Advanced constant potential controlled impressed current cathodic protection system with pulse width modulation circuit

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

Akihiro Kawashima
Beatec Corporation, 1-104-63 Nishitobecho Nishi-ku, Yokohama-city, Kanagawa prefecture, 220-0046, Japan

Abstract

When a pipeline is subject to very marked and quick stray-current variations from dc traction system, circumstances of insufficient or excessive cathodic protection (CP) current to the pipeline are caused. To maintain acceptable CP levels on the pipeline at all times, constant potential controlled impressed current cathodic protection (ICCP) system is extremely useful. The authors have developed the advanced ICCP system comprising of a dc power source and a constant potential controller equipped with pulse width modulation (PWM) circuit so that rapid response to stray-current variations can be accomplished. In addition, data on voltage and current outputs of the system, pipe-to-soil potential, and total circuit resistance are displayed by remote monitoring instrument via internet. This paper provides the validation of the advanced ICCP system by presenting measurement data on the cathodically protected steel pipeline affected by stray-current activity during the dc-electrified railway system is in operation.

1 Stray-current identification

Stray-currents can be recognized easily by variations in on-potentials of pipelines. On-potential is defined according to ISO 8044 as follows. [1]
“in cathodic protection technique, a non IR-free potential of the object to be protected measured when the protection current is still flowing”

This paper deals with cathodically protected steel pipelines coated with plastic coatings. In the case of a pipeline with an external coating in good condition, coupons are used to evaluate cathodic protection levels. Very marked and quick variations of coupon on-potential including IR-drop along with coupon dc current are signs of stray-current during the operating periods of dc-electrified railway system.

2 Constant potential controlled ICCP system

2.1 Usefulness of constant potential controlled ICCP system to reduce the risks of stray-current corrosion and overprotection

Potential gradients in the earth surrounding a railway crossing are caused by current flowing to and from the point of crossing arising from the passage of dc trains with regenerative braking devices. Where a buried steel pipeline passes through earth potential gradients around a railway crossing, the risks of stray-current corrosion and overprotection on the pipeline are likely to occur.

The effects of stray-current activity surrounding a railway crossing on a well coated pipeline in soil are very limited areas. In such a case, the operation of constant potential controlled ICCP system as local CP is extremely effective to control stray-current activity. [2] This system is designed to maintain a constant protective potential on the pipeline at the location of the system installed. This can be accomplished by burying a permanent reference electrode at the point where constant coupon on-potential is to be maintained. A coupon is installed as close as possible to the permanent reference electrode. The voltage and current outputs of constant potential controlled ICCP system change very rapidly to supply proper cathodic protection current to the pipeline according to stray-current activity. In this paper, coupon on-potential referred to a permanent reference electrode in the ICCP system is termed as pipe-to-soil potential.

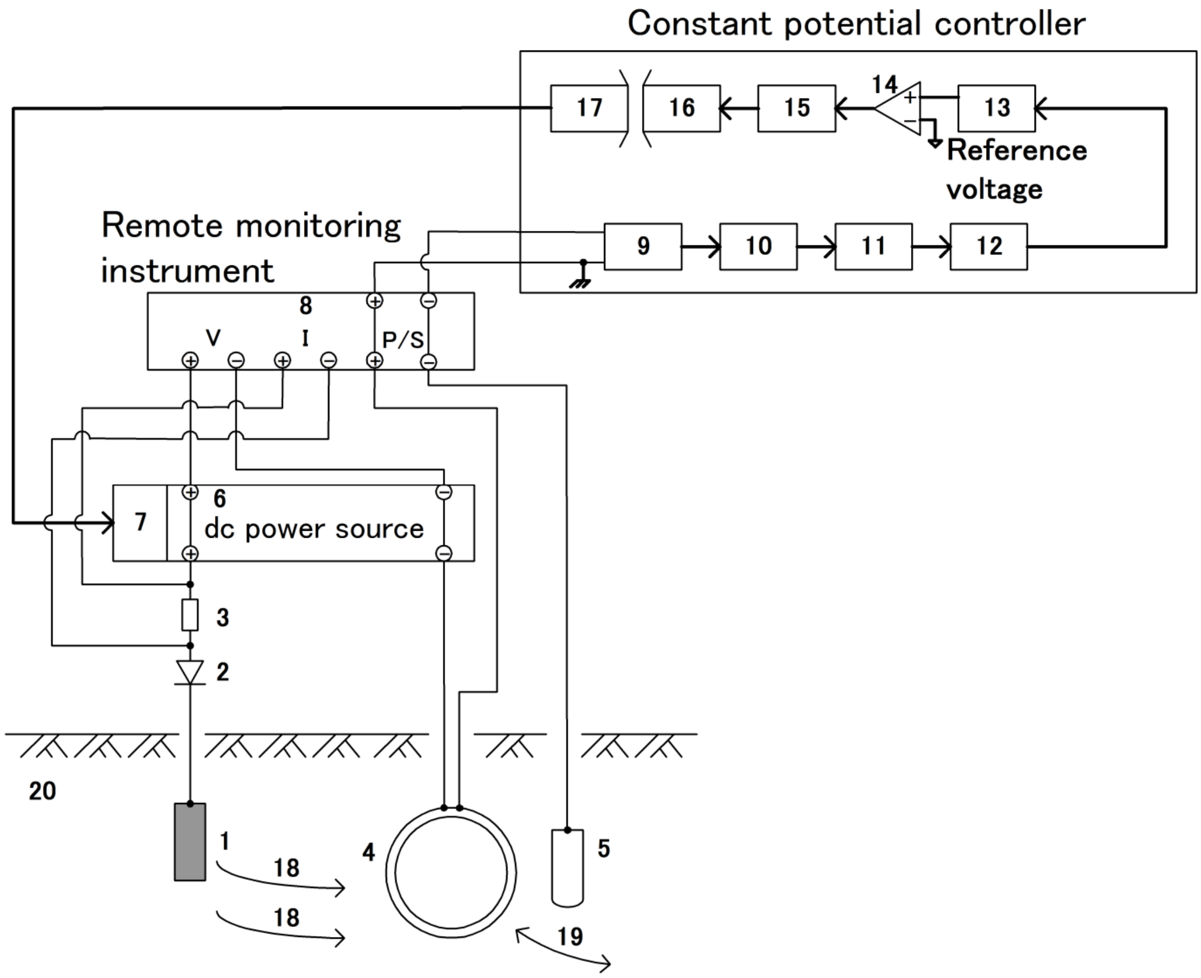
If pipe-to-soil potential is more positive than the reference voltage resulting in insufficient cathodic protection current (the resultant of cathodic current minus discharge stray-current) condition where stray-current corrosion is likely to occur, on time is increased to increase the voltage and current outputs automatically until balance is regained. On the other hand, if pipe-to-soil is more negative than the reference voltage resulting in excessive current (the resultant of cathodic protection current and entering stray- current) condition where overprotection resulting hydrogen embrittlement for high strength steels may result, on time is reduced to decrease the voltage and current outputs automatically until balance is regained.

