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Petroleum, petrochemical and natural gas industries — Prevention of corrosion on pipeline systems influenced by stray currents

Industries du pétrole, de la pétrochimie et du gaz naturel — Prévention de la corrosion sur les systèmes de conduites soumis à l'influence de courants vagabonds

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 2, *Pipeline transportation systems,* in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 219, *Cathodic protection,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

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Introduction

This document provides guidance for the prevention of external corrosion when a pipeline is influenced by electrical interference. Electrical interference can be from stray currents (defined in ISO 8044) and from naturally occurring interference caused by geomagnetic or tidal activity.

International Standards on cathodic protection (e.g. ISO 15589-1 and ISO 15589-2) refer to a structure-to- electrolyte potential value that is considered to indicate that cathodic protection is effective. When the potential is influenced by stray currents, however, it is not always possible to obtain a meaningful structure-to-electrolyte potential and other methods of assessment are needed. These other methods can include mathematical analysis of the potentials and/or direct assessment of the corrosion rate using electrical resistance probes.

An affected structure carrying stray currents, e.g. a pipeline or cable can itself affect other nearby structures.

This document is not intended to inhibit the use of alternative equipment or engineering solutions for individual applications. Where an alternative is offered, it is intended that any variations from this document be identified and documented.

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Petroleum, petrochemical and natural gas industries — Prevention of corrosion on pipeline systems influenced by stray currents

1 Scope

This document establishes the general principles for the evaluation and minimization of the effects of stray current corrosion on external surfaces of buried or immersed pipeline systems caused by AC and DC electrical interference.

Other stray current effects such as overheating, and interference with welding operations are not covered in this document.

A brief description of AC effects, general principles and some guidelines, are provided.

NOTE 1 See ISO 18086 for the effects of alternating current on buried or immersed pipelines.

Systems that can also be affected by stray currents include buried or immersed metal structures such as the following:

a) pipeline systems;

b) metal sheathed cables;

c) tanks and vessels;

d) earthing systems;

e) steel reinforcement in concrete;

f) sheet steel piling.

This document gives guidelines for

— the design of cathodic protection systems that might produce stray currents,

— the design of pipeline systems, or elements of pipeline systems, which are buried or immersed, and which can be subject to stray current corrosion, and

— the selection of appropriate protection or mitigation measures.

Internal corrosion risks from stray currents are not dealt with in detail in this document but principles and measures described here can be applicable for minimizing the interference effects.

NOTE 2 The impact of electromagnetic interference on above-ground appurtenances of pipeline systems is covered in EN 50443, IEC 61140, IEC 60364-4-41, IEC 60479-1, IEC 60364-5-52, IEC/TS 61201 and IEC/TR 60479-5.

This document can also be used for pipeline systems outside of the petrochemical and natural gas industries and other buried or immersed structures.

NOTE 3 EN 50162 provides guidance for railway related structures.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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IEC 62128-2:2013, *Railway applications - Fixed installations - Electrical safety, earthing and the return circuit - Part 2: Provisions against the effects of stray currents caused by d.c. traction systems*

ISO 15589-1, *Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline systems — Part 1: On-land pipelines*

ISO 8044, *Corrosion of metals and alloys — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15589-1, IEC 62128-2:2013, ISO 8044 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
coating
electrically insulating covering bonded to a metal surface for protection against corrosion by preventing contact between the electrolyte and the metal surface

3.2
remote earth
theoretical concept that refers to a ground electrode of zero impedance placed an infinite distance away from the ground under test

Note 1 to entry: In practice, remote earth is approached when the mutual resistance between the ground under test and the test electrode becomes negligible. Remote earth is normally considered to be at zero potential.

[SOURCE: IEEE Std 81-2012[1]]

3.3
conductive coupling
transfer of energy occurring when a part of the current belonging to the interfering system returns to the system earth via the interfered system

Note 1 to entry: Also, when the voltage to the reference earth of the ground in the vicinity of the influenced object rises because of a fault in the interfering system, and the results of which are conductive voltages and currents.

3.4
drainage
electrical drainage
transfer of stray current from an affected structure to the current source by means of a deliberate bond

Note 1 to entry: For drainage devices see *direct drainage bond* (3.5), *unidirectional drainage bond* (3.7) and *forced drainage bond* (3.6).

3.5
direct drainage bond
device that provides *electrical drainage* (3.4) by means of a bi-directional, metallic bond between an affected structure and the stray current source

Note 1 to entry: The bond can include a series resistor to reduce the current.

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3.6
forced drainage bond
device that provides *electrical drainage* (3.4) by means of a bond between an affected structure and the stray current source

Note 1 to entry: The bond includes a separate source of DC power to augment the transfer of current.

3.7
unidirectional drainage bond
device that provides *electrical drainage* (3.4) by means of a unidirectional bond between the affected structure and the stray current source

Note 1 to entry: The bond includes a device such as a diode to ensure that current can only flow in one direction.

3.8
telluric interference
voltages generated by geomagnetic field variations that cause variations in the observed pipe-to-soil potentials

3.9
electrical resistance probe
ER probe
device that measures metal loss by comparison of the calibrated resistance value of a piece of metal with known physical characteristics

3.10
sampling rate
measuring interval set by the operator

3.11
alternating current interference
AC interference
electrical disturbance generated by AC systems that affects buried or immersed pipelines by conduction and/or induction

Note 1 to entry: Powerlines, railway traction systems.

3.12
direct current interference
DC interference
disturbance, generated by DC systems, that affects buried or immersed metallic structures primarily by conduction

4 Abbreviations and symbols

4.1 Abbreviations

AC	Alternating current
ACVG	Alternating current voltage gradient
CP	Cathodic protection
DC	Direct current
DCVG	Direct current voltage gradient
emf	Electromotive force

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GIC	Geomagnetically induced currents
HVAC	High voltage alternating current
HVDC	High Voltage Direct Current
IR	Product of the current and resistance (I and R) that indicates the voltage drop error in a potential measurement
PV	Photovoltaic
r.m.s.	Root mean square

4.2 Symbols

a^{-1}	Per annum
B	Magnetic field
E	Structure/soil potential for non cathodically protected structures
E_a	Anodic potential
E_c	Cathodic potential
ΔE	Potential difference due to operation / non-operation of the interfering source
ΔE_a	Anodic potential shift (IR drop included)
$\Delta E_{a,avg}$	Average anodic potential shift
$\Delta E_{a,IR\ free}$	Anodic potential shift (IR drop excluded)
ΔE_c	Cathodic potential shift
ΔE_m	Measured interference
$\Delta E_{c,avg}$	Average cathodic potential shift
E_{cor}	Structure potential of a metal in a given corrosion system (ISO 8044)
$E_{IR\text{-}free}$	Structure potential without measurement error due to current flowing in the circuit
E_{on}	ON potential
$E_{on,avg}$	Average ON potential
E_p	Protection potential according to ISO 15589-1
E_{ref}	On potential required to achieve effective cathodic protection
F	Electric field
I_{cpn}	Coupon current
J	Current density
J_a	Anodic current density
J_c	Cathodic current density

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J_{cpn}	Coupon current density
J_{ref}	Reference value for current density (analogous to I_{ref})
ρ	Soil resistivity (Ω·m)
Q_a	Anodic charge during the period of anodic interference
Q_c	Cathodic charge during the period of cathodic interference
R_c	Coupon element resistance
R_{iso}	Isolation resistance, usually of a cable insulation
s	Seconds
$S \cdot km^{-1}$	Siemens per unit length
t	Time
T_a	Interval when the structure is anodic with respect to the selected value of E_{ref} or J_{ref}
$T_{a,max}$	Maximum duration of the anodic period
T_c	Interval when the structure is cathodic with respect to the selected value of E_{ref} or J_{ref}
v_{cor}	Corrosion rate
V_{CSE}	Voltage with respect to a copper/copper sulfate reference electrode

5 Information exchange and co-operation

Common sources of interference that can cause stray current corrosion are given in Clause 6. During the design stage of buried or immersed metallic pipeline systems, the possibility of both causing and suffering from stray current interference shall be taken into consideration and documented. The pipeline system should achieve the acceptance criteria identified in Clause 8. Construction work, major changes on existing structures, regenerative braking, etc. can require a detailed consideration of the interference situation.

Electrical interference problems on buried or immersed metallic pipeline systems shall be considered, and documented, with the following points in mind:

— The operator of the pipeline system can protect a structure against corrosion with the method that the operator considers to be the most suitable. However, levels of electrical interference on neighbouring structures shall be maintained within the defined limits given in Clause 8

— Stray currents, especially from DC traction systems, are directly related to the design of the traction return circuits. This means that it is possible to limit the stray current by traction circuit design, but not to eliminate it.

— Where other structures that might be affected are present, the requirement to maintain interference within the defined limits applies to all affected structures.

— Utility-scale photovoltaic (PV) installations can develop a steady state DC interference to adjacent buried pipelines. It is expected that the operator of the PV installation will maintain constant monitoring of the R_{ISO} value to verify the isolation resistance between the PV panels and the earth. The pipeline operator should be informed of any changes in the R_{ISO} values outside the threshold value.

— The operating characteristics of HVDC systems can change under fault and maintenance conditions. These changes can affect the corrosion risk to buried pipelines and such changes should be communicated in a timely manner to the pipeline operator.

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These goals are best achieved by agreement, co-operation and information exchange between the parties involved. Information exchange and co-operation are important and shall be carried out both at the design stage and during operation of the systems. In this way possible effects, suitable precautions and remedies can be assessed.

The following information is required to make a sound engineering judgement:

— details of buried metallic structures;

— cathodic protection installations or significant modifications to existing installations;

— DC traction system installations or significant modifications to existing installations;

— HVDC transmission line installation or modification to existing installations or modes of operation;

— details of any sources of DC installations that can cause interferences to buried pipelines;

— utility scale photovoltaic systems.

Agreement and co-operation is more effectively achieved and maintained by periodic meetings between interested parties, committees or other associations who can establish information exchange procedures and protocols.

6 Common sources of interference that can affect corrosion

6.1 General

DC systems that can cause currents to flow in the earth or any other electrolyte, whether intentional or unintentional, include the following:

a) traction systems;

b) overhead lines for vehicles;

c) trolley bus systems;

d) power systems;

e) equipment at industrial sites, e.g. welding;

f) communication systems;

g) instrumentation systems;

h) cathodic protection systems;

i) high voltage transmission systems. See Annex E;

j) track circuit signalling systems. (For stray currents from traction systems, IEC 62128-2 gives requirements for minimizing their production and for the effects within the railway system);

k) photovoltaic power systems. See Annex H;

l) offshore wind farm power systems;

m) geomagnetic interference (telluric currents). See Annex D;

n) tidal fluctuations. See Annex G.

AC systems (see Annex F) that can induce voltages into buried structures include

— three phase power transmission overhead cables,

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— buried three phase power cables, and

— AC operated railways.

6.2 Direct current

6.2.1 General

Sources of DC that can affect the structure-to-electrolyte potentials on pipelines can either originate from industrial or natural sources.

6.2.2 Traction systems

There are various configurations of DC traction systems that are in common use. They generally differ in respect of the way that the current is returned to the substation(s). Whichever system configuration is used there will be some current that returns via the earth. IEC 62128-2 gives guidance on permissible limits.

6.2.3 Industrial systems

6.2.3.1 General

Industrial systems that use, or generate, DC should be provided with earthing systems that neither rely on long earth return paths nor deliberately utilize third-party structures for earthing purposes.

6.2.3.2 Welding

Welding return circuits should be configured to ensure that the return paths are as short as possible and do not exacerbate the risk of currents returning via third-party structures.

6.2.3.3 Photovoltaic interference on buried pipelines

Leakage currents in photovoltaic systems originate from a fault or from the systematic and inevitable flow of DC where there is cable insulation damage to PV modules and other array components. Under certain conditions, the DC leakage currents, if left unattended, or not detected at all, can cause accelerated stray current corrosion on metallic underground infrastructure, such as pipelines, buried near large, utility-scale PV systems.

6.3 Alternating current

6.3.1 General

AC powered systems can cause interference on pipelines due to inductive, conductive and capacitive coupling mechanisms, which are described in References [3] and [6].

It is possible that the voltage resulting from interference on the pipe can exceed acceptable levels of touch-potential and/or current densities that will lead to corrosion damage of exposed steel surfaces.

The potentials and current densities that are used to determine the risk of corrosion from AC interference are detailed in References [3] and [6].

Annex F provides additional information and one method to calculate the induced voltage in a section of pipe.

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6.3.2 Overhead and buried power lines

6.3.2.1 General

Overhead power lines can generate unacceptable voltages onto buried pipelines, primarily by induction. The induction is a result of magnetic coupling. The magnitude of the induced voltage depends on the distance, length of parallelism, inducing current magnitude, frequency and phase relationship.

6.3.2.2 Buried power cables

Buried power lines can generate unacceptable voltages onto buried pipelines, primarily by induction, in the same way as overhead power lines. It is preferable if buried cables are laid with the phase cables close to each other and formed in a trefoil configuration. Trefoil formation refers to a method of arranging the individual phase cables to reduce the net inductance because the phases are in anti-phase and cancel each other.

6.3.2.3 Railway systems

AC railway systems can be a source of interference. Where the pipeline is parallel to the railway, the coupling is primarily inductive. The rails of AC powered railways are earthed, and this can also result in conductive coupling to adjacent buried structures. AC railways can operate at 60 Hz, 50 Hz and 16,67 Hz. When evaluating the risks resulting from the effects of electromagnetic interference on buried pipelines running near AC electrified traction systems, the harmonic distortion in railway systems should be considered. The presence of harmonics can exacerbate voltages induced on buried pipelines[5].

6.4 High-voltage direct current transmission systems

There are two main configurations for high voltage direct current transmission systems, monopolar and bipolar. Bipolar HVDC systems should be given preference to avoid stray current interference. The earthing of HVDC systems shall be designed in such a way as to avoid current flowing through the earth during normal operation and to minimize earth current during faulty or unbalanced load conditions.

The entire system design shall consider the possible high-level of stray currents to which buried or immersed metal structures can be exposed, even at a substantial distance from the electrode station.

Buried HVAC and HVDC cables are joined together in joint bays installed along the cable route. The separation distance between joint bays is dependent on the cable operating voltage, conductor size and construction. Not all joint bays will have an earth local to the joint bay, but the cable screens will be bonded in each joint bay. The location of all earths should be advised by the cable system operator. Where an operator decides to install an earth at a joint bay the earth should be installed at a distance from buried pipelines that will ensure that the touch voltage created on a pipeline during fault conditions is within safe limits. AC and DC leakage currents through earth systems can also result in interference on buried utilities and should be minimized.

Additional information is given in Annex E.

6.5 Natural interference

6.5.1 General

Natural low frequency interference is caused by geomagnetic field variations and by tidal water movements.

6.5.2 Geomagnetic (telluric) interference

Geomagnetic field variations are variations in the earth's magnetic field. The geomagnetic field variations induce electric currents in the Earth and in long conductors such as pipelines and power

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transmission lines. These induced currents are generally referred to as telluric currents when related to pipelines and as GIC by the electric power industry. Both terms are used in literature and to be consistent with present pipeline practice this document will use the term telluric currents. (See Annex D for additional information).

6.5.3 Tidal interference effects

The movement of conductive seawater through the Earth's magnetic field acts like a dynamo and generates an electric field in the seawater. This drives an electric current (a flow of charge) in the seawater, perpendicular to the direction of water movement. Where this electric current meets the land, there is a build-up of electrical charge that creates a potential gradient both along the seafloor and inland perpendicular to the coast. (See Annex G for additional information).

