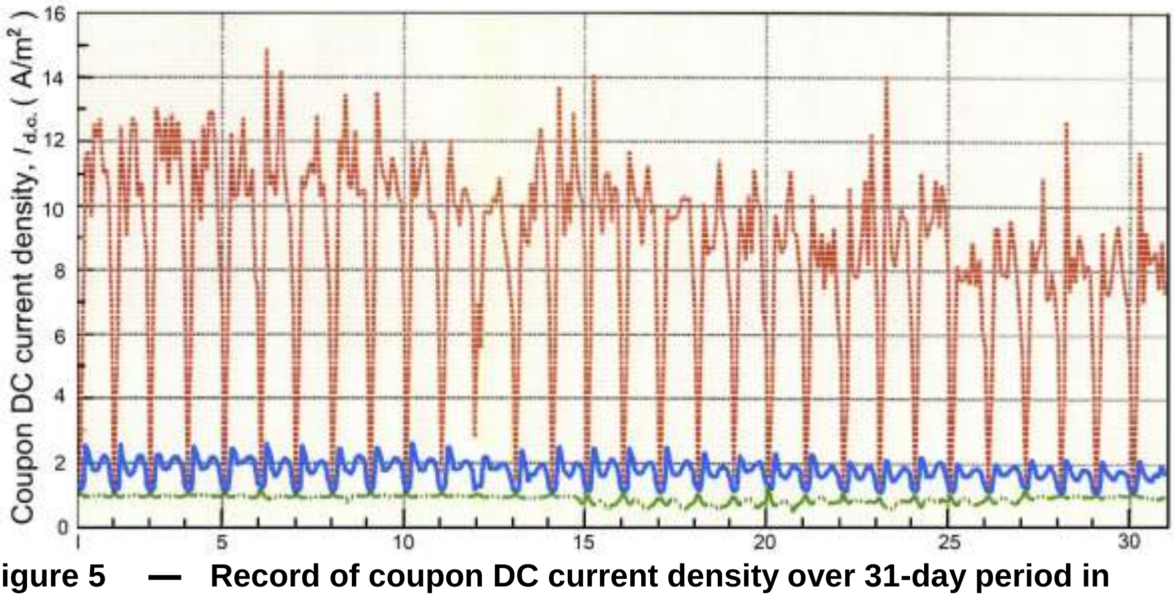


Figure 5 — Record of coupon DC current density over 31-day period in November/December, 2017.

Average values of output voltage and current were positive as shown in Figures 6 and 7, indicating normal operation of ICCP system.

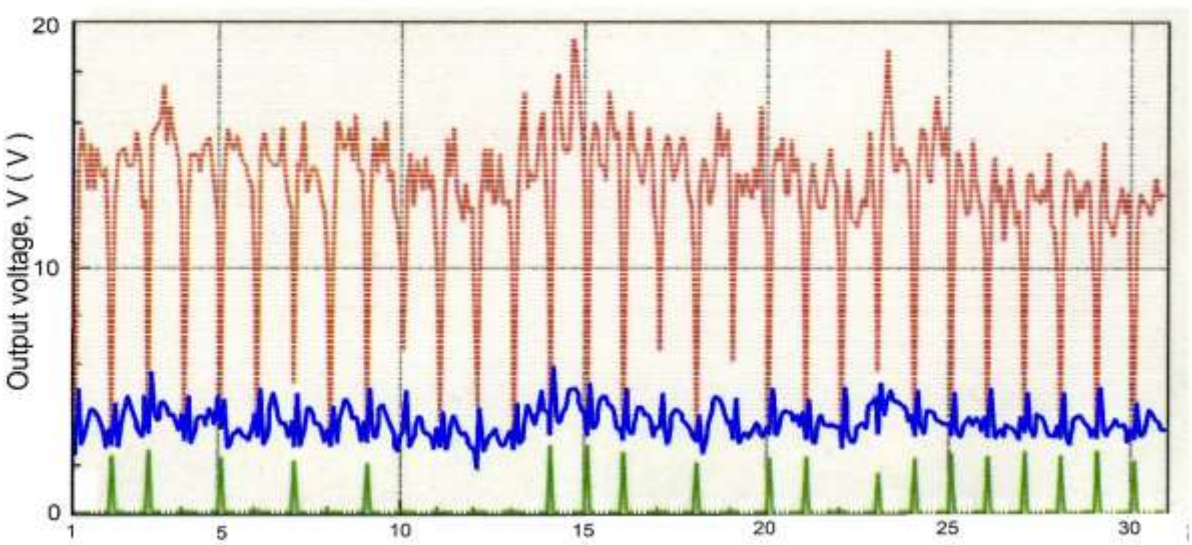


Figure 6 — Record of the output voltage of a DC power source over 31-day period in November/December, 2017.