2.2 Configuration of the developed constant potential controlled ICCP system

The developed constant potential controlled ICCP system consists of vertical anode(s), a first recovery diode, a shunt, a dc power source, a constant potential controller, and a permanent reference electrode as shown in Figure 1. Furthermore, a remote monitoring instrument is connected to a dc power source and a constant potential controller to monitor voltage and current outputs and pipe-to-soil potential. The data are sent to a centre server once a day.

A first recovery diode with features of reverse high voltage-proof is connected to anode(s). This diode is preventive of stray-current flowing onto the anode(s) from the earth. A shunt to measure the output current of the ICCP system is set between a first recovery diode and a dc power source in series with the circuit. The dc power source used is equipped with a power factor correction circuit to eliminate harmonic currents, thereby power factor is as high as 0,980. There is a strong possibility that 12-bit A/D converter of successive approximation register model will take in abnormal electrical noise because of high rate of conversion of analog into digital data, accordingly a total of 1000 data are averaged. Specifically a sampling period is 0,25 ms. Averaging procedure is conducted during a period of 250 ms, so P/S is obtained by averaging 1000 data.

As depicted in Figure 1, by comparing the delivered pipe-to-soil potential to a pre-selected reference voltage, an error signal is generated using a comparator. The reference voltage is a pre-selected pipe-to-soil potential. This error signal is applied to a pulse width modulator (PWM) circuit, which stabilised the output voltage by adjusting the duty ratio, that is, the ratio of on time to a switching period of 0,2 ms (the frequency is 5 kHz). If the output voltage is higher than the reference voltage, on time is reduced. On the other hand, if the output voltage is lower than the reference voltage, on time is increased. Thus even if the input voltage varies with circumstances, the output voltage can be stabilised to adjust duty ratio by PWM circuit.

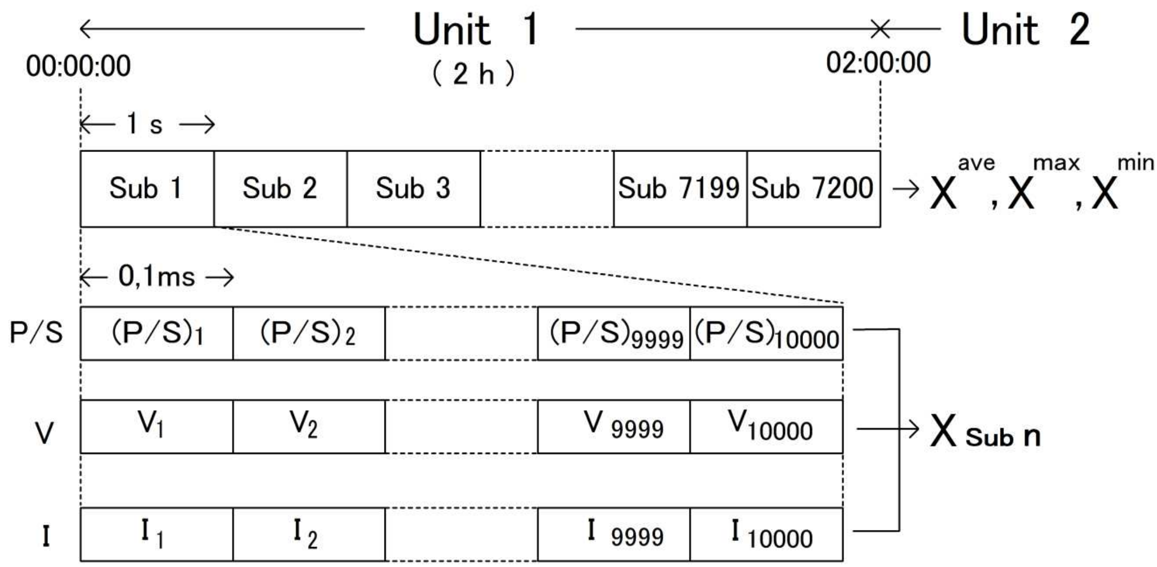


Key

1	Anode	11	Sample & hold circuit
2	First recovery diode	12	12-bit A/D converter of successive approximation register model
3	Shunt	13	Averaging procedure
4	Pipeline	14	Comparator
5	Permanent reference electrode	15	Pulse width modulation circuit
6	dc power source	16	Digital circuit
7	Control on output voltage by external voltage	17	Analog circuit
8	Remote monitoring instrument	18	Cathodic protection current
9	Voltage divider	19	Stray-current
10	Anti-aliasing circuit	20	Earth

Figure 1 — Setup of the developed constant potential controlled impressed current cathodic protection (ICCP) system.