7 Identification and measurement of stray current interference

7.1 Principle

The identification of the stray current interference is achieved by analysis of the measurements. The evaluation of the interference is performed by a comparison of the data with the acceptance criteria.

The measurements shall be planned to consider any known information relating to the interference acceptance criteria (Table 1 for DC). In particular, the following points should be considered:

— type of coupling of the interference (AC and/or DC);

— relative position to the stray current source (remote or nearby);

— anticipated duration of the anodic excursion ($T_{a,max}$);

— anticipated time dependence of the amplitude of $E_a - E_c$ as well as $J_a - J_c$ (Interference amplitude is constant or seasonally changing at constant T_a).

The measurement requires determination of the following:

a) the correct position for the reference electrode and/or coupons to be measured (See Annex B);

b) identifying the area of highest interference (Annex B);

c) Configuration of the coupon or probe (size and shape);

d) Connection of coupon or probe to the pipeline;

e) Sampling rate of the measuring system;

f) Duration of the measurements (see 7.3.6);

g) Switching ON/OFF ratio;

The evaluation of interference can be based on several different measurements at representative locations with respect to a reference electrode:

— structure potentials;

— current flowing through a coupon or probe;

— IR-free potential measurement of a coupon or probe;

— voltage between two reference electrodes;

— corrosion rate determined on a coupon or probe;

— line current measurement.

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A description of the representative location for determining the relevant position for a simple situation is given in Annex B for the case of a conductive coupling.

Annex C provides information on the operational principles of the electrical resistance (ER) probe.

7.2 Stray Current interference

7.2.1 Inductive and conductive coupling from remote sources

The worst-case assessment of interference in the case of inductive coupling and remote conductive coupling is obtained when placing the reference electrode at remote earth. The method for determining remote earth is described in ISO 18086:2019, Annex G. Since inductive coupling is usually associated with high isolation quality of the interfered structure, the positioning of the reference electrode above the interfered structure can be used as an approximation of the remote earth.

In such a configuration, the probe should ideally be installed next to the pipeline in the same bedding material as the pipeline, outside the influence of any field gradients generated by coating defects.

7.2.2 Conductive coupling from nearby sources

In the case of conductive coupling, the corrosive effect of the stray current is a result of the change in soil potential because of the electrical field generated by the stray current source. Therefore, the reference electrode or the probe shall be placed within the electrical field, taking into account worst-case situations. See Annex B for further information with respect to assessing worst-case conditions in the case of conductive coupling. The smallest distance of the pipeline to the interference source represents, in the case of conductive coupling, the portion of the pipeline with the largest level of interference. Therefore, the reference electrode, the coupon or the probe shall have a distance to the interference source that corresponds to this smallest distance. For specific conditions, this worst-case is given as follows:

— pipeline parallel to the rail: Reference electrode shall be placed above the pipeline;

— pipeline intersection with a rail: Reference electrode shall be placed above the pipeline with a distance to the outer rail that corresponds to the smallest distance between rail and pipeline;

— pipeline within the gradient of an anode bed: Reference electrode shall be placed above the pipeline at the location with the smallest distance between pipeline and anode.

There are cases where it is not possible to place the reference electrode, coupon or probe at the relevant location described above. In these cases, the electrical field distribution shall be assessed by measurement or calculation. The expected level of interference at the relevant position is then extrapolated based on the electrical field distribution to the position with the smallest distance between pipeline and interference source.

IEC 62128-2 and Reference [26] provide examples of a calculation method to determine the electrical field distribution from a rail. Based on these equations a correction for the electrode placement can be made.

7.3 Measurement of electrical parameters

7.3.1 Data acquisition systems

Sampling rates for potential, voltage and current measurements are typically between 0,1 s and 5 s for time variant values.

Coupon on/off measurements, for example, can require fast switching and sampling rates. Sampling rates shall be selected to enable accurate and meaningful measurement of the signal and phenomena under investigation.

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In the case of time variant DC interference such as tidal or telluric currents, longer intervals between the measurements can be used. The data acquisition system shall have an input impedance of at least 10 MΩ for voltage measurements.

7.3.2 Possible errors in AC measurements

ISO 18086[3] requires measured root mean square potential values as part of its risk assessment process. The r.m.s. values might not be correctly measured by some digital voltmeters if the AC waveform is not sinusoidal. Non-sinusoidal waveforms can occur if the load is non-linear (i.e. not predominantly resistive). Non-linear loads can include loads with inductive or capacitive components, e.g. switch mode power supplies, furnaces, industrial systems.

The harmonics produced when the load is non-linear distort the waveform and the triplen harmonics (3^{rd}, 6^{th}, 9^{th}, etc.) can significantly increase the peak voltage.

To measure the r.m.s. potential value correctly, digital voltmeters with a true rms function shall be used.

7.3.3 Potential measurement

The pipeline potential measurements shall be performed by connecting the data logger to the pipeline and a reference electrode. The positioning of the reference electrode depends on the type of interference and is described in Clause 7.

If no direct connection to the interfered pipeline is possible, the measurement with respect to remote earth can be performed. In this case, instead of the pipeline connection, a reference electrode at remote earth is connected to the data logger.

7.3.4 Current measurement on probes

The effect of the inclusion of the shunt in the circuit that is being measured should not result in a measurement accuracy worse than +/–2,5 % because of the shunt. A typical value for the shunt is 10 Ω. Lower value shunts can be necessary to measure currents greater than 1 mA.

7.3.5 IR-free potential measurement on coupons or probes

All IR-drop measurement errors shall be minimized by calculation or measurement. In the case of conductive coupling, the ohmic drops in the ground shall be considered. Possible methods include at least one, or a combination, of the following:

— positioning of the reference electrode permanently or temporarily close to the coupon or probe surface;

— interruption of the protection current through the coupon/probe;

— taking readings when the interfering source is out of operation;

— calculation of the IR-drop caused by the protection current;

— calculation of the IR-drop caused by the interference source.

7.3.6 Duration of the measurement

The data acquisition shall be performed over a representative period. The following aspects require consideration:

— in the case of a constant interference (e.g. cathodic protection) this corresponds to at least 3 cycles with the interference source switched on and off;

— in the case of time variant interference from timetabled traction systems an initial measurement should be performed for at least 24 h. From this data, the periods of the maximum and minimum

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interference can be determined. Subsequent measurements can be performed over a shorter duration in the period of the highest interference;

— in the case of a time variant interference (e.g. telluric, HVAC) with unknown operational characteristics, the measurement should be performed over a time period of at least 24 h with the period of maximum and minimum interference included.

In the case of known and documented interference frequency, shorter recording times can be used.

7.3.7 Specific requirements for coupons or probes

In the case of AC interference, the use of 1 cm^2 coupons is required by Reference [3]. For DC stray current interference different sizes of coupon can be used[6].

The current flow through a probe is dependent on its spread resistance. For buried pipelines the spread resistance is dependent on the soil resistivity as well as change of soil composition because of the current flow through the steel surface. The coupon shall be polarized until the IR-free potential has stabilized before making the measurement. This will allow for the formation of representative conditions.

It is not always possible to install the probe in the original soil. In this case a documented (i.e. chemical characteristics) replacement soil can be chosen that represents worst-case conditions (see Reference [6]).

7.4 Corrosion rate measurement

Acceptance criteria for DC interference can be based on either direct measurement of corrosion rate (see 8.2) or general electrical parameters (see 8.1) or a combination of both.

The measurement of the external corrosion rate is direct evidence of the effectiveness of cathodic protection. In the case of a probe or coupon the positioning at the representative location as described in 7.2 is required.

8 Acceptance criteria for DC interference

8.1 Overview of criteria

The level of stray current interference shall be deemed acceptable if the criteria mentioned in Table 1 are met.

For structures that are not cathodically protected the baseline value used to assess anodic and cathodic interference levels is the potential measured during periods when the interference is not present [Corrosion potential (E_{cor})].

For structures that are cathodically protected the baseline value used to assess anodic and cathodic interference levels can be the on potential required to achieve effective cathodic protection [Reference potential (E_{ref})].

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Table 1 — Overview of criteria for the assessment of stray current interference

	Non-cathodically protected	Cathodically protected
Steel and cast-iron structures		
Anodic interference (i.e. when the potential is more anodic than the potential during the periods of non-interference) Time constant	Anodic potential shift (relative to E_{cor}) ΔE_a (IR-drop included): $\Delta E_a \leq 300$ mV ($\rho > 200$ Ω·m) or $\Delta E_a \leq 1{,}5$ mV$(\Omega\cdot m)^{-1}\bullet\rho$ (15 Ω·m ≤ $\rho \leq$ 200 Ω·m) or $\Delta E_a \leq 20$ mV ($\rho < 15$ Ω·m) or anodic potential shift (relative to E_{cor}) $\Delta E_{a,IR\text{-}free}$ (IR- drop excluded): $\Delta E_{a,IR\text{-}free} \leq 20$ mV See 8.3.1.1.2	IR-free potential $E_{IR\text{-}free}$: $E_{IR\text{-}free} \leq E_p$ (E_p=protection potential according to Reference [7]) See 8.3.1.1.3
Cathodic interference Time constant	Cathodic potential shift ΔE_c: $\Delta E_c \leq 500$ mV (IR-drop included) See 8.3.1.2	
Anodic/cathodic interference Time variant	Average anodic potential shift (relative to E_{cor}) $\Delta E_{a,avg}$: $\Delta E_{a,avg} \leq \Delta E_a$ See 8.3.1.1.2	IR-free potential $E_{IR\text{-}free}$: $E_{IR\text{-}free} \leq E_p$ (E_p=protection potential according to Reference [7]) Shift of $E_{on,avg}$: $E_{on,avg} \leq E_{ref} - \Delta E_{a,avg}$ See 8.3.1.1.3[a]
	Average cathodic potential shift $\Delta E_{c,avg}$: $\Delta E_{c,avg} \leq 500$ mV (IR-drop included) See 8.3.1.2	
All conditions	Corrosion rate design value See 8.2	$v_{cor} \leq 0{,}01$ mm·a^{-1} See 8.2
Steel in concrete without cathodic protection		
Anodic interference Time constant Time variant	Anodic potential shift (relative to E_{cor}) ΔE_a: $\Delta E_a \leq 200$ mV see 8.4.1 $\Delta E_{a,avg} \leq 200$ mV see 8.4.2	
[a] Further information can be found in Annexes A and J.		

8.2 Corrosion rate

According to Reference [7] the pipe-to-electrolyte potential at which the corrosion rate is less than 0,01 mm per year (10 µm·a^{-1}) for carbon steel and cast iron is the protection potential, E_p. This corrosion rate is sufficiently low that corrosion will usually be acceptable for the design life. The corrosion rate criterion is therefore:

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v_{cor} ≤ 0,01 mm per year (10 µm·a^{-1})

It is possible that under certain interference conditions, this corrosion rate cannot always be met, and an accepted corrosion rate (design value) for a given design life shall therefore be considered. The accepted corrosion rate shall be justified and accepted by all interested parties.

For pipelines that are not cathodically protected, there is no active corrosion mitigation and the acceptable corrosion rate shall be the rate of corrosion used in the pipeline design.

For pipelines that are cathodically protected and subjected to external AC electrical interference[3], provides guidance on the corrosion risks associated with AC and combined AC and DC electrical interference.

These values can be measured in accordance with Annex B.

8.3 Criteria for steel and cast iron

8.3.1 Time constant interference

8.3.1.1 Anodic interference

8.3.1.1.1 General

The relevant anodic interference is evaluated from the anodic potential shift ΔE_a when the interfering source is in and out of operation.

8.3.1.1.2 Non-cathodically protected structures

Anodic interference shall be deemed acceptable if the criteria according to Table 2 are met.

Table 2 — Acceptable anodic potential shifts ΔE_a for buried or immersed steel or cast-iron structures that are not cathodically protected

Resistivity of the electrolyte (Ω·m)	**Maximum anodic potential shift ΔE_a** (mV) **(including IR-drop)**	**Maximum anodic potential shift $\Delta E_{a,IR\text{-}free}$** (mV) **(excluding IR-drop)**
≥200	300	20
15 to 200	1,5 mV (Ω·m)$^{-1}$ • ρ [a]	20
<15	20	20

[a] ρ in Ω·m.

8.3.1.1.3 Cathodically protected structures

Anodic interference shall be deemed acceptable if the IR-free potential of the structure, $E_{IR\text{-}free}$, meets the criteria for the protection potential, E_p, given by Reference [7].

8.3.1.2 Cathodic interference

The relevant cathodic interference is evaluated from the cathodic potential shift ΔE_c when the interfering source is in and out of operation. This value is determined by the difference of the potential measured with the interference source operating minus the potential with the interference source off.

Cathodic potential shifts, ΔE_c, due to cathodic interference on a certain part of a structure imply that there exist other parts that are subject to anodic interference, i.e. an anodic potential shift ΔE_a. If very negative potential shifts (e.g. ΔE_c > 500 mV, IR-drop included) are measured, it is recommended to

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identify areas with anodic potential shifts to confirm conformity with criteria mentioned in 8.3.1.1.2 and 8.3.1.1.3.

Values recorded during the non-operational period of the interfering system shall be considered as the normal or unaffected potentials.

8.3.2 Time variant interference

8.3.2.1 General

Subclause 8.3.2 covers time variant interference, e.g. due to DC operated railways, telluric currents and tidal effects.

The time (t) variations of the interference signal, e.g. $E(t)$ or $E_{on}(t)$, are considered to consist of successive intervals with anodic, $E_a(t)$, and cathodic, $E_c(t)$, polarization. The terms "anodic" and "cathodic" are defined with respect to a selected reference level E_{ref} (see Annex J) The interference signal is monitored over a representative duration.

$E(t)$ or $E_{on}(t)$ are measured with the reference electrode placed according to Annex B and without any coupon placed nearby.

For installed coupons, the assessment is based on the measurement of the coupon current (I_{cpn}), from which the current density (J_{cpn}) is calculated. Anodic and cathodic current densities that are due to time variant interference are defined with respect to a selected reference level J_{ref} (see Annex J).

8.3.2.2 Time variant anodic interference

8.3.2.2.1 Non-cathodically protected structures

The average anodic interference, $\Delta E_{a,avg}$, is assessed from a representative measurement of $E(t)$ showing intervals when the interfering source is in and out of operation.

A reference potential E_{ref} is evaluated from the interval when the interfering source is out of operation, e.g. during the night.

Intervals of anodic interference are identified from $E_a(t) = E(t) - E_{ref} > 0$, which had been measured over a representative time interval (see 7.3.6). The average anodic potential shift, $\Delta E_{a,avg}$, is evaluated from the average of $E_a(t)$ over the representative time interval.

Anodic interference shall be deemed acceptable if $\Delta E_{a,avg}$ is within the limits defined for ΔE_a (see 8.3.1.1.2).

8.3.2.2.2 Cathodically protected structures

One of these four methods can be used to determine whether the time variant interference is acceptable:

a) Time variant interference shall be deemed acceptable if the IR-free potential of the structure, E_{IRfree}, is within the limits for the protection potential, E_p, given by Reference [7]. The IR-free potential can be measured with the use of coupons.

b) The reference on-potential E_{ref}, at which effective CP in accordance with Reference [7] is just achieved, is determined during the period without interference (e.g. during the night in the absence of train operation). Subsequently the average anodic potential shift $\Delta E_{a,avg}$ is determined over a representative period of time, typically 24 h, with the CP system in continuous operation (no switching of the rectifiers). A sufficient level of cathodic protection is ensured, if the following equation is satisfied:

$$E_{on,avg} \leq E_{ref} - \Delta E_{a,avg}$$

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[This methodology is based on the assessment of traction system interference where the maximum interval ($T_{a,max}$) of anodic excursion does not exceed 250 s.]