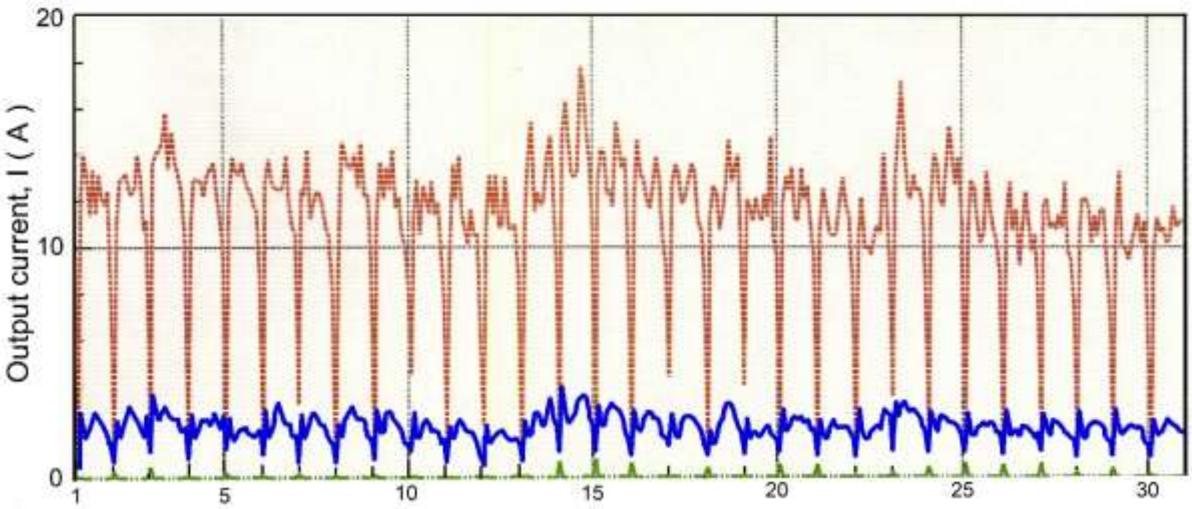


Figure 7 — Record of the output current of a DC power source over 31-day period in November/December, 2017.

Significant changes in total circuit resistance, R(=(average output voltage, V)/(average output current, I)) indicate malfunctions of ICCP systems. For example, a lower total circuit resistance is indicated, if the output current has significantly increased possibly due to shorts with metallic components (contact between the carrier and casing pipes, and/or shorts to other underground structure(s) etc.) or major coating damage.

Figure 8 shows a record of total circuit resistance, R. The values R ranged between 1,42 and 5,56 Ω, indicating no threat to the pipeline integrity.

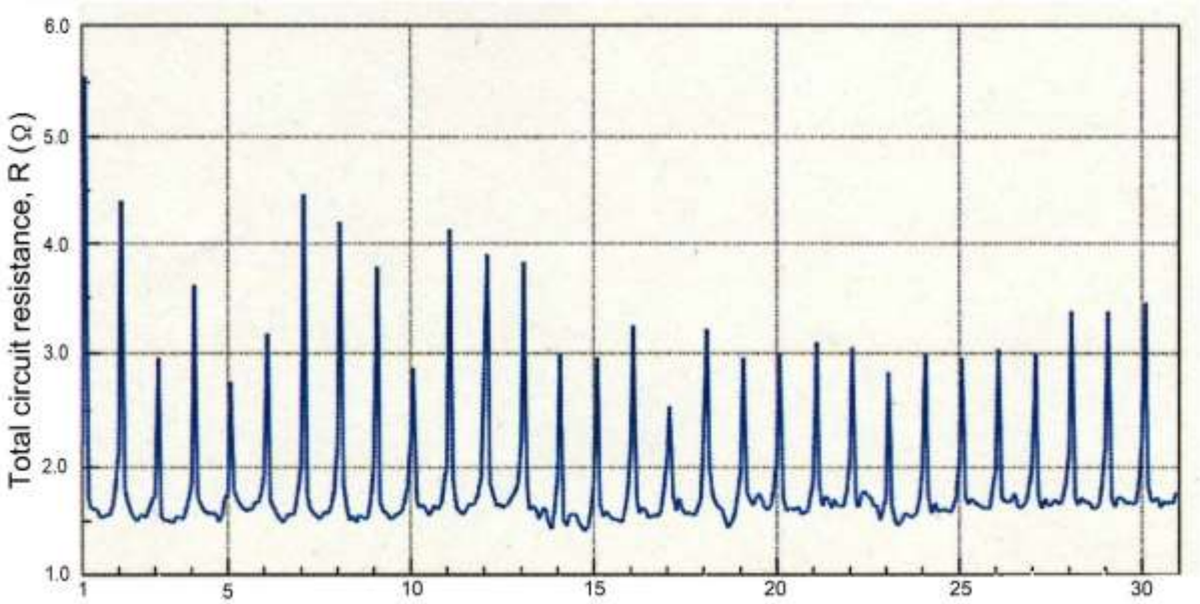


Figure 8 — Record of total circuit resistance over 31-day period in November/December, 2017.

6 Conclusions

Developed coupon DC current density-controlled ICCP system for a well-coated pipeline has proved to be a good long-term CP performance without leaving current on a coupon being controlled. This system can confirm whether the adequate CP current is being delivered to the crucial point of a pipeline.

References

[1] EN 50162 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] G. Mulcahy, “Successfully adapting high frequency switch mode power supply technology to impressed current cathodic protection,” CORROSION 2015, NACE International, Paper No. 5437 (2015)

[5] F. Kajiyama, A. Kawashima, “Advanced constant potential controlled impressed current cathodic protection system with pulse width modulation circuit,” CEOCOR 2016, Paper 2016-07 (2016)