Figure 2 shows the schematic representation of measurement of pipe-to-soil potential P/S, output voltage V, and output current I over 2 hours (each unit) taken at 0,1 ms intervals in the developed constant potential controlled impressed current cathodic protection (ICCP) system. Simultaneous measurements on the values of P/S, V, and I are made. Measurement starts on the even hour. Each unit has continuous 7200 subunits (Sub). Each subunit is a period of 1 s having 10000 data. The average, maximum, and minimum values of P/S, V. and I in each unit are obtained from calculating 7200-subunit data.



where

Sub: Subunit having 1 second (1 s) of time

$X_{Sub\ n}$ = **Fout!**, X^{ave} = **Fout!**

Figure 2 — The schematic representation of measurement of pipe-to-soil potential P/S, output voltage V, and output current I over 2 hours (each unit) taken at 0,1 ms intervals in the developed constant potential controlled impressed current cathodic protection (ICCP) system.

2.3 The use of coupon technology to evaluate fluctuating stray-current interference on cathodically protected pipelines

Coupons simulating coating defects (holidays) can be used to evaluate the levels of cathodic protection on pipelines affected by stray-currents originating from dc traction systems.[2] The coupon is installed near the pipeline and then connected to it through an aboveground monitoring station. The coupon can then be disconnected from the pipe during coupon instant-off potential measured.

Figure 3 shows measuring system for coupon potential (coupon on-potential and coupon instant-off potential) and coupon current. Measurements are made by using a developed instrument by the authors. [3] Coupon potentials (coupon on-potential and coupon off-potential) and coupon currents are measured with resolution of 16-bit at intervals of 0,1 ms. A low pass filter with a cut-off frequency of 73 Hz is used to avoid abnormal electrical spike and harmonic components. Coupon currents are measured by the voltage drop across a shunt resistor with 0,1 ohm so that significant disturbance of the system can be avoided. On or off-state between the coupon and the pipe is created by operating a solid state relay.

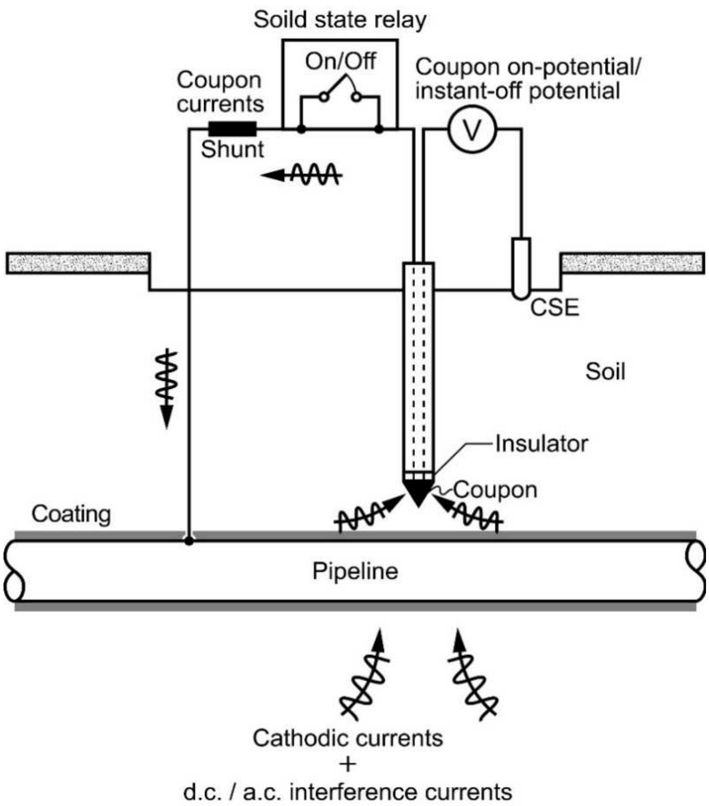


Figure 3 — Measuring system for coupon potential and coupon current.

Figure 4 shows the schematic representation of measurement on coupon on-potential E_{on}, coupon instant-off potential E_{off}, coupon dc current density $I_{d.c.}$, and coupon ac 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.

Each unit (10 s) consist of on-time of 8,5 s and off-time of 1,5 s between the coupon and the pipe. Each unit has continuous 400 subunits (Sub). Each subunit corresponding to a period of 50 Hz is 20 ms. Measurements of coupon potential and current are made during 8 seconds in each unit. The values of E_{on}, $I_{d.c.}$, and $I_{a.c.}$ are obtained from the equations (1) to (3) in each subunit, respectively:

E_{on} = **Fout!** (1) $I_{d.c.}$ = **Fout! · Fout!** (2)

$I_{a.c.}$ = **Fout! · Fout!** (3) E_{off} = **Fout!** (4)

E_{off} is obtained from averaging 200 coupon potentials during 80 to 100 ms after disconnecting the coupon from the pipe using equation (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 unit