NOTE The value of $T_{a,max}$ = 250 s is a conservative value derived from field measurements of typical DC traction interference.

c) Annex J provides a generalized description of the method (b) applicable for the entire frequency domain of stray current interference and details of the Q method. The Q method uses the ratio between the anodic and cathodic charge to determine if the level of interference is acceptable. This evaluation is more conservative when compared to (b) for $T_{a,max}$ greater than 250 s and less conservative for $T_{a,max}$ less than 250 s.

d) Annex A provides details of an alternative method. This method is more conservative than b) or c).

8.3.2.3 Time variant cathodic interference

Time variant cathodic interference can be expected, for example, from the anodes of potential controlled cathodic protection rectifiers. Analogous to $\Delta E_{a,avg}$ (see 8.3.1.1.2), the average cathodic potential shifts, $\Delta E_{c,avg}$, shall be evaluated from a record of the potential E (non-cathodically protected structures) or E_{on} (cathodically protected structures). If the evaluation yields very negative potential shifts (e.g. $\Delta E_{c,avg}$ > 500 mV, IR-drop included) it is recommended to identify areas with anodic potential shifts to confirm conformity with criteria mentioned in 8.3.2.2.

8.4 Criteria for steel pipes in concrete based on potential measurements without cathodic protection

8.4.1 Time constant anodic interference

The relevant anodic interference is evaluated from the potential shift ΔE_a when the interfering source is in and out of operation.

Anodic interference shall be deemed acceptable if ΔE_a < 200 mV.

8.4.2 Time variant interference

Analogous to 8.3.2.2, the relevant anodic interference is evaluated from the average potential shift $\Delta E_{a,avg}$ when the interfering source is in and out of operation. Anodic interference shall be deemed acceptable if $\Delta E_{a,avg}$ < 200 mV.

9 Reduction of DC stray current interference

9.1 General

Measures taken to minimize the effects of stray current interference should commence with the source of the interference. If this is impractical or ineffective, then attention should be turned to the interfered structure. In some cases, it is necessary to introduce interference mitigation measures to both to achieve an acceptable interference level.

It is possible that the source of interference originates from a structure that is itself interfered with. This is known as secondary interference. Where secondary interference exists, it is advised to modify the original source of interference first. The source of secondary interference might have to be modified if it is not possible to modify the original source.

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9.2 Modifications to the source of interference

9.2.1 Principles

Under normal operating conditions the earth shall not be used to carry any direct currents. Exceptions to this principle are:

— cathodic protection systems;

— DC traction systems (within the limits given in IEC 62128-2).

Structures which are a source of interference shall not be connected to foreign buried or immersed metal structures unless it is necessary for safety or stray current corrosion protection reasons.

9.2.2 Direct current systems at industrial sites

All conductors of direct current systems (such as direct current power systems and direct current welding equipment) should be insulated from earth. When, for some reasons, (e.g. for the safety of personnel) earthing or equipotential bonding is necessary, special care shall be taken in order to avoid stray currents, for instance earthing at only one point.

For welding operations, the weld current circuit shall be as short as possible. Earthed metal structures such as railroad or crane tracks, overhead pipe crossings or other foreign buried pipelines shall not be used to conduct welding current.

9.2.3 Direct current systems at ports

9.2.3.1 Cranes

New crane installations at ports should be designed for alternating current operation with any direct current required for crane operation generated locally at the point of use. Each conductor carrying direct current should be insulated from earth.

If a direct current crane system cannot be operated without an earth connection, as in the case of an existing installation, special measures shall be taken in order to avoid stray currents, e.g. by installing an insulated return conductor.

9.2.3.2 Quayside direct current welding stations

Each ship shall be served by one or several independent quayside welding stations. A single direct current welding system serving several ships can be a source of stray currents between the ships causing severe dolphin or fender corrosion damage as stray current interference is not significantly reduced by equipotential bonds between ships. Pipelines can be similarly affected.

9.2.3.3 Direct current power supply to ships

Direct current power systems on ships featuring complete earth insulation and earth protective relays are often supplied with DC electric power from shore.

If a direct-current power system on a ship features single phase earthing, alternating current power shall be supplied to the ship and rectified on board for use in the direct-current power systems.

9.2.4 Direct current traction systems

Stray current from DC tractions systems is an inevitable consequence of the use of the running rails as the return circuit for the traction supply current. There are two types of earthing systems commonly used in such systems: the earthed system and the floating earth system. In a floating system, the running rails (and, hence, the DC negative bus) are allowed to float with respect to earth. In an earthed system, the running rails are effectively bonded (solidly or through a diode) to earth at the substation.

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The earthed system holds the negative potential at, or near, earth potential. With this arrangement, stray currents might be increased with respect to a floating earth system, other things (substation spacing, conductivity and insulation of the return circuit, power supplied, etc.) being equal. From the stray current corrosion point of view earthed systems are to be avoided. Modern DC operated railways use a floating earth system in accordance with IEC 62128-2.

All modern traction systems will use a current feedback system during braking (i.e. regenerative braking).

The stray current control design requirement is to minimize the impact of the stray current on the supporting infrastructure and on third party infrastructure. Acceptable stray current control can be achieved by a set of measures, mostly, at the design phase. The control methods to be carried out shall conform with the requirements given IEC 62128-2. The set of measures for any individual DC traction system is a balance of the different constraints each system will have. In broad terms, DC traction design issues that impact on stray current can be summarized as:

a) conductivity of the return circuit (e.g. the rails);

b) insulation of the return circuit from earth;

c) spacing of supply substations;

d) substation and system earthing;

e) regenerative braking.

Many of these parameters are inevitably fixed early in the design process. Once a system is operational, the largest sole factor that modifies the stray current levels is the resistance of the rails to earth[8] [9]. Poor control of the resistance of rails to earth can be the critical factor behind excessive rail and infrastructure corrosion.

9.2.5 Cathodic protection systems

9.2.5.1 Adjustment of transformer rectifier output

The current output of the rectifier installed on an interfering structure shall be adjusted to the minimum level required to achieve cathodic protection (see Reference [7]). The possibility of distributing the total current by additional rectifiers and groundbeds helps to control DC interference and reduce the risk of over-polarisation.

9.2.5.2 Increasing coating resistance

Structures with high quality coatings (e.g. $>10^6$ $\Omega \cdot m^2$) require less cathodic protection current and hence minimize the risk of stray current interference from their cathodic protection system.

Coating defects on a cathodically protected structure might need to be located and repaired with a high-quality coating if the level of interference to nearby structures is to be reduced.

9.2.5.3 Groundbed location

The interference from impressed current anodes depends on the anode current output, distance to neighbouring structures, and the resistivity of the surrounding medium.

The soil potential gradient will determine the level of interference to adjacent structures. Calculations can be made using standard formulae or modelling (see Reference [10]). Annex I provides general requirements for modelling.

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The interference can be reduced by ensuring that the neighbouring structures are not within the area of the anode field where the potential gradient causes the potential to shift outside the limits detailed in Clause 8. This can be achieved by the following:

— increasing the distance from the anode to neighbouring structures (either horizontally or vertically) - this is the most effective method;

— reducing the voltage gradient around the groundbed by enlarging the groundbed geometry or by reducing the current output;

— locating distributed anodes close to the structure to be protected;

— the use of linear anodes close to the structure to be protected.

9.2.6 Telluric interference

The basic mechanism for telluric interference is that the geomagnetic field variations induce an electric field in the pipeline that drives currents in the pipeline. Where currents flow on or off the pipeline, the flow through the resistance between the pipe and the ground (e.g. coating resistance or groundbed resistance) produces a voltage drop (Ohm's Law). This is seen as a telluric variation in the structure-to-electrolyte potential. Normally, the telluric current flows onto the pipeline at one end, along the pipeline, and discharges to ground at the other end of the pipeline. If there is a low resistance between the pipe steel and the ground, either intentionally because of good ground connections or unintentionally because of a poor coating, the voltage-drop produced by the telluric current will be small and the telluric interference will be small. However, anything that obstructs the flow of telluric current on, along, and off the pipeline will increase the voltage drop. (See Annex D for additional information).

Factors in pipeline design that should be considered when assessing the voltage drop caused by telluric interference that might occur are as follows:

— modifications to the interfered structure coating resistance. Higher coating resistance leads to larger telluric fluctuations;

— the length of electrically continuous pipeline. Longer pipelines experience larger fluctuations;

— the use of insulating flanges. Insulating flanges will divert the telluric current off the pipeline, into the ground, and back onto the pipeline. This results in anti-phase potentials either side of the insulation;

— bends, (Telluric currents tend to flow on and off the pipeline at bends);

— changes in the series resistance of the pipeline system;

— location of groundbeds and the use of potential controlled transformer-rectifiers.

9.2.7 Direct current communication systems

Direct currents from communication systems shall not be the source of any stray-current interference with nearby pipelines or cables. Pipelines or cables shall not be used for earthing connections.

10 Modifications to the interfered structure

10.1 General

Modification to the interfered structure can consist of one or more of the following:

a) application of mitigation (e.g. raise local soil potential, see Reference [11]);

b) modifying the electrical continuity of the interfered structure (e.g. installation of isolation joints);

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c) increasing the distance from the interfering structure.

Bonding between the source of interference and the interfered structure should only be used as a last resort and even then, only after careful consideration of the secondary and long-term effects that the bonding might have.

The choice of remedial measures that can be applied to the interfered structure is dictated by criteria relating to both the interfering and the interfered structure includes the following:

— the location of the interfering source, which can be important in finding a solution that is both technically and economically satisfactory;

— the electrical status of the interfered structure (e.g. the nature of its insulation), its electrical continuity and whether cathodic protection is applied;

— the electrical status of the interfering structure (e.g. the nature of its insulation), its electrical continuity and whether cathodic protection is applied;

— the characteristics of the environment between the interfered structure and the interfering structure (soil conductivity and presence of nearby metallic structures).

10.2 Design prerequisites

10.2.1 Coatings

The application of high resistance coatings to the interfered structure reduces the overall level of stray currents in the structure due to an increase of the structure to soil resistance. This simplifies the design and operation of countermeasures that might be required but is not necessarily a cost-effective solution.

10.2.2 Isolation from other structures

There should be no unintentional direct metal contact with stray current sources or other metal structures (e.g. casings) that might be affected by stray currents; e.g. reinforced concrete structures shall have no direct metal contact with stray current sources.

10.2.3 Distance to be maximized

Since the interference level decreases with distance, new structures should be located as far as possible from known stray current sources.

10.2.4 Installation of mitigation devices

10.2.4.1 General

The installation of mitigation devices aims to reduce or eliminate stray current interference from the interfered structure directly into the environment, to meet the criteria detailed in Clause 8.

This can be achieved by the following:

— application of impressed current cathodic protection;

— shifting the structure potential more negative via bonding.

When using these techniques, the selection of a suitable site for the permanent or temporary reference electrode for measurement or sensing shall be made with care (see Clause 7 and Annex B).

In all cases the devices shall be adjusted so that the minimum current is used to achieve the desired objective.

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The application of these measures requires the co-operation and approval of the concerned parties (see Clause 5).

10.2.4.2 Cathodic protection

A cathodic protection system, when properly designed and applied, can mitigate the adverse effects of stray current interference. This can be achieved in two ways. Either by conventional cathodic protection using the methods detailed in Reference [7] or by adjusting the soil potential gradient in accordance with Reference [11] in order to satisfy the criteria in Clause 8.

10.2.4.3 Bonding

Bonding is intended to shift the potential of the interfered structure more negative (cathodic). This can be achieved via a direct drainage bond or a unidirectional drainage bond from the interfered structure back to the DC current source. In some circumstances, it is necessary to use a forced drainage bond, which will require a dedicated power source.

The inevitable consequence of this, however, is that all bonding has the possibility to increase the overall amount of stray current generated. This risk can be controlled using series resistors. For this reason, bonding shall only be considered as a last resort.

For cathodically protected structures, there shall be no direct drainage bonds to time variant interference sources. (e.g. DC traction systems).

In all cases the devices shall be adjusted so that the minimum current is used to achieve the desired objective.

The application of these measures requires the co-operation and approval of the concerned parties (see Clause 5).

Following such a connection, investigations should be carried out on the source, and nearby or crossing foreign structures. If necessary, further counter-measures should be carried out.

This method is not intended to provide cathodic protection to the interfered structure.

10.2.4.4 Earthing electrode system

The use of electrical earthing electrodes or earth mats to reduce the effects of DC stray current, either temporarily or permanently, is not recommended. The risks of increasing the stray current effects outweigh the possible benefits.

If earth electrodes are used for temporary mitigation of AC interference, then they shall be cathodic with respect to the structure to be protected (e.g. zinc, magnesium).

In the case of permanent AC mitigation, the electrodes should be connected via a DC decoupling device unless they are specifically required by design to provide cathodic protection to the pipe.

10.2.5 Modifying the electrical continuity of the interfered structure

For stray current interference on long structures (e.g. steel pipelines or reinforced concrete structures), it might be possible to limit the area of the structure exposed to interference by electrically isolating sections of the structure and hence to reduce the potential difference between the structure and the electrolyte. Electrical isolation can be achieved by installing isolating joints (see Reference [7] for more information).

When isolating joints are used for this purpose, precautions should be taken to ensure that no corrosion is caused at the isolating joint by current flow across the isolating joint via the ground[12]. The criteria mentioned in Clause 8 shall be met.

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For pipes carrying a conductive electrolyte, precautions should be taken against possible internal corrosion on the pipe wall at the anodic side of the isolating joint (see Reference [7]).

Due to their isolating seals, interference on coated cast iron pipes only needs to be considered in areas with steep potential gradients (e.g. exceeding 200 mV per individual pipe length). Such conditions can occur within 10 m around the rails of DC operated traction systems and in the vicinity of ground beds. If unacceptable interference is expected, the pipe joints shall be short-circuited by cables and measures detailed in 10.2.4 shall be applied.

11 Inspection and maintenance

All plant and equipment which has been installed to limit the flow of stray current into the electrolyte, or to mitigate its effect, should be inspected and maintained at prescribed intervals at least according to the intervals given in Reference [7].

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Annex A
(informative)

Use of current probes to evaluate fluctuating stray current interference on cathodically protected structures

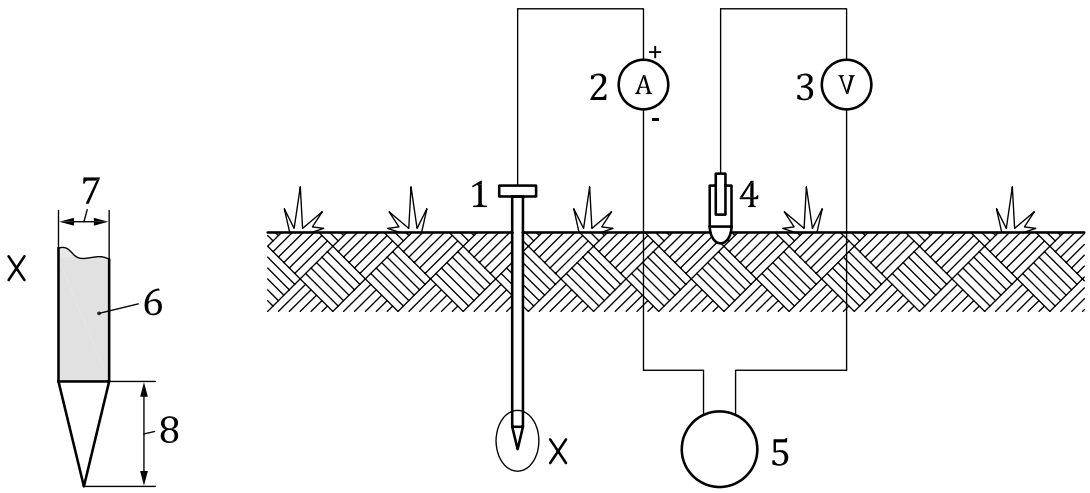
A.1 General

A.1.1 Background

This method was developed from practical experience in the Netherlands for pipelines historically being operated at on potentials between –0,85 V to –1,0 V_{CSE}. The corrosion risk is correctly assessed when applied under these conditions. This method, however, can result in an over-estimation of the corrosion risk when more negative levels of cathodic protection are applied.