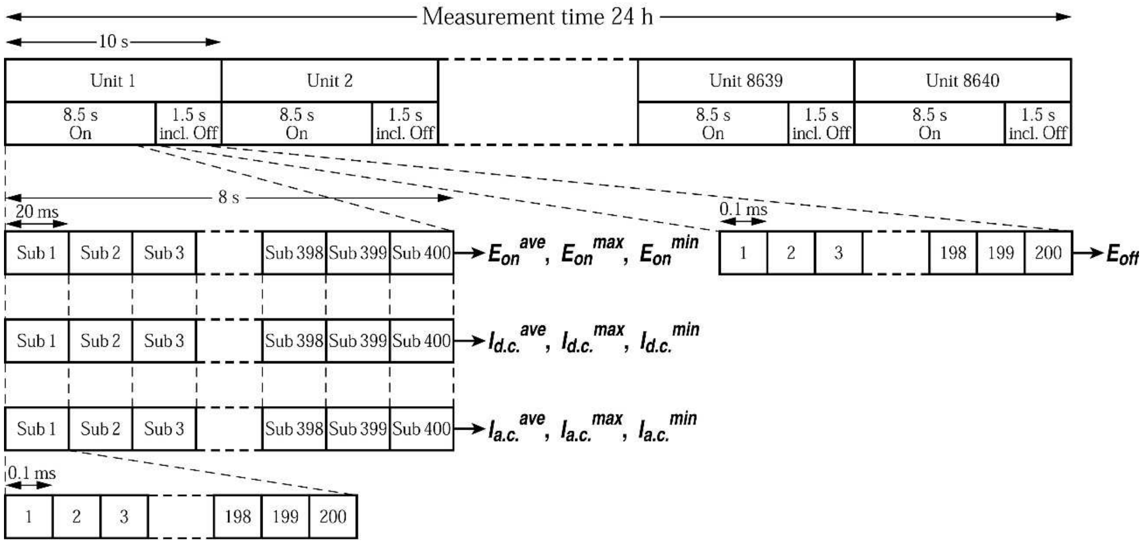


Figure 4 — The schematic representation of measurement on coupon on-potential E_{on}, coupon instant-off potential E_{off}, coupon dc current density $I_{d.c.}$, and coupon ac current density $I_{a.c.}$ at frequency of 50 Hz for a period of 24 hours.

3 Validation of the developed constant potential controlled ICCP system

Validation of the developed constant potential controlled ICCP system was conducted for the buried pipeline just under a dc railway crossing. The line is double-tracked. At this location, dc trains of ten or fifteen carriages (about 200 m or 300 m in length) with regenerative braking devices passed with a speed of approximately 100 kilometers an hour at about 5-minute intervals. The 1,5 kV dc powered railway system did not operate after midnight until early morning.

Figure 5 shows the use of the developed constant potential controlled ICCP system nearby a railway crossing for stray-current control on the polyethylene coated 600 mm diameter steel natural gas pipeline. The railway crossing is located between two stations. A coupon to evaluate cathodic protection levels of the pipeline was installed in the monitoring station in the immediate vicinity of the ICCP system.

The dc power source rating is 6 A / 60 V. The shunt rating is 10 A/50 mV.

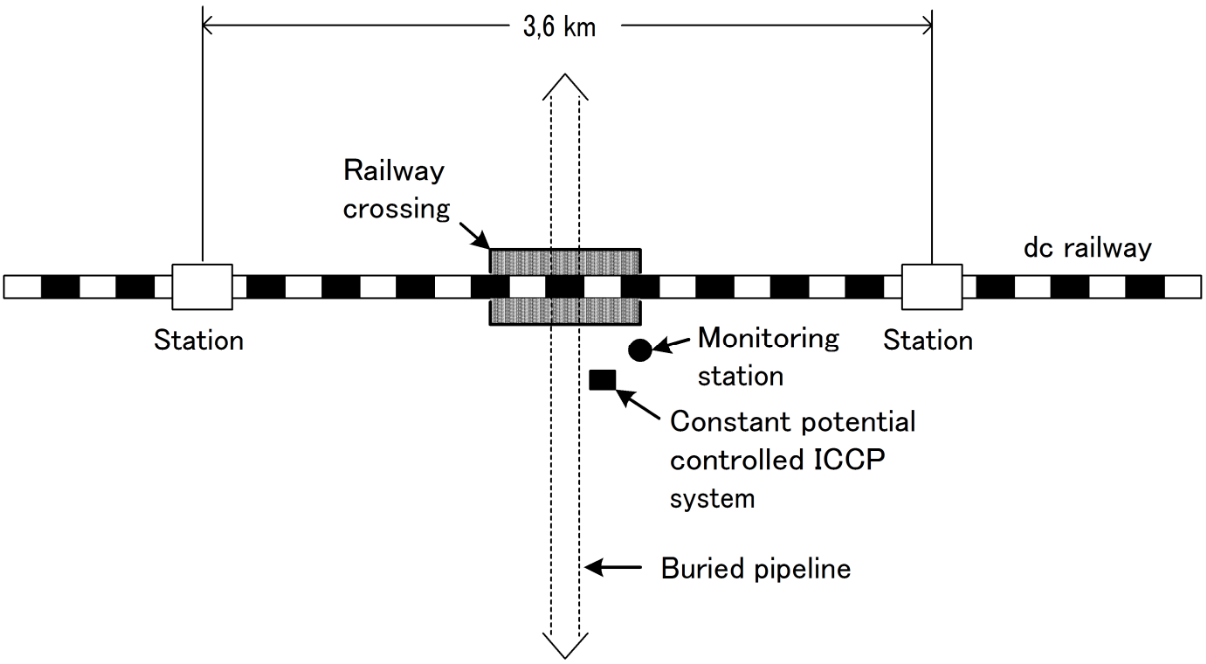


Figure 5 — Use of the developed constant potential controlled ICCP system for stray-current corrosion control on the buried pipeline under a dc railway crossing.

Prior to the installation of the ICCP system, specialized surveys have ascertained that:

1) This pipeline is affected by stray-current activity arising from dc-electrified railway system and the areas of influence surrounding the railway crossing is sufficiently limited.
2) Both directional potential gradients in the earth around the railway crossing are

caused by current flowing as trains equipped with regenerative breaking devices pass, due to low track-to-earth resistance. This pipeline under the railway crossing passes through this gradient.

3.1 Operation of the developed constant potential controlled ICCP system

A pre-selected constant protective potential was –1,125 V_{CSE}.

The voltage and current outputs, pipe-to-soil potential, and total circuit resistance were recorded every unit (2 h) after unit. Total circuit resistance was given by the following equation (5).

Total circuit resistance = (Average output voltage)／(Average output current) (5)

Figures 6 through 9 show the records of pipe-to-soil potential (P/S), output voltage (V), output current (I), and total circuit resistance (R) of the developed constant potential controlled ICCP system over 7 days, respectively. In Figures 6 through 8, the upper, medium, and lower lines show the maximum, average, and minimum values, respectively.