A.1.2 Measuring method

Current probes can be used to evaluate fluctuating stray current interference on cathodically protected structures. A typical method to carry out the measurement with current probes is shown in Figure A.1:



Key

1 Probe
2 recording ammeter
3 recording voltmeter
4 electrode
5 structure
6 Insulation
7 16 mm diameter (for example)
8 65 mm (for example)

Figure A.1 — Measuring method

An insulated steel probe with a bare steel surface is pushed into the ground to the depth of the pipeline (see Annex B for further guidance on coupon positioning). The probe is electrically connected to the pipeline. The bare surface of the probe now functions as the steel surface in a simulated coating defect.

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The recording ammeter is used to determine the direction and the magnitude of the current. The measurement is typically carried out during a period of 24 h.

A.2 Measurement evaluation

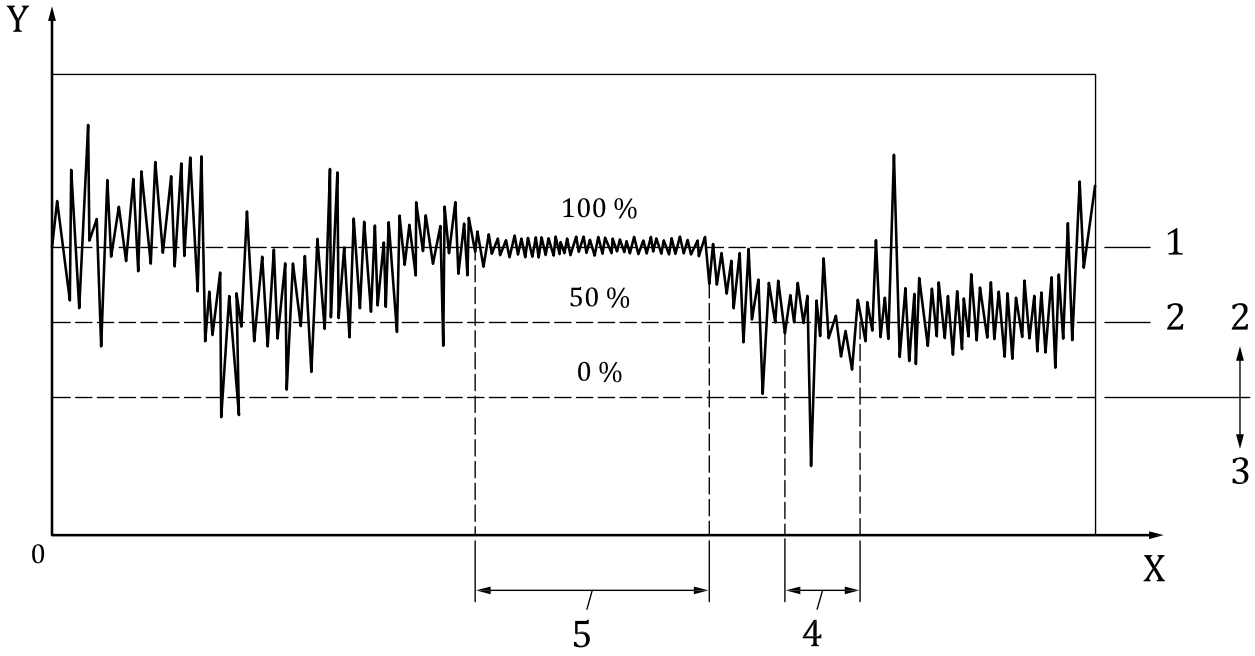
A.2.1 The probe current corresponding to the cathodic protection potential of the pipeline (in accordance with ISO 15589-1) is measured during a period when the pipeline is not interfered by fluctuating stray current (e.g. at night). This probe current is defined as 100 % (reference value) as shown in Figure A.2, period "A").

A.2.2 The probe current (the result of cathodic protection current and stray current) is continuously recorded during a period of typically 24 h.

A.2.3 For evaluation, the hour with the highest probe current reductions (i.e. the hour with the most positive potential fluctuations) is identified (period "B" in Figure A.2).

A.2.4 Probe currents below any of the values given in column 1 of Table A.1 indicate a high risk of corrosion if their accumulated duration exceeds the corresponding values of column 3 of Table A.1.

Corrosion risk is shown graphically in Figure A.3.



Key

1 reference level
2 entering
3 leaving
4 period B (worst hour)
5 period A
Y probe current, in mA
X time, in hours
A period in which the reference level is measured
B period with the highest reduction of the reference level

Figure A.2 — Example of the result of a probe current measurement

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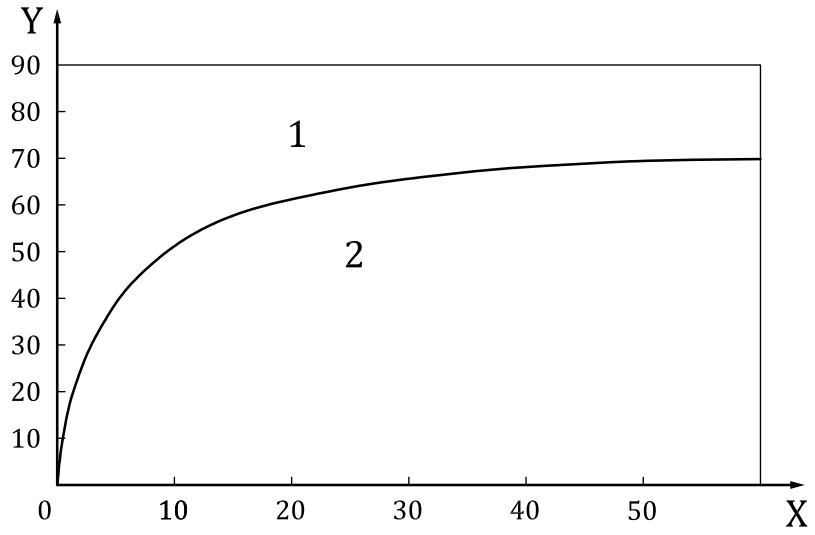
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Table A.1 — Current criteria in case of interference due to DC traction systems

Probe current of the reference level %	Maximum acceptable occurrence period	
	worst hour %	in seconds
>70	Unlimited	unlimited
<70	40	1 440
<60	20	720
<50	10	360
<40	5	180
<30	2	72
<20	1	36
<10	0,5	18
<0	0,1	3,6

NOTE 1 The figures in Table A.1 are based on practical experience.

NOTE 2 Evaluation according to Table A.1 might result in an overestimation of the corrosion risk in cases where the IR-free potentials (e.g. as measured in step 1) is considerably (e.g. 250 mV) more negative than the protection potential according to ISO 15589-1.



Key

1 low risk of corrosion
2 high risk of corrosion
X time in % worst hour
Y probe current in % of cathodic protection current

Figure A.3 — Graphical representation of Table A.1

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Annex B
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Determining the relevant position for placing reference electrodes, coupons and probes in case of any conductive coupling caused by stray currents

B.1 Introduction

The stray current leaving the rail causes an ohmic drop ΔE in the soil, which is picked up by the two coating defects shown in Figure B.1. Since the two coating defects have identical size and, therefore, similar spread resistance, the anodic potential shift ΔE_a and the cathodic potential shift ΔE_c can be assumed to be identical in a first approach.

The measurement of the stray current interference in the configuration in Figure B.1 will result in the correct determination of the anodic interference ΔE_a caused by the stray current. The field distribution shown in the lower image in Figure B.1 represents the field distribution picked up by the reference electrode at the soil surface with respect to remote earth. The potential distribution shown in Figure B.1 represents the field distribution picked up by the reference electrode at the soil surface.

Applying the interference levels in Clause 8 will allow for estimating the actual corrosion risk. Clearly, the configuration with only two coating defects does not represent a typical interference case. Instead, a large number of coating defects remote from the intersection may be assumed. Hence, the spread resistance of the one coating defect within the stray current gradient in the crossing area is significantly larger than the one of all the remote coating defects. This configuration is illustrated in Figure B.2, where the large number of small coating defects remote from the crossing is illustrated with one large coating defect. The potential drop ΔE is in this configuration no longer equally shared among the two coating defects. Instead, a strong cathodic interference ΔE_c on the small coating defect and a weak anodic interference ΔE_a on the large coating defect are observed. This confirms that a stray current leaving the rail causing a cathodic interference does in most cases not lead to a critical anodic interference.

The situation is more complex in the case of a stray current returning to the rail in the case of a cathodic rail potential as illustrated in Figure B.3. The measurement results in a small cathodic interference, while the small coating defect at the crossing with the rail experiences a strong anodic interference. Hence, the measurement not only lead to an erroneous value with respect to the extent of the interference, but also with respect to its polarity. A more detailed analysis of the situation reveals clearly that the anodic interference cannot be assessed based on a potential measurement in the given configuration. The same applies to a coupon placed in the ground below the reference electrode in Figure B.3. Similar to the reference electrode, the coupon will experience a small cathodic interference.

The position of the reference electrode with respect to the rail is crucial for the assessment of the stray current risk. In Figure B.4 the effect of different reference electrode positions with respect to the rail is illustrated. At position (a) a small cathodic shift, at position (b) no shift, at position (c) an anodic shift and at position (d) a strong anodic interference ΔE_m is measured. This is primarily the result of the positioning of the reference electrode within the gradient caused by the rail. This consideration demonstrates that based on the positioning of the reference electrode, any interference value can be obtained. None of the interference levels ΔE_m in Figure B.4 corresponds however to the actual interference at the coating defect.

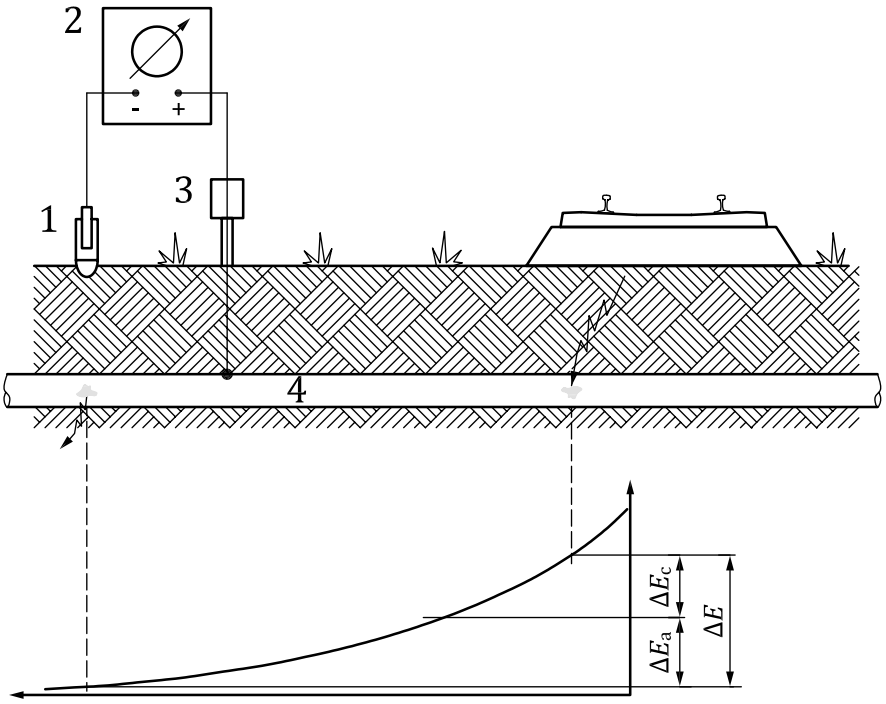
Similarly, coupons buried at pipeline depth below the reference electrodes would not reveal the actual interference condition of the critical coating defect. Both the potential and the coupon measurement significantly underestimate the actual corrosion risk at any of the locations (a) to (d). The situation is further complicated by the fact, that a measurement at position (d) would indicate an anodic

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interference even in absence of any coating defects within the gradient of the rail. The optimum coupon and reference electrode location is described in B.2 and shown in Figure B.5.

The discussion of the experimental problems associated with the assessing of the stray current interference demonstrates that the actual stray current interference can only be determined based on a more profound analysis. Most stray current measurements without consideration of these aspects results in a significant underestimation of the actual corrosion risk. This is not only true with respect to the extent of the interference but also with respect to its polarity.



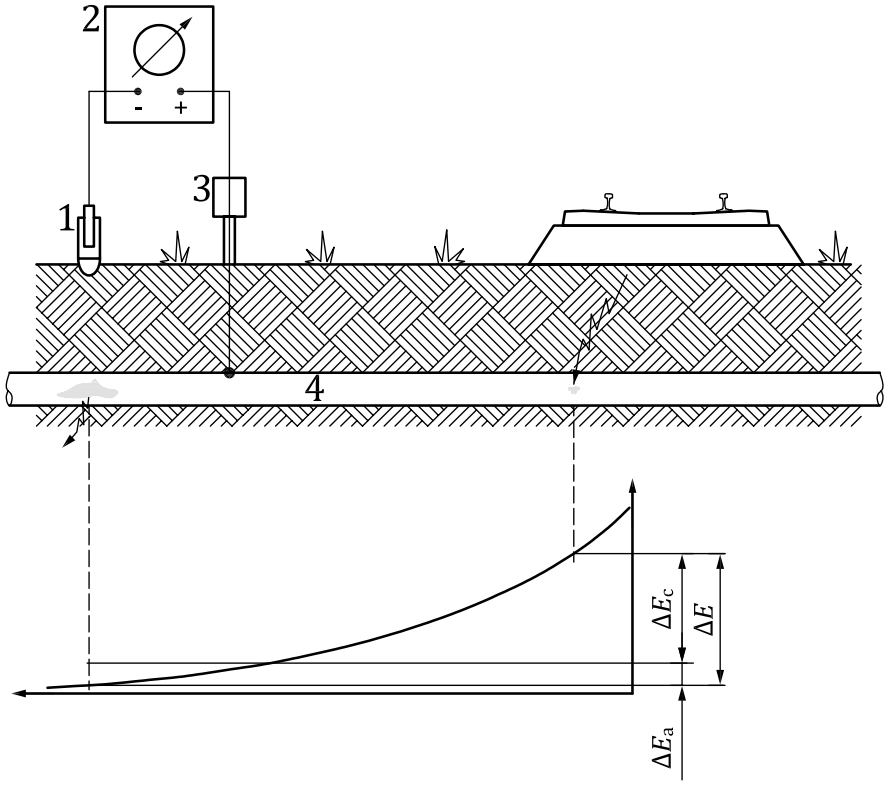
Key

1	electrode	ΔE	voltage shift
2	voltmeter	ΔE_a	anodic shift
3	test post	ΔE_c	cathodic shift
4	structure		