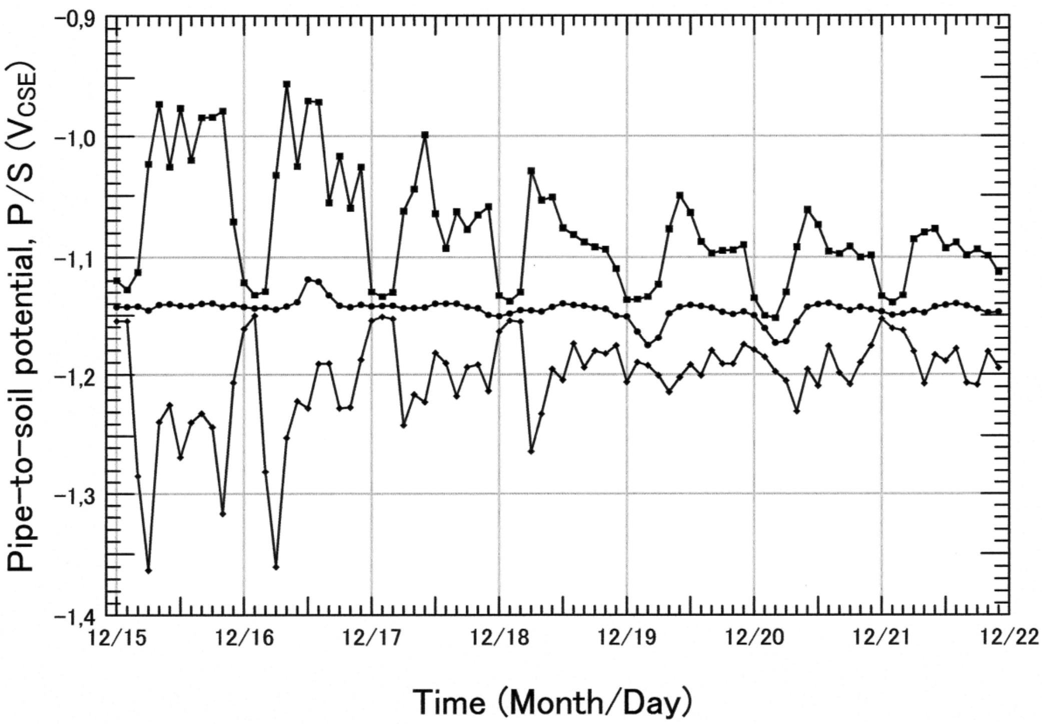


Figure 6 — Record of pipe-to-soil potential referred to CSE over 7 days.

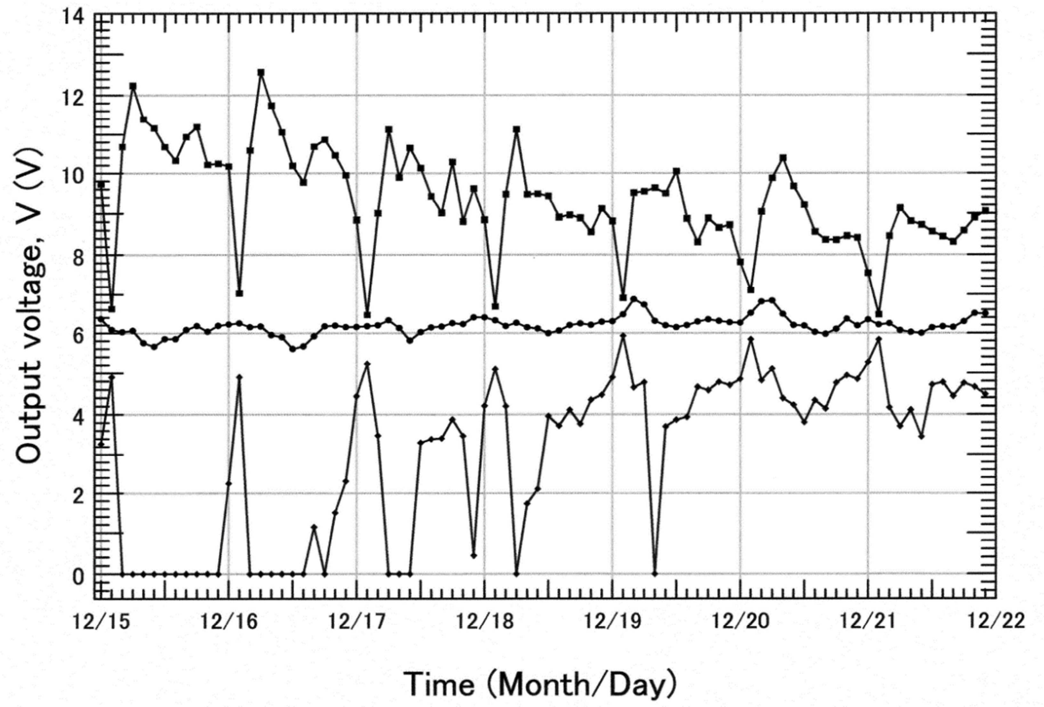


Figure 7 — Record of output voltage of the developed ICCP system over 7 days.