Figure B.1 — Stray current interference of a pipeline with only two identical coating defects. The potential distribution shown at the bottom illustrates the potential distribution at the soil surface

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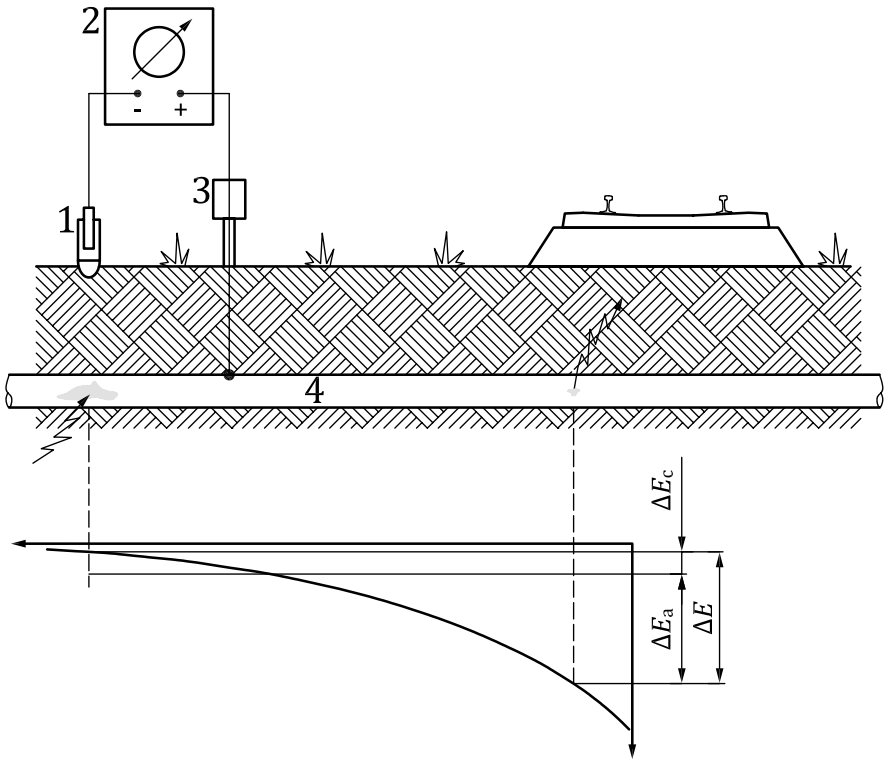
Key

1	electrode	ΔE	voltage shift
2	voltmeter	ΔE_a	anodic shift
3	test post	ΔE_c	cathodic shift
4	structure		

Figure B.2 — Cathodic stray current interference of a pipeline with asymmetric distribution of the coating defects corresponding to a typical configuration

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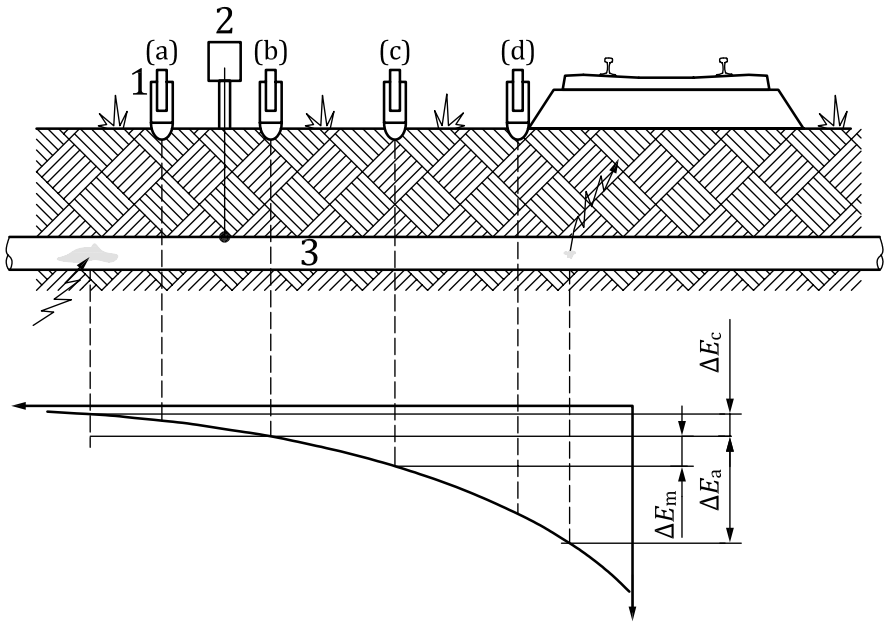
Key

1	electrode	ΔE	voltage shift
2	voltmeter	ΔE_a	anodic shift
3	test post	ΔE_c	cathodic shift
4	structure		

Figure B.3 — Anodic stray current interference of a pipeline with asymmetric distribution of the coating defects corresponding to a typical configuration

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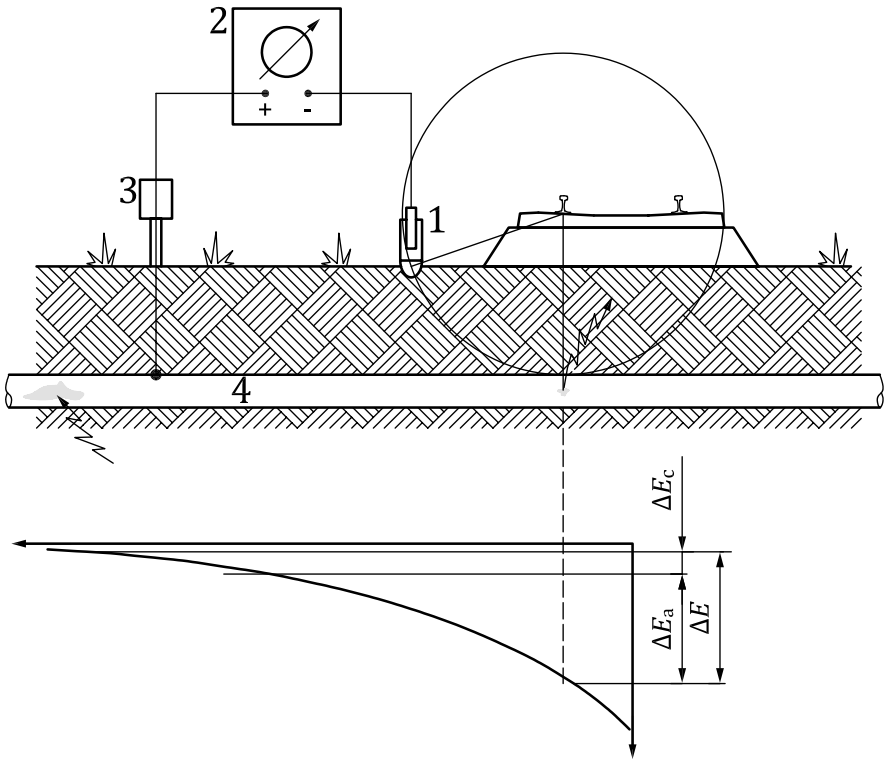
Key

1	(a), (b), (c), (d) electrodes	ΔE_m	measured interference
2	voltmeter	ΔE_a	anodic shift
3	structure	ΔE_c	cathodic shift

Figure B.4 — Anodic stray current interference of a pipeline with asymmetric distribution of the coating defects corresponding to a typical configuration

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Key

1	electrode	ΔE	voltage shift
2	voltmeter	ΔE_a	anodic shift
3	test post	ΔE_c	cathodic shift
4	structure		

Figure B.5 — Correct positioning of the reference electrode (or coupon) for correct assessment of the anodic stray current interference of a pipeline

B.2 Optimized assessment of the stray current interference

Since the direct assessment of the stray current interference is not possible based on a potential or a coupon measurement in the given configuration, the question arises with respect to an improved measurement method. The above argumentation has clearly demonstrated that the positioning of the reference electrode within the gradient of the track only leads to a measurement of the gradient rather than the actual interference of a coating defect. Even in absence of a coating defect on the pipeline a similar interference level will be obtained. Consequently, any measurement can only be done based on a worst-case consideration with the assumption of the presence of a coating defect. The worst position of the coating defects is at the closest approach of the pipeline to the track exhibiting the largest gradient. Assuming a homogeneous soil resistivity and a homogeneous current distribution, it follows immediately that this worst-case interference can be determined by placing the reference electrode or coupon at the same distance to the rail. This configuration is illustrated in Figure B.5 for anodic stray current interference of a pipeline with asymmetric distribution of the coating defects corresponding to a typical configuration. The measured interference is illustrated by means of ΔE_m.

This concept applies similarly to a pipeline parallel to the rail. In this case, however, the measurement shall be performed in that part of the parallelism with the most negative rail potential and/or the poorest rail to earth insulation resulting in the maximal voltage gradient in the soil.

In many cases, the positioning of the reference electrode is not necessarily possible in the required location. This especially is true in the case of a stray current interference caused by a cathodically protected pipeline on a non-protected pipeline. Since the distance between the pipelines is typically

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smaller than the pipe depth any measurement performed above the intersection of the two pipelines is bound to result in an important underestimation of the actual interference level.

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Annex C
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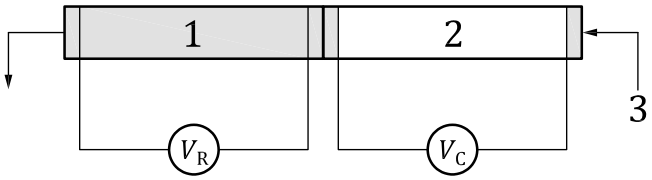
Operating principles of electrical resistance probes

The Electrical Resistance or ER probe technique can be applied for corrosion rate assessment. Other coupon quantities such as instant-off potential, AC current density, DC current density, spread resistance, etc. can also be measured using ER probes.

The ER technique consists in measuring the change of the resistance of a metal element. When the metal element suffers from metal loss due to corrosion, the electrical resistance of the element increases. Since the resistance of the element also changes due to temperature variations, a second element, which is coated to protect it from corrosion, is utilized for temperature compensation. The probe then consists of an element exposed to the corrosive environment (coupon element) and the element protected from corrosion by the coating (see Figure C.1).

When current is exchanged between the exposed element and the soil, the ER technique should provide means for temperature compensation due to heating of the exposed element by the current exchange in addition to the conventional temperature compensation.

The resistance values of the two individual elements are usually measured by passing an excitation current through the elements and measuring the voltage generated over the element length caused by the excitation current.



Key

1 reference element - R_r

2 coupon element - R_c

3 excitation current

Figure C.1 — Principle of ER probe with excitation current and voltage measurement

The thickness of the exposed element at time (t) can be assessed throughout time using the sketched circuit principle. The exposed element thickness at time (t) is then quantified by a formula, for instance:

$$d(t) = d(t=0) \cdot \frac{R_r(t)}{R_c(t)} \cdot \frac{R_c(t=0)}{R_r(t=0)}$$

where

($t = 0$) refers to initial probe conditions;

R_r reference element resistance (Ω);

R_c coupon element resistance (Ω).

The slope of a thickness versus time curve can be used for simple assessment of the corrosion rate.

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Annex D
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Geomagnetic interference

D.1 Introduction

The influence of telluric effects can be a concern for maintaining proper cathodic protection for pipelines and can be seen on pipelines around the world. Telluric effects have previously been seen mainly at high latitude locations but are now also being seen on pipelines at lower latitudes.

Telluric currents in pipelines are driven by the electric fields produced by geomagnetic disturbances and cause changes in the measured pipe-to-soil potential. Modelling methods have been developed that allow the telluric potentials to be determined for specified electric fields[13]. These show that the largest potential variations occur where the pipeline structure disrupts the flow of telluric currents along the pipeline, for example at bends, insulating flanges, and the ends of the pipeline. The magnitude of the pipe-to-soil potential variations is influenced by the electrical properties of the pipeline. The use of coatings with higher electrical resistance has resulted in larger pipe-to-soil potential variations than on older pipelines with lower electrical resistance (i.e. more earthy).

This annex shows how a pipeline network can be modelled to determine the telluric potentials produced by specified electric fields. This employs a combination of transmission line theory to describe the variation of telluric potentials within a pipeline section and network modelling techniques to determine the potentials at the junctions between sections of a pipeline network.

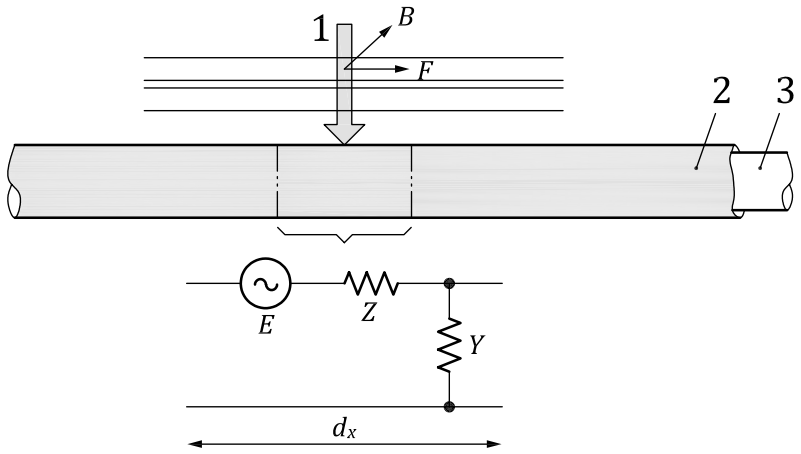
An example network is used with typical pipeline features e.g. bends, change of pipeline dimensions, junctions with a branch line, and insulating flanges. Numerical values for each step of the process are provided so that the example can be used as a test case for telluric modelling software.

D.2 Pipeline Modelling

Telluric currents are produced by a geomagnetic disturbance with electric field, F, and magnetic field, B, incident on the pipeline as shown in Figure D.1. This can be modelled by considering the pipeline as a transmission line with series impedance Z and parallel admittance Y, and the induced electric field represented by a voltage source, E, in each distributed element (Figure D.1).

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Key

1	incident field	B	magnetic field
2	coating	F	electric field
3	pipe steel	d_x	distance

Figure D.1 — Schematic of electromagnetic induction in a pipeline and the equivalent circuit for a short pipeline section

The series impedance, Z, is given by the resistance per unit length ($\Omega \cdot km^{-1}$) along the pipeline. This can be calculated from the steel resistivity, ρ, and the cross-sectional area of the pipeline steel as shown in Formula (D.1).

$$Z = \frac{\rho}{\pi\left(r_o^2 - r_i^2\right)} \tag{D.1}$$

Where r_o and r_i are the outer radius and inner radius of the pipe respectively.

The parallel admittance, Y, expressed in Siemens per unit length ($S \cdot km^{-1}$), is determined from the coating conductance, C, and the surface area per unit distance of the pipeline as shown in Formula (D.2).

$$Y = C\ 2\pi r_o \tag{D.2}$$

These parameters can be used to give the propagation constant, γ, and the characteristic impedance, Z_0, that describe the electrical response of the pipeline as shown in Formulae (D.3) and (D.4).

$$\gamma = \sqrt{ZY} \tag{D.3}$$

$$Z_0 = \sqrt{\frac{Z}{Y}} \tag{D.4}$$

For a pipeline section of length, L, running from node i to node k, the transmission line equations are used to derive equations for the voltage and current as a function of distance, x, along the pipeline.

$$V = \left(\frac{V_k e^{\gamma L} - V_i}{e^{\gamma L} - e^{-\gamma L}}\right) e^{-\gamma(L-x)} + \left(\frac{V_i e^{\gamma L} - V_k}{e^{\gamma L} - e^{-\gamma L}}\right) e^{-\gamma x} \tag{D.5}$$

$$I = -\frac{1}{Z_0}\left(\frac{V_k e^{\gamma L} - V_i}{e^{\gamma L} - e^{-\gamma L}}\right) e^{-\gamma(L-x)} + \frac{1}{Z_0}\left(\frac{V_i e^{\gamma L} - V_k}{e^{\gamma L} - e^{-\gamma L}}\right) e^{-\gamma x} + \frac{E}{\gamma Z_0} \tag{D.6}$$

Where V_i and V_k are the voltages at nodes i and k respectively.