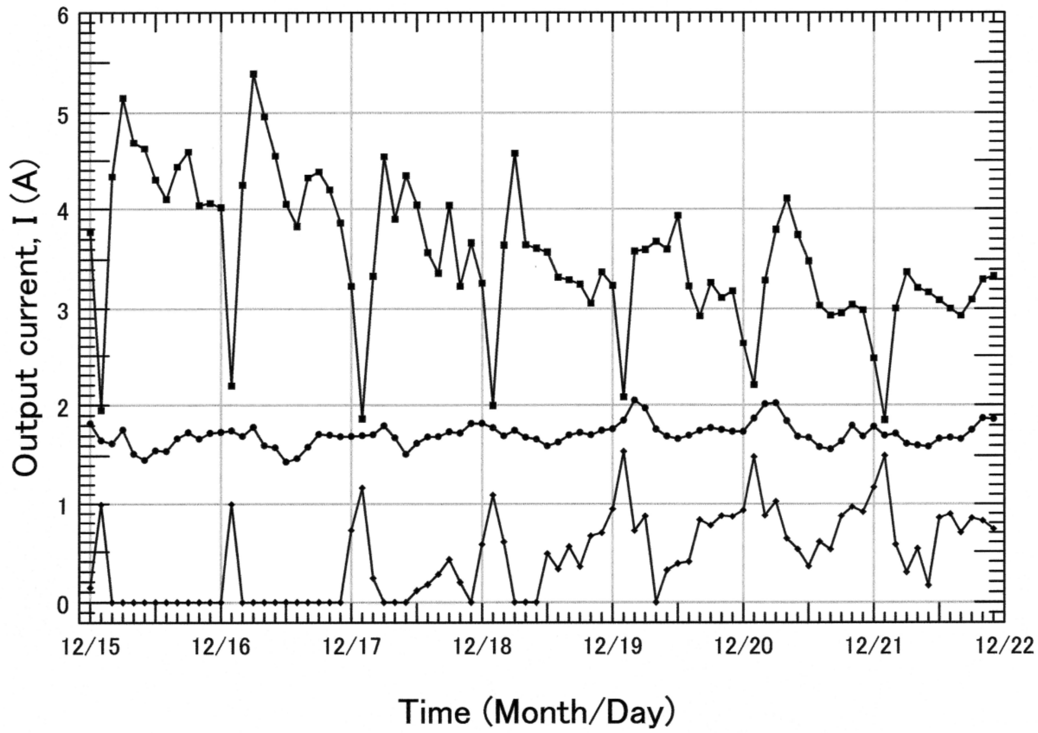


Figure 8 — Record of output current of the developed ICCP system over 7 days.

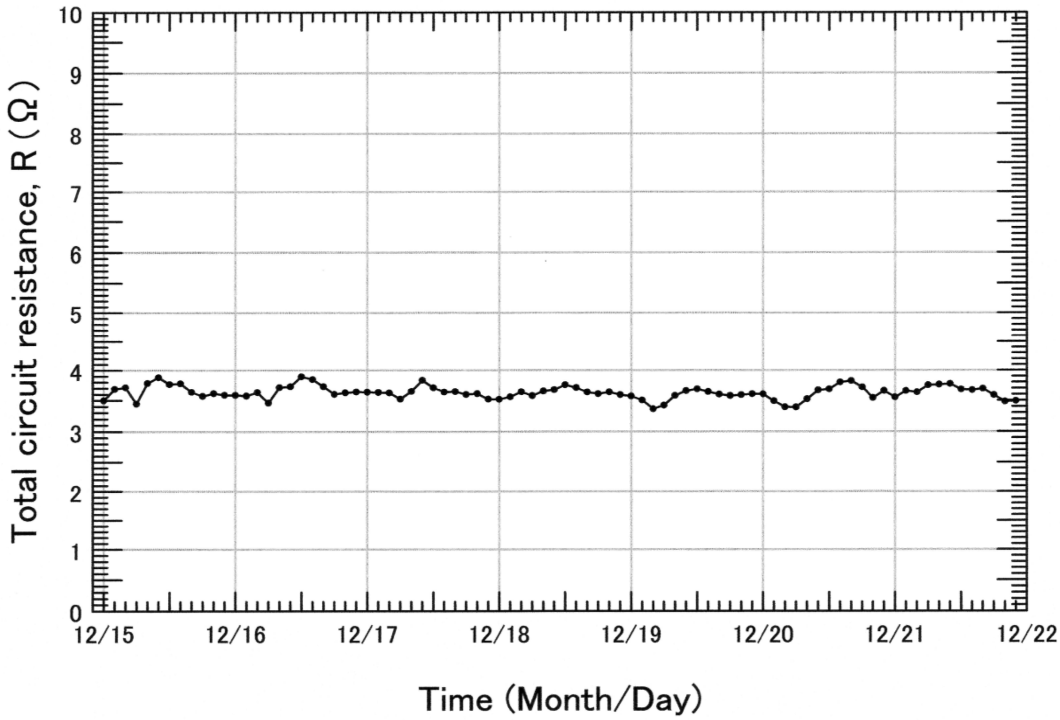


Figure 9 — Record of total circuit resistance (=average V/average I).

Table 1 shows the average, maximum, and minimum data along with standard deviation on P/S, V, I, and R.

Table 1 — The average, maximum, and minimum data and standard deviation on pipe to-soil potential P/S, output voltage V, output current I, and total circuit resistance R over 7 days in the developed constant potential controlled ICCP system.

		Average	Maximum	Minimum	Standard deviation
Pipe-to-soil potential P/S (V_{CSE})	Average	–1,145	–1,119	–1,176	0,00862
	Maximum	–1,078	–0,955	–1,152	0,0489
	Minimum	–1,204	–1,150	–1,363	0,0406
Output voltage V (V)	Average	6,19	6,87	5,60	0,231
	Maximum	9,36	12,57	6,47	1,275
	Minimum	3,02	5,93	0,00	2,039
Output current I (A)	Average	1,71	2,05	1,44	0,113
	Maximum	3,54	5,39	1,85	0,743
	Minimum	0,45	1,54	0,00	0,433
Total circuit resistance R (Ω)		3,6	3,9	3,4	0,109

The results obtained from Figures 6 through 9 and Table 1 were as follows:

1) Pipe-to-soil potentials ranged from –1,363 to –0,955 V_{CSE} (with an average of –1,145 V_{CSE}); output voltages ranged from 0,00 to 12,57 V (with an average of 6,19 V); output currents ranged from 0,00 to 5,39 A (with an average of 1,71 A); and total resistances ranged from 3,4 to 3,9 Ω (with an average of 3,6 Ω).
2) As the maximum value of pipe-to-soil potential became more positive, the maximum values of voltage and current outputs became greater in each unit (2 h), resulting in the increase of cathodic protection current supplied by ICCP system. Specifically the output of ICCP system (voltage and current outputs) would automatically adjust itself to supply additional cathodic protection current to the pipeline by providing the output voltage higher than 9,77 V when the maximum value of pipe-to-soil potential became more positive than –1,05 V_{CSE}.
3) As the minimum value of pipe-to-soil potential became more negative, the minimum values of voltage and current output became zero in each unit (2 h),

leading to cut off the supply of cathodic protection current.