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Evaluation of the telluric interference on a complete pipeline network requires a network of pipeline sections that takes into account the changes in direction of the pipeline and changes of pipeline properties, for example between a main pipeline and branches. The junctions between sections are then defined as nodes in the network. The formulae for voltage and current in each section are still given by Formulae (D.5) and (D.6) but the voltages at each node depend not only on the conditions in one section but also on the other sections of the network. These nodal voltages can be calculated by modelling the pipeline as a nodal admittance network.

To construct the nodal admittance model each pipeline section is represented by its equivalent-pi circuit as shown in Figure D.2 where the circuit components are given as Formulae (D.7), (D.8) and (D.9):

$$Y_E = \frac{1}{Z_0 \sinh \gamma L} \tag{D.7}$$

$$\frac{Y'}{2} = \left(\cosh \gamma L - 1\right) \frac{1}{Z_0 \sinh \gamma L} \tag{D.8}$$

$$I_E = \frac{E}{Z} \tag{D.9}$$

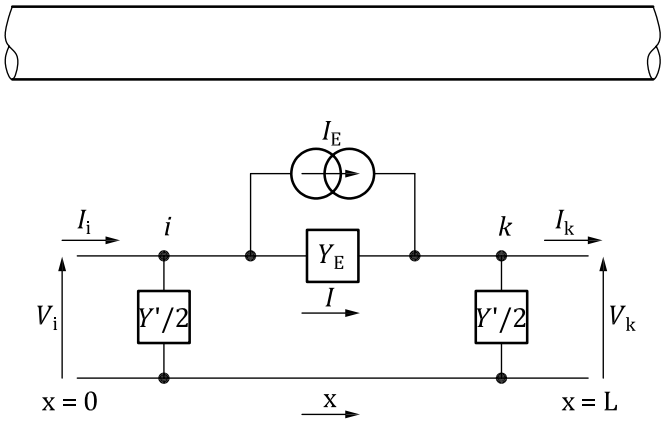
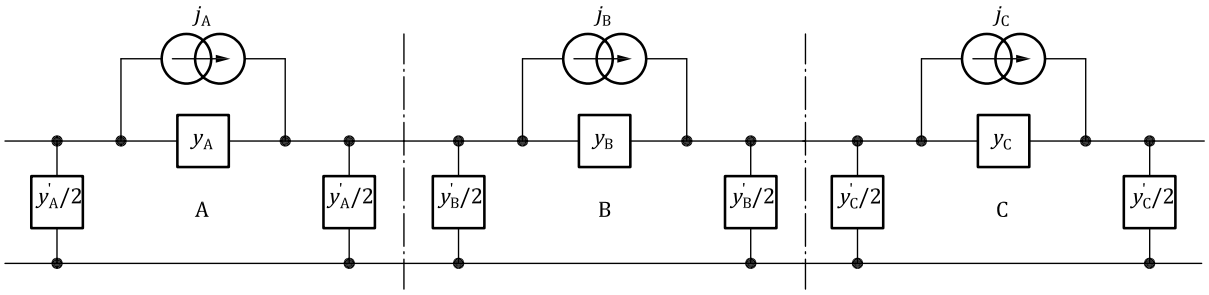


Figure D.2 — Equivalent-pi circuit for a pipeline section

The equivalent-pi circuits are then combined into a nodal admittance network, by adding the $Y'/2$ values for all equivalent-pi circuits that share a common node to give an admittance to ground from that node. For example, the equivalent-pi sections shown in Figure D.3 (top) are combined to give the admittance network of Figure D.3 (bottom) where the junction between sections A and B becomes node 2 and the junction between sections B and C becomes node 3 and the admittance to ground at these nodes is given by combining the admittances from the adjacent sections.

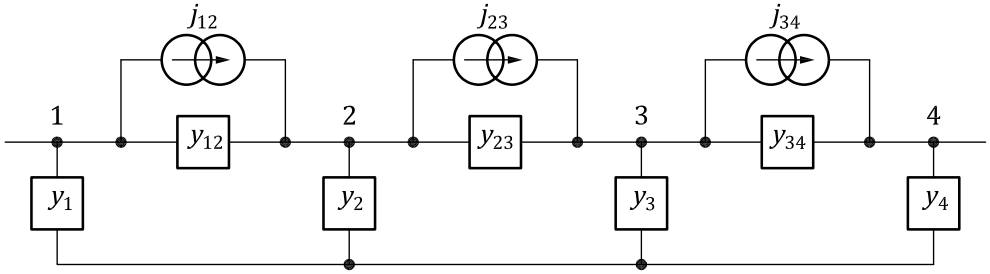
$$y_2 = \frac{y'_A}{2} + \frac{y'_B}{2} \qquad y_3 = \frac{y'_B}{2} + \frac{y'_C}{2} \tag{D.10}$$



a) Equivalent-pi sections for a pipeline

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b) A nodal admittance network

Figure D.3 — Pipeline represented as equivalent pi sections and a nodal admittance

This approach forms a nodal admittance network that can be used to calculate the telluric potentials in any general pipeline network. For each pipeline section between two nodes *i* and *k*, the section length, pipeline characteristics and induced electric field can be used to determine an equivalent-pi circuit model with parameters I_E, Y_E as shown above. These are combined to give the nodal admittance network as shown in Figure D.4 where y_{ik} is the admittance of the line between nodes *i* and *k*, and y_i is the admittance to ground from node i.

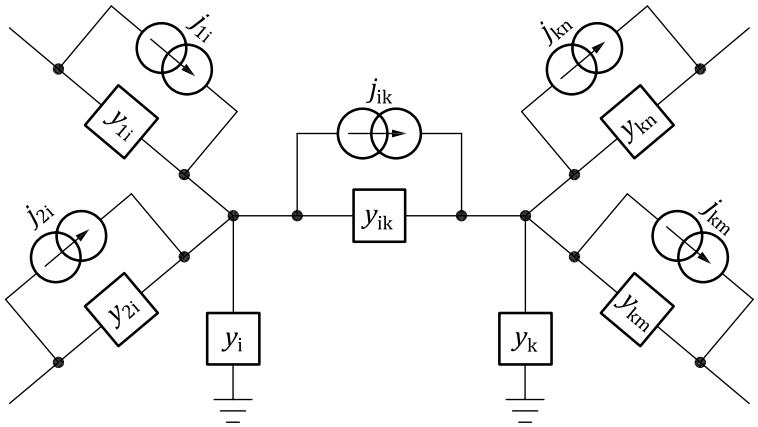


Figure D.4 — Nodal admittance network for modelling telluric potentials produced in a pipeline system

Applying Kirchhoff's current law for each node leads to a set of equations that can be written in matrix form:

$$[J]=[Y][V] \tag{D.11}$$

where

$[J]$ is the current source vector where each term is the sum of the current sources, I_E, directed into a particular node.

$$J_i = \sum_{k=1}^{N} j_{ik} \qquad k \neq i \tag{D.12}$$

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[Y] is the admittance matrix in which the diagonal elements are the sum of the admittances of all paths connected to node i, and the off-diagonal elements are the negatives of the admittances between nodes i and k, i.e. Formulae (D.13), (D.14) and (D.15).

$$Y_{ii} = y_i + \sum_{k=1}^{N} y_{ki} \qquad k \neq i \tag{D.13}$$

$$Y_{ki} = -y_{ki} \tag{D.14}$$

The voltages of the nodes are then found by taking the inverse of the admittance matrix and multiplying by the nodal current sources:

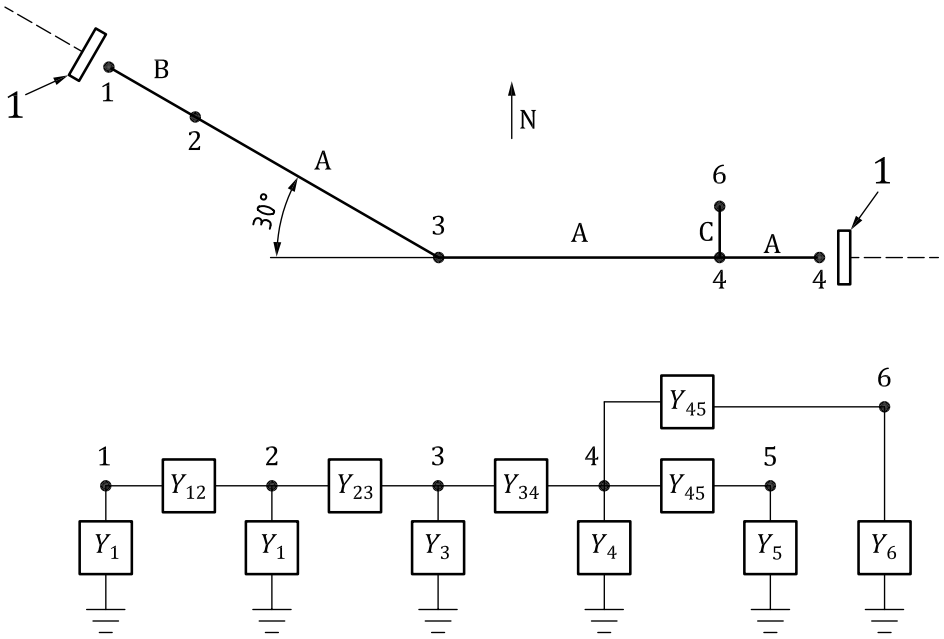
$$[V] = [Y]^{-1}[J] \tag{D.15}$$

These voltages at the "nodes" in the network derived from Formula (D.15) represent the values for V_i and V_k at the ends of the pipeline sections that can be used in Formulae (D.5) and (D.6) to determine the voltage $V(x)$ and current $I(x)$ in each pipeline section.

D.3 Example model calculation

D.3.1 General

To illustrate how the network modelling can be applied in practice, calculations are presented for the example pipeline network shown in Figure D.5 where sections labelled A, B and C are pipelines with different characteristics. This pipeline contains features that would occur on a real pipeline such as a change in pipeline dimensions, a bend, a junction with a branch line and insulating flanges all of which influence the telluric potentials that are produced.



Key

1 insulating flange

Figure D.5 — Example pipeline and its nodal admittance network model

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Note that the values are shown to either 2 or 4 decimal places. The actual calculations are performed with a greater precision.

The steps in the calculation are in D.3.2 to D.3.10:

D.3.2 Step 1 Collect the pipeline parameters

Typically, the outside diameter and wall thickness are given and are used to calculate the outside radius and inside radius. In this example, the values for the three different pipeline characteristics are in Table D.1:

Table D.1 — Pipeline diameter and wall thickness

	Outside diameter (inch)	Outside diameter (mm)	Wall thickness (mm)	Outside radius (m)	Inside radius (m)
Type A	30	762	15,6	0,381	0,365 4
Type B	20	508	12,5	0,254	0,241 5
Type C	15	381	10,0	0,190 5	0,180 5

D.3.3 Step 2 Calculate electrical parameters

The steel resistivity and coating conductance are given. Use these, and pipeline dimensions, to calculate series impedance, Z (1) and parallel admittance, Y, (2) and use the Z and Y values to calculate the propagation constant, γ (3), and characteristic impedance, Z_0 (4).

Pipeline steel and coating characteristics are shown in Table D.2.

Calculated equivalent pi circuits for each section are shown in Table D.3.

Calculated node values are shown in Table D.4.

Calculated admittance matrix values are shown in Table D.5.

Table D.2 — Steel resistivity, coating conductance, and impedance/admittance calculated values

	Steel resistivity, ρ (Ω·m)	Coating conductance, C ($S \cdot m^{-2}$)	Series Impedance, Z ($\Omega \cdot km^{-1}$)	Parallel Admittance, Y ($S \cdot km^{-1}$)	Characteristic Impedance, Z_0 (Ω)	Propagation Constant, γ (km^{-1})
Type A	$0{,}18 \times 10^{-6}$	5×10^{-6}	0,004 921	0,011 97	0,641 1	0,007 7
Type B	$0{,}18 \times 10^{-6}$	5×10^{-6}	0,009 251	0,007 98	1,076 7	0,008 6
Type C	$0{,}18 \times 10^{-6}$	5×10^{-6}	0,015 444	0,005 98	1,606 3	0,009 6

D.3.4 Step 3 Determine equivalent-pi circuit for each pipeline section

Use Formulae (D.7), (D.8) and (D.9) to calculate the equivalent-pi circuit components I_E, Y_E and $Y/2$.

Table D.3 — Calculated equivalent pi circuit for each section

Section	Type	Length (km)	I_E (A) for E=1 $V \cdot km^{-1}$	Y_E (S)	$Y/2$ (S)
1-2	B	11	108,10	9,812 8	0,043 9
2-3	A	24	203,22	8,420 0	0,143 2
3-4	A	29	203,22	6,950 2	0,172 8
4-5	A	8	203,22	25,387 0	0,047 9
4-6	C	2,5	64,75	25,898 2	0,007 5

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D.3.5 Step 4 Combine equivalent-pi circuits into a nodal admittance network

At each node, *i*, the *Y* /2 value for each section meeting at that node is combined to give the admittance to ground Y_i at that node.

Table D.4 — Calculated node values

Node	Sections involved	*Y* /2 (S)	*Y* /2 (S)	*Y* /2 (S)	Y_i (S)
1	1-2	0,043 9	—	—	0,043 9
2	1-2, 2-3	0,316 1	0,143 2	—	0,187 1
3	2-3, 3-4	0,143 2	0,172 8	—	0,316 1
4	3-4, 4-5, 4-6	0,172 8	0,047 9	0,007 5	0,228 2
5	4-5	0,047 9	—	—	0,047 9
6	4-6	0,007 5	—	—	0,007 5

D.3.6 Step 5 Construct the admittance matrix

The diagonal elements are the sum of the admittances of all paths connected to a particular node. These paths are the branches between nodes and the path to ground from the node. The table below shows the branches connected to each node and their admittances as well as the admittance to ground from the node. The final column shows the diagonal elements, Y_{ii}, for the matrix calculated as the sum of the individual admittance values (previous columns) for each node.

Table D.5 — Admittance matrix

Node	Branches	Y_E values for each branch (S)			Y_i (S)	Y_{ii} (S)
1	1-2	9,812 8			0,043 9	9,856 7
2	1-2, 2-3	9,812 8	8,420 0		0,187 1	18,419 9
3	2–3, 2-4	8,420 0	6,950 2		0,316 1	15,686 3
4	3-4, 4-5, 4-6	6,950 2	25,387 0	25,898 2	0,228 2	58,235 4
5	4-5	25,387 0			0,047 9	25,434 9
6	4-6	25,898 2			0,007 5	25,905 7

The off-diagonal elements are the negatives of the admittances between nodes Y_E. There is a symmetry in the matrix because the off-diagonal elements occur in pairs because $Y_{ki} = Y_{ik}$.

The resulting admittance matrix is given in Table D.6:

Table D.6 — Resulting admittance matrix

	1	2	3	4	5	6
1	9,856 7	–9,812 8				
2	–9,812 8	18,419 8	–8,420 0			
3		–8,420 0	15,686 2	–6,950 2		
4			–6,950 2	58,463 5	–25,387 0	–25,898 2
5				–25,387 0	25,434 8	
6				–25,898 2		25,905 7

D.3.7 Step 6 Invert the admittance matrix

This is most easily done using the matrix inversion function built into many software packages. The resulting inverse of the admittance matrix is given in Table D.7:

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Table D.7 — Matrix inversion

1,370 9	1,275 1	1,191 8	1,145 1	1,143	1,144 8
1,275 1	1,280 8	1,197 1	1,150 2	1,148 1	1,149 9
1,191 8	1,197 1	1,230 0	1,181 8	1,179 5	1,181 4
1,145 1	1,150 2	1,181 8	1,273 7	1,271 3	1,273 3
1,143	1,148 1	1,179 5	1,271 3	1,308 2	1,270 9
1,144 8	1,149 9	1,181 4	1,273 3	1,270 9	1,311 6

D.3.8 Step 7 Determine equivalent current sources for northward and eastward electric fields and Sum these at each node to give nodal current sources, *J*

Useful calculations can be done by assuming a northward electric field of 1 V·km^{-1} and an eastward electric field of 1 V·km^{-1}. The telluric potentials for any amplitude and direction of electric field can then be found by a simple scaling and addition of the results for these northward and eastward electric fields.

In each case, northward or eastward electric field, the procedure is to calculate the component of the electric field parallel to each pipeline section.

For the pipeline shown in Figure D.5, for a northward electric field of 1 V·km^{-1}, the electric field parallel to sections 1–2 and 2–3 is $E_{//} = 1{,}0 \cdot \cos(60°)$, while for sections 3–4 and 4–5, $E_{//} = 0$ because the electric field is perpendicular to these sections. For an eastward electric field of 1 V·km^{-1}, the electric field parallel to sections 1–2 and 2–3 is $E_{//} = 1{,}0 \cdot \cos(30°)$, while for sections 3–4 and 4–5, $E_{//} = 1{,}0$ because this electric field is parallel to these sections. The parallel electric field is then used in Formula (D.9) to calculate the equivalent current source, I_E. For each node the equivalent current sources directed into each node are then combined [see Formula (D.12)] to give the nodal current source, J_i.

For a northward electric field of 1 V·km^{-1}, the sections connected to each node are shown below together with their equivalent current sources I_E and the resulting value for J_i. See Table D.8.

Table D.8 — Calculated equivalent current sources (Northward electric field)

Node	Sections involved	I_E (A)	I_E (A)	I_E (A)	J_i (A)
1	1–2	54,05			54,05
2	1–2, 2–3	–54,05	101,62		47,57
3	2–3, 3–4	–101,62	0		–101,62
4	3–4, 4–5, 4–6	0	0	–64,75	–64,75
5	4–5	0			0
6	4–6	64,75			64,75

Similarly, for an eastward electric field of 1 V·km^{-1}, the sections connected to each node are shown below together with their equivalent current sources I_E and the resulting value for J_i. See Table D.9.

Table D.9 — Calculated equivalent current sources (Eastward electric field)

Node	Sections involved	I_E (A)	I_E (A)	I_E (A)	J_i (A)
1	1–2	93,62			–93,62
2	1–2, 2–3	93,62	–176,00		–82,365
3	2–3, 3–4	176,00	–203,22		–27,22
4	3–4, 4–5, 4–6	203,22	203,22	0	0
5	4–5	203,22			203,22
6	4–6	0			0

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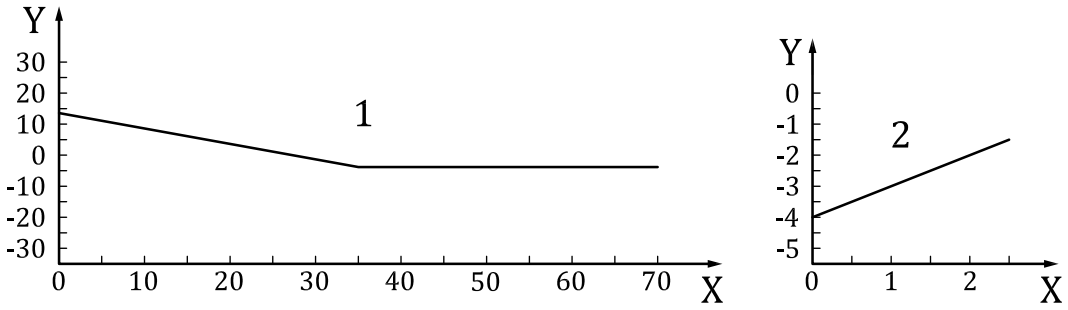
D.3.9 Step 8 Multiply inverted admittance matrix by *J* column matrix to give nodal voltages (see Table D.10)

Table D.10 — Calculated nodal voltages

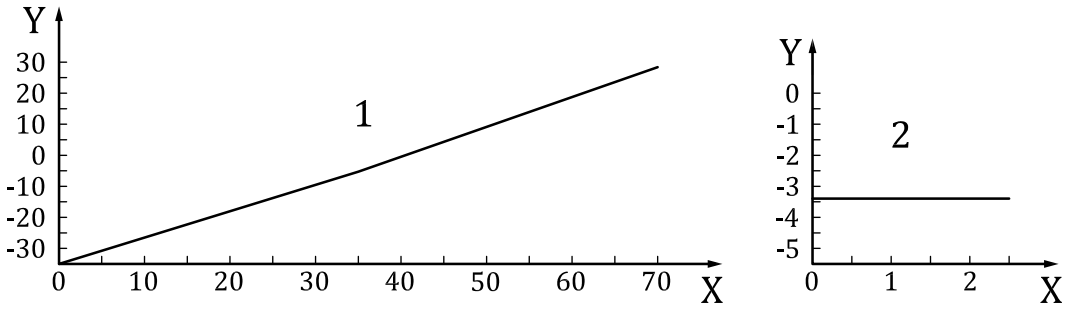
Node	Voltages produced by a northward electric field of 1 V·km^{-1} (V)	Voltages produced by an eastward electric field of 1 V·km^{-1} (V)
1	13,619 2	–33,555 6
2	8,171 8	–24,164 8
3	–3,643 7	–3,974 1
4	–3,503 5	24,223 1
5	–3,496 9	32,167 5
6	–1,003	24,216 1

D.3.10 Step 9 Use the nodal voltages to calculate the pipeline potentials within each section

For each section use Formula (D.5) with the end voltages from the tables above to calculate the telluric potential as a function of distance within each section. This gives the results shown in the Figures D.6 a) and b).



a) Northward



b) Eastward

Key

1 main pipeline
2 branch
X distance along pipeline, in km
Y pipe to soil potential, in V

Figure D.6 — Telluric potentials produced by an electric field of 1 V·km^{-1}

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Annex E
(informative)

High voltage direct current interference

E.1 Terminal earth electrodes

Terminal earth electrodes shall be designed for installation in low-resistivity soil or seawater to minimize the total earthing resistance and near-surface voltage gradients around the earth electrodes.

The location of terminal earth electrodes can significantly affect the stray current interference on buried or submerged structures and shall be carefully considered.

Calculated near surface voltage gradients should be checked by current tests with a test electrode prior to final decision on the location of the permanent earth electrodes.

E.2 Interference measurements prior to commissioning

When the earth electrodes are installed, and prior to commissioning, the stray current exposure areas (areas where the potential gradients might cause interference to other structures) shall be identified by reference to further calculations and preferably by a test at reduced current. Metallic structures in the stray current exposure areas shall be located and tested for stray current interference such that the degree of interference on final commissioning can be estimated.

E.3 Interference measurements after commissioning

After commissioning, further measurements of buried or immersed metallic structures within the stray current exposure area shall be undertaken. On bipolar systems with an earthing system, the test shall be carried out at monopolar operation with each electrode operating both as an anode and as a cathode.

E.4 Protective measures

If the interference is unacceptable (see Clause 8), protective measures shall be taken (see Clause 9). Protective measures are required, even if interference only occurs at fault or unbalanced conditions in a bipolar system.

Instead of protective measures, the parties concerned can enter into an agreement on the limits for fault and unbalanced operation of a bipolar system, e.g. highest level of current and maximum length of operation.

E.5 Converter stations

The basic types of HVDC systems include back-to-back, bipolar, monopolar and multi-terminal systems. The type of an HVDC scheme defines the current path under both normal operation and emergency operation, and whether earth return operation (continuous or intermittent) can take place. The return operation can be facilitated by single or multiple earthing points and/or a complete or partial dedicated metallic return conductor between the converter stations. Outage of any converter station/pole can result in high unbalanced current that may flow in the earth or in the metallic return conductors depending on the configuration. The converter stations, in such systems may use either Line Commutated Converter (LCC with thyristors) or Voltage Sourced Converter (VSC). The converter stations are advised to be located far enough from the earthing electrodes to diminish, among

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others, remote impacts that include corrosion or electrical interference with existing or new buried infrastructure (e.g. pipelines). The required separation distance would be the product of a detailed techno-economic assessment based on technical requirements, actual information and assumptions.

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Annex F
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Alternating Current Interference

F.1 General

An electrical current will always have a magnetic field associated with it. The magnitude of the magnetic field is directly proportional to the magnitude of the current.

In the presence of changing values of magnetic field, a voltage will be induced into a pipeline. For power lines the magnitude of the induced voltage will be directly proportional to the current and the mutual impedance of each phase.

This form of induction is known as Low Frequency Induction (LFI).

F.2 LFI Calculations

The extent and magnitude of the induced voltages can be approximated by mathematical modelling and by calculation. Calculations are mainly suitable for simple configurations of pipeline and AC conductors, but these calculations can be used to validate a numerical mathematical model.

One way to perform these calculations is using the formulae and methodology developed in Annex F. It should be noted that the original calculations were developed for pipelines that are above- ground. For buried pipelines parallel to the overhead line, the pipe to ground voltage would reach a maximum at each end and would be equal to half the total voltage induced along the length of the pipe. Under this condition, the instantaneous pipe-to-ground voltages would be opposite in polarity at each end, and the pipe-to-ground voltage at the middle of the pipe would be zero.

Examples of the calculation are given below. The examples assume that there are no other sources of interference.

The steps to follow in the calculation are:

a) Establish the frequency of the AC.

b) Establish the current and the phase angle for each phase.

c) Establish the pipeline and the overhead power line route.

d) Establish the separation between the cable (usually above ground) and the buried pipeline along the route.

e) Using the information from step 4 break the pipeline down into segments that have similar soil resistivities and separation between the powerline and the pipeline.

f) Establish the soil resistivity along the pipeline route.

g) Establish the distance of the conductors from the centre of the pipe.

h) Establish the distance between phase A and phase B.

i) Establish the distance between phase B and phase C.

j) Establish the distance from the centre of the pipe to phase B.

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k) Calculate the distance of each phase from the centre of the pipe.

l) Calculate the equivalent distance from the conductor.

m) Calculate the geometric mean separation distance.

n) Calculate the mutual impedances for each phase.

o) Sum the products of the phase current and the mutual impedance for that phase.

The information for steps a), b), c), d), g), h), i) and j) can usually be obtained from the operator of the AC system.

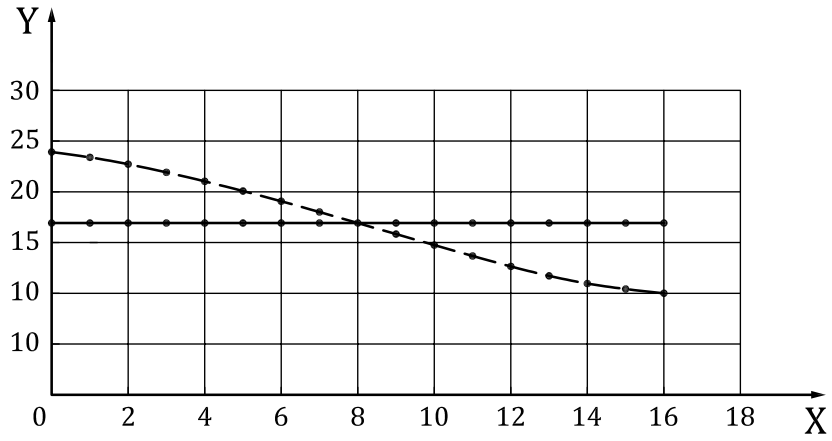
Step 6 information can either be by measurement or provided by others.

It is common for overhead powerlines to be provided with an overhead earth wire(s) (EW) (also known as a shielding wire(s)). Due to the close proximity of the EW with the energized phase conductors, some current is induced on the EW. This current is flowing along the earth wire and is producing an induced emf on the pipeline in addition to the emf produced by the phase conductors.

The total inductive coupling on the pipeline is, therefore, determined by the currents flowing through the energized phase conductors as well as through the earth wire. The location of the earth wire with respect to the phase conductors can be critical when calculating LFI on nearby pipelines.

The location of the earth wire on a lattice tower, with respect to the phase conductors, is determined by the shielding angle. This angle should be sufficient to protect phase conductors from lightning strike.

Figure F.1 illustrates the difference in the calculated induced voltage on the pipe for the earth wire at different positions between 0 m and 16 m. From 0 m to 8 m there is a decreasing adverse effect and from 8 m to 16 m there is an increasing beneficial effect.



Key

earth wire

no earth wire

X direction of movement, in m

Y voltage, in $V \cdot km^{-1}$

Figure F.1 — Difference in the calculated induced voltage on the pipe for the earth wire

F.3 Calculation examples (without and with earth wire)

Case 1. No earth wire

Vector phase current A (A) $I_a := 500 \angle 0°$

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Vector phase current B (A) $I_b := 500 \angle -120°$

Vector phase current C (A) $I_c := 500 \angle 120°$

Calculation of mutual impedances (Carson)

Frequency (Hz) $f := 50$

Resistivity (Ω·m) $\rho := 100$

Height of conductor from centre of pipe (m) $h := 12$

Distance between phase A and B (m) $d_1 := 8$

Distance between phase B and C (m) $d_2 := 8$

Distance from centre of pipe to phase B (m) $d_3 := 15$

$$D_{ap} := \sqrt{(d_2 + d_3)^2 + h^2} = 25{,}942 \angle 0° \text{ (m)}$$

$$D_{bp} := \sqrt{d_3{}^2 + h^2} = 19{,}209 \angle 0° \text{ (m)}$$

$$D_{cp} := \sqrt{(d_3 - d_2)^2 + h^2} = 13{,}892 \angle 0° \text{ (m)}$$

Equivalent distance from pipeline conductor

$$D_{ep} := 658{,}37 \cdot \sqrt{\frac{\rho}{f}} = 931{,}076 \angle 0° \text{ (m)}$$

Geometric mean separation distance

$$D_{1p} := \left(\sqrt[3]{D_{ap} \cdot D_{bp} \cdot D_{cp}}\right) = 19{,}059 \angle 0° \text{ (m)}$$

Mutual impedances

$$Z_{ap} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{ap}}\right) = 0{,}230\,3 \angle 77{,}628\,4° \text{ (Ω/km)}$$

$$Z_{bp} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{bp}}\right) = 0{,}248\,8 \angle 78{,}56° \text{ (Ω/km)}$$

$$Z_{cp} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{cp}}\right) = 0{,}268\,8 \angle 79{,}420\,9° \text{ (Ω/km)}$$

Induced voltage

$$V_p := I_a \cdot Z_{ap} + I_b \cdot Z_{bp} + I_c \cdot Z_{cp} = 17 \angle -121° \text{ (V·km}^{-1}\text{)}$$

Case 2. Single earth wire

Vector phase current A (A) $I_a := 500 \angle 0°$

Vector phase current B (A) $I_b := 500 \angle -120°$

Vector phase current C (A) $I_c := 500 \angle -120°$

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Calculation of mutual impedances (Carson)

Frequency (Hz) $f := 50$

Resistivity (Ω·m) $\rho := 100$

Height of conductor from centre of pipe (m) $h := 12$

Distance between phase A and B (m) $d_1 := 8$

Distance between phase B and C (m) $d_2 := 8$

Distance from centre of pipe to phase B (m) $d_3 := 15$

Distance between the phase A conductor and the earthwire $D_{aw} := 8$

Distance between the earthwire and the pipeline (m) $D_{wp} := 23$

AC resistance of the earthwire (Ω/km) $r_w := 5$

Geometric mean radius of the earth wire (m) $GMR_w := 0{,}2$

$D_{ap} := \sqrt{(d_2 + d_3)^2 + h^2} = 25{,}942 \angle 0°$ (m)

$D_{bp} := \sqrt{d_3^2 + h^2} = 19{,}209 \angle 0°$ (m)

$D_{cp} := \sqrt{(d_3 - d_2)^2 + h^2} = 13{,}892 \angle 0°$ (m)

Equivalent pipeline distance from conductor

$D_{ep} := 658{,}37 \cdot \sqrt{\frac{\rho}{f}} = 931{,}076 \angle 0°$ (m)

Mutual impedances

$Z_{ap} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{ap}}\right) = 0{,}230\,3 \angle 77{,}628\,4°$ (Ω/km)

$Z_{bp} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{bp}}\right) = 0{,}248\,8 \angle 78{,}56°$ (Ω/km)

$Z_{cp} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{cp}}\right) = 0{,}268\,8 \angle 79{,}420\,9°$ (Ω/km)

$Z_{aw} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{aw}}\right) = 0{,}302\,9 \angle 80{,}625\,2°$ (Ω/km)

$Z_{wp} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{D_{wp}}\right) = 0{,}237\,7 \angle 78{,}019°$ (Ω/km)

$Z_{cw} := 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{GMR_w}\right) = 0{,}533 \angle 84{,}687\,5°$ (Ω/km)

$Z_w := r_w + 9{,}869 \times 10^{-4} \cdot f + 1i \cdot 2{,}893\,5 \times 10^{-3} \cdot f \cdot \log\left(\frac{D_{ep}}{GMR_w}\right) = 5{,}072\,2 \angle 5{,}999\,5°$ (Ω/km)

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Consider a high voltage power line with one overhead earthwire:

$$Z'_{ap} := Z_{ap} - \frac{Z_{aw} \cdot Z_{wp}}{Z_w}$$

$$Z'_{bp} := Z_{bp} - \frac{Z_{aw} \cdot Z_{wp}}{Z_w}$$

$$Z'_{cp} := Z_{cp} - \frac{Z_{aw} \cdot Z_{wp}}{Z_w}$$

$V_p := I_a \cdot Z'_{ap} + I_b \cdot Z'_{bp} + I_c \cdot Z'_{cp} = 13{,}564 \angle -137{,}161°$ ($V \cdot km^{-1}$)

For the consideration of more than one earthwire or other continuously earthed conducting medium for shielding purposes, the expressions Z'_{ap}, Z'_{bp}, and Z'_{cp} shall be expanded to include their effects. The expressions shall also include the interaction between the earthwires and/or other conducting mediums. This increases the complexity of the formulae.

The determination of the induced voltage, V_p in the pipeline as a consequence of the presence of shielding effects has increased the calculations required to include those effects. Since these shielding mediums reduce the LFI in the pipeline, they need only be considered in the calculation if the voltage limits are exceeded and measures to reduce the LFI warrant their inclusion.

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Annex G
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Tidal Effects

The movement of conducting seawater through the Earth's magnetic field acts like a dynamo and generates an electric field in the seawater. This drives an electric current (a flow of charge) in the seawater, perpendicular to the direction of water movement. Where this electric current meets the land, there is a build-up of electrical charge that creates a potential gradient both along the seafloor and inland perpendicular to the coast.

Tidal movements repeatedly move seawater back and forth through the Earth's magnetic field producing electric currents and Earth potential variations with an approximately 12,5 h period. The "tidal dynamo" process at any particular location depends on the vertical component of the Earth's magnetic field at that location as well as the speed of the tidal currents.

The Earth's magnetic field is horizontal at the equator and gets more and more vertically inclined with increasing latitude, becoming perpendicular to the Earth's surface at the north and south magnetic poles. The efficiency of the tidal dynamo process, therefore, increases with latitude.

Tidal currents are increased where the tidal action causes seawater flow in and out of large estuaries (e.g. the Bay of Fundy in Canada and the Severn Estuary in England), through narrow channels (such as the Cook Strait in New Zealand), or around headlands (such as the north of Scotland).

To give an example of the Earth potentials that can be produced, calculations have been made[1] for the Bay of Fundy in the Maritimes region of Canada. The Bay of Fundy is at a high enough latitude that there is a significant vertical component (approximately 50.10^{-6} Tesla) to the Earth's magnetic field. Also, the Bay of Fundy has the highest rise and fall of tide in the world with peak flow rates ranging from 2,2 knots (1,13 $m \cdot s^{-1}$) during neap tides to 4,0 knots (2,06 $m \cdot s^{-1}$) during spring tides. Using these values and taking account of the width of the bay, the ebb and flow of the tides has been estimated to give a maximum potential difference across the bay of 5,15 V at spring tides and 2,8 V at neap tides.

The Earth potentials produced at the coast on either side of the bay fall off with distance away from the coast. Therefore, a pipeline perpendicular to the coast will experience different Earth potentials at different locations along the pipeline. Electric currents in a pipeline near the Cook Strait in New Zealand were found to vary with a 12,5 h period, synchronized with tidal potential difference measured across the strait.

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Annex H
(informative)

Photovoltaic interference

H.1 Photovoltaic interference on buried pipelines

DC Photovoltaic Interference results from conductive coupling:

a) when part of the normal DC leakage emanating from the Photovoltaic (PV) System returns to the system's earth via an interfered system (i.e. buried pipeline) and

b) when the change in the soil potential gradient (due to a DC ground fault in the PV system), in the vicinity of the influenced pipeline, facilitates the formation of conductive voltages and currents.

Leakage currents in PV systems originate from a fault or from the systematic and inevitable flow of DC through non-ideal materials of the cables, PV modules and other array components. Under certain conditions, the DC leakage currents, if left unattended, or not detected at all, may cause accelerated stray current corrosion on metallic underground infrastructure (e.g. gas pipelines) buried in the vicinity of large, utility-scale PV systems.

H.2 Source of DC leakage currents

H.2.1 Normal operating conditions

Under normal operating conditions of the PV system, the total ground leakage current, is formed by the contribution of all system components:

a) photovoltaic Modules;

b) DC cables;

c) inverters.

For a certain voltage level, the DC leakage is dependent on the effective insulation resistance (R_{ISO}) of the system. The effective insulation resistance can be measured before connecting the PV system to the grid[14] and will provide an indication of the magnitude of the anticipated leakage currents to ground. The level (magnitude) of DC leakage current is dependent on external factors such as solar irradiance, ambient temperature, degraded sealants and moisture ingress at the modules' level, soil resistivity, etc.

H.2.2 Undetected fault conditions

DC leakage currents to ground may be sourced

a) by virtue of the distinct potential of the system against ground and the potential difference between active system elements, and

b) from DC ground faults. Ground faults in PV systems occur when there is an unintentional connection between any current-carrying conductor with a grounded surface or earth.

Faults on the DC side can be found in both grounded and floating PV systems. The detection mechanisms of these faults depend upon the DC grounding characteristics of the PV system and are inevitably different for grounded and floating configurations[15]. These faults can remain undetected since the allowable DC fault detection thresholds can be set high, to avoid lost production from false detections or "nuisance" trips from regular and inevitable leakage currents. The undetected DC faults arise as the

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existing detection thresholds for permissible DC leakage from PV systems have been based on other issues such as fire prevention or personnel safety.

H.3 Photovoltaic interference and stray current corrosion

Stray current corrosion refers to corrosion damage resulting from DC flow other than in the intended circuit. The first prerequisite to facilitate stray current corrosion is a ground fault that falls within the undetected threshold zones, defined by the inverters. The second prerequisite is for the leakage current flowing into the earth, to be persistent. When considering stray current corrosion, the location where the current first enters the ground will most likely be the PV module frame or buried cabling, where the insulation is damaged. Stray current corrosion at secondary locations is thus possible (e.g. national networks of buried gas and oil pipelines).

H.4 Identification and measurement of stray current interference

PV interference is time variant (See Clause 7) and will normally follow the changing solar irradiance (i.e. the power per unit area received from the sun). It is therefore expected to be more pronounced during the daylight. The dynamic nature of PV interference suggests that any measurements should be made using a digital data logger. This should be operated for long enough to capture some PV interference disturbances. DC leakage currents can be also sensed as the difference between the positive PV and negative PV currents coming from the PV array to the inverter.

If the PV system's fault detector/interrupter is blind to high impedance faults, the leakage current to ground may exist indefinitely (provided that it is not sufficiently high to cause arcing and fire). The latter implies that the PV array will continue to operate with a permanent reduction in power output. Briefly, in the event of an undetected ground fault the MPPT (maximum power point tracker) of the inverter will set a new operating point to a lower power than before the fault. This is because the MPPT may take the fault as an ordinary power drop (usually caused by changing irradiance) and will shift the operation to a new optimal power point.

H.5 Reduction of DC stray current interference

The mechanism of stray current corrosion in utility-scale PV applications can be summarized as follows:

The leakage current, from PV modules and buried DC cables experiencing a fault or deteriorated insulation, will flow into the soil and may subsequently flow along parallel circuits either directly through the soil or through buried metallic structures, before returning to the energy source. To this end, a current loop is formed. Thus, any nearby metallic structures that provide a convenient (mainly) parallel conductive corridor can be very good candidates to provide a path for ground-fault leakage currents to return to the energy source. Given that current flow in a metallic conductor is electronic, while that through electrolytes is ionic, it follows that there must be an electrochemical reaction (involving either ion to electron transfer as current enters a metallic conductor or electron to ion transfer as current discharges to earth). Therefore, where a current leaves metallic-pathways to earth to return to the energy source, there will be an oxidation, or electron- producing, reaction. This reaction is visible after time as corrosion damage. For pipelines or structures with cathodic protection applied, PV stray current may not always generate corrosion, and low levels of interference may be tolerated.

Factors that should be taken into account in assessing the size of PV interference or to mitigate it are:

At the source level:

a) For detecting DC leakage faults in grounded PV systems, the UL 1741[16] and the NEC[17] require the installation of a Ground Fault Protection Device (GFPD). These devices are designed to interrupt the flow of DC fault currents and also to alert about fault occurrences.

b) Ground fault detection in floating PV systems (isolated & non-isolated) is typically achieved by monitoring the DC insulation resistance from the PV input (array) to ground[14]. The measurements are typically achieved by monitoring the insulation impedance of each pole (positive and negative)

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relative to ground. The measurements are achieved by the use of embedded insulation monitoring devices (IMDs)[18] and they usually take place before the inverter starts operation[14]. This type of monitoring is commonly referred to as R_{ISO} measurements. The IMD set point should be in accordance to the minimum insulation resistance of PV array under some worst meteorological conditions to avoid nuisance tripping events.

c) If the DC cables of the PV system are placed in plastic conduits, then any DC leakage to ground arising from these cables will be limited.

At the pipeline level:

— The extent of stray current corrosion damage on a nearby gas pipeline would be specific to the characteristics and topology of each large-scale PV installation. It will also be specific to the relative position of the buried pipeline with respect to the faulted sections of the PV system. The electrical and material characteristics of the pipeline as well as the soil resistivity are also important to assess the risk[19].

— Liaison of the PV operator with the utility company is needed to assess the risk. Specialized audits at regular intervals maybe necessary including measurement and monitoring. The PV operator may have to consider the cost of increased infrastructure's inspections and retrofit monitoring devices against the potential cost and damage from DC corrosion. In cases where the level of stray current cannot be controlled to acceptable levels, measurement and monitoring of the third-party assets may be required, with mitigation applied to the affected structure if required.

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Annex I
(informative)

Modelling the effects of stray current interference on cathodically protected pipelines

I.1 Introduction

The purpose of modelling the effects of stray current influences on pipelines is to help in predicting the distribution of the interference effects and to enable "what-if" scenarios to be assessed. The extent and the type of calculations required mean that they can only realistically be undertaken with the aid of computers.

The presentation of the calculation reports can include graphics and visualisations.

I.2 Pre-modelling requirements

Before the modelling process begins it is important to clearly define the purpose of the modelling as well as the desired outputs.

Desired outputs from the model will define what is required by the end user. Usually this is a written report with graphs, images and tables along with descriptive text. It can also include electronic versions that allow simple manipulation and viewing of the model.

The end user should specify the levels of competence required by the modeller. In this sense, the modeller is the engineer responsible for the development of the model, the data input and analysis. This may require a combination of academic qualifications and practical experience in transmission line modelling and cathodic protection design and application.

Modelling can be carried out using standard software programs. These may be either in-house programs, bespoke software or commercial programs. In the case of commercial programs, usually licensed, it is important to establish that the engineer responsible for the works has the required knowledge and experience, since there is a high-risk associated with unskilled engineers operating software packages that require specialist knowledge input as well as being able to critically evaluate the validity of the output.

Detailed information of the pipeline is required.

Such detail can include the following:

a) Operating characteristics;

b) Mechanical details;

   1) Outside diameter;

   2) Length;

   3) Route;

   4) Geometry;

   5) Date of installation;

   6) Design life;

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7) Leakage history;
8) Details of any connected structures (e.g. tees, tie-ins, etc.);
9) Third party crossings;
10) Possible structure changes over the remaining design life (e.g. additional wells and hook-ups).

c) Coating details;
1) Coating type;
2) Field joint coating type;
3) Coating condition;
4) Coating resistivity ($\Omega \cdot m^2$).

d) Environmental details;
1) Soil resistivity (including seasonal variations);
2) Climate;
3) Pollution and contamination;
4) Access restrictions (e.g. Sites of Special Scientific Interest (SSI).

e) Cathodic protection;
1) Detailed design documents and calculations;
2) Location of all facilities;
3) Transformer-Rectifier electrical parameters (e.g. output voltage and current) ;
4) Present operating status;
5) All monitoring and maintenance records;
6) Stray current data logging records;
7) Close Interval Potential Survey records;
8) Coating defect survey records (e.g. DCVG, ACVG);
9) Date of anode installations;
10) Details of any bonding and electrical drainage systems;
11) Location and status of electrical isolation (isolated flanges, monobloc isolation joints).

f) Interfering system details (time-variant DC);
1) Traction systems (e.g. trains, metro, trams, trolley-buses, industrial);
2) Route details;
3) Power configuration;
4) Track formation;
5) Sub-station locations;

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6) Operational characteristics (e.g. operational hours, voltage, current).

g) Interfering system details (steady-state DC);

1) Location;

2) Operational characteristics (e.g. operating hours and electrical characteristics).

h) Interfering system details (High Voltage AC);

1) Routing details;

2) Configuration;

i. Height;

ii. Conductor spacing;

iii. Conductor material and diameter;