To be concrete, the output ICCP system would automatically adjust itself to cut off cathodic protection current by cutting off the output voltage when the minimum value of pipe-to-soil potential became more negative than –1,25 V_{CSE}.

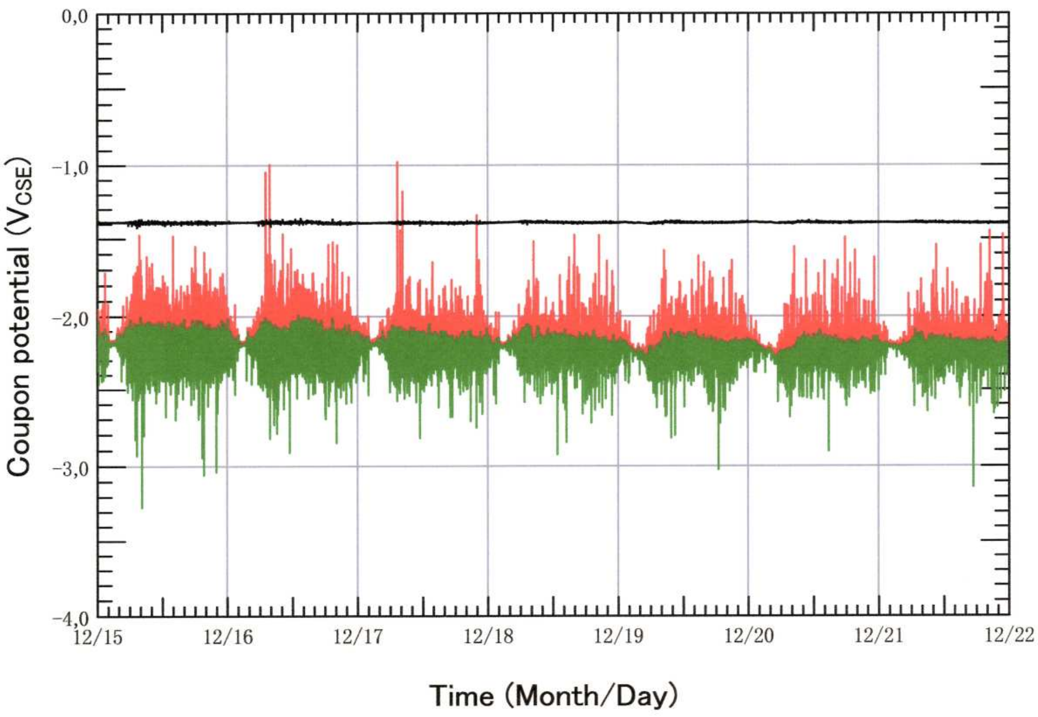
4) The average pipe-to-soil potential in the ICCP system was –1,176 to –1,119 V_{CSE} with standard deviation of 0,00862, indicating the ICCP system was adjusted to the pre-selected pipe-to-soil potential of –1,125 V_{CSE}.
5) The average values of pipe-to-soil potential, voltage and current outputs, and total circuit resistance showing the stable ones were presented.

The above-mentioned results show that the advanced constant potential controlled ICCP system has ideal characteristics.

3.2 Cathodic protection levels of the buried pipeline just under a dc railway crossing

The maximum and average coupon ac current densities were 12,174 A/m^2 and 0,872 A/m^2, respectively. This means the pipeline had not a risk of ac corrosion. [4]

Figure 10 shows the data on coupon potentials and coupon dc current densities over 7 days in December in 2015.



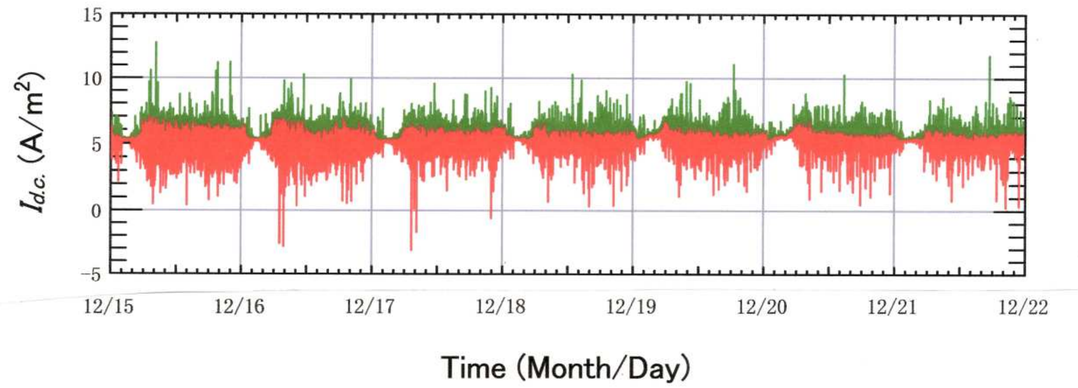


Figure 10 — Record of coupon potential and coupon dc current density $I_{d.c.}$ over 7 days. The upper line in coupon potential shows coupon instant-off potential.

Table 2 summaries coupon on-potential, coupon instant-off potential, and coupon dc current density data over 7 days.

Table 2 — Summary of coupon on-potential, coupon instant-off potential, and coupon dc current density data over 7 days.

	Statistics		Appearance time
Maximum coupon on-potential including IR drop E_{on}^{max} (V_{CSE})	Average	–2,155	
	Maximum	–0,980	12/17 07:21:40
	Minimum	–2,432	
	Standard deviation	0,0637	
Average coupon on-potential including IR drop E_{on}^{ave} (V_{CSE})	Average	–2,190	
	Maximum	–1,954	
	Minimum	–2,499	
	Standard deviation	0,0490	
Minimum coupon on-potential including IR drop E_{on}^{min} (V_{CSE})	Average	–2,226	
	Maximum	–1,993	
	Minimum	–3,269	12/15 08:17:30
	Standard deviation	0,0612	
Coupon instant-off potential E_{off} (V_{CSE})	Average	–1,393	
	Maximum	–1,363	
	Minimum	–1,426	
	Standard deviation	0,00299	
Maximum coupon dc current density $I_{d.c.}^{max}$ (A/m^2)	Average	5,558	
	Maximum	12,767	12/15 08:17:30
	Minimum	4,000	
	Standard deviation	0,0415	
Average coupon dc current density $I_{d.c.}^{ave}$ (A/m^2)	Average	5,312	
	Maximum	7,483	
	Minimum	3,767	
	Standard deviation	0,0330	
Minimum coupon dc current density $I_{d.c.}^{min}$ (A/m^2)	Average	5,077	
	Maximum	6,983	
	Minimum	–3,109	12/17 07:21:40
	Standard deviation	0,0430	

The results obtained from Figure 10 and Table 2 were as follows:

- Very marked and quick coupon on-potential including IR-drop and coupon dc current density variations were observed during dc-electrified railway system was in operation. This indicated that stray-current interference on the cathodically protected pipeline was caused by the operation of dc-electrified railway system.
  There were significant fluctuations in coupon on-potentials between –3,269 V_{CSE} and –0,980 V_{CSE}, that was the result of both directional potential gradients in the earth arising from the passage of dc trains with regenerative braking devices.
- On the other hand, coupon instant-off potential maintained very stable value of –1,426 to –1,363 V_{CSE} with very small standard deviation of 0,00299 over 7 days. Thus acceptable cathodic protection levels on the pipeline were maintained at all times. This means the validation of the developed constant potential controlled ICCP system.
- A 7-day record of coupon dc current density showed identifiable pattern. Very marked and quick coupon dc current fluctuations between –3,109 A/m^2 and 12,767 A/m^2 were observed.
- Coupon dc current reductions showing negative values were presented. The appearance time (07:21:40) of the maximum E_{on}^{max} of –0,980 V_{CSE} coincided with that of the minimum $I_{d.c.}^{min}$ of –3,109 A/m^2. On the other hand, the appearance time (08:17:30) of the minimum E_{on}^{min} of –3,269 V_{CSE} coincided with that of the maximum $I_{d.c.}^{max}$ of 12,767 A/m^2.
  In any case, remarkable stray-current activity has been observed during the morning rush hour period.

As previously mentioned, leaving (anodic) currents on the coupon are observed in Figure 10. Leaving (anodic) coupon dc current densities shown in bold letters along with coupon instant-off potentials are tabulated in Table 3. Before and after the appearance time of leaving coupon dc current, coupon dc current densities and coupon instant-off potentials are also shown.

Table 3 — Leaving coupon dc current densities and relevant data.

Appearance time		$I_{d.c.}^{min}$	$I_{d.c.}^{ave}$	E_{off}
Y/M/D	H : M : S	A/m^2	A/m^2	V_{CSE}
2015/12/16	07:05:20	4,917	5,217	–1,380
	07:05:30	**–2,600**	5,917	–1,391
	07:05:40	4,767	5,133	–1,394
	07:49:40	4,317	4,767	–1,397
	07:49:50	**–2,833**	4,350	–1,391
	07:50:00	3,633	4,067	–1,390
2015/12/17	07:21:30	4,950	5,150	–1,392
	07:21:40	**–3,109**	5,317	–1,392
	07:21:50	5,133	5,383	–1,393
	08:16:30	4,117	4,783	–1,393
	08:16:40	**–1,700**	4,900	–1,393
	08:16:50	4,850	4,967	–1,394
	21:57:30	4,817	5,383	–1,393
	21:57:40	**–0,600**	5,300	–1,394
	21:57:50	5,233	5,367	–1,393

From Table 3, the average coupon dc current density was higher than 4,350 A/m^2 along with coupon instant-off potential more negative than –1,391 V_{CSE} that was considerably negative than the protection potential of –0,850 V_{CSE} [5] when leaving coupon dc current was observed. Coupon dc current did not have a continuance of leaving current. The leaving current phenomenon was for only very limited time periods, then the pipeline may not experiencing corrosion damage.

The above mentioned results indicated that the developed constant potential controlled ICCP system with PWM circuit implemented the accurate and rapid control on stray- current activity.

The risks of stray current corrosion and overprotection were significantly lowered by the operation of the developed constant potential controlled ICCP system.

4 Conclusions

The developed constant potential controlled ICCP system for a buried steel pipeline has been successfully operating since energizing in order to control stray-current activity arising from the operation of dc-electrified railway system. The most distinguished feature is accurate and rapid control on fluctuating stray-current interference on cathodically protected pipelines by using PWM circuit, thus a pre-selected pipe-to-soil potential, that is, constant protective potential can be maintained.

The developed constant potential controlled ICCP system is currently in use at several locations.

References

[1] ISO 8044 Corrosion of metals and alloys – Basic terms and definitions (2015)

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

[3] F. Kajiyama, Y. Nakamura, "Development of an advanced instrumentation for assessing the AC corrosion risk of buried pipelines, "CORROSION 2010, NACE International, Paper No. 10104 (2010)

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

[5] ISO 15589-1 Petroleum and natural gas industries – Cathodic protection of pipeline transportation systems – Part 1: On-land pipelines (2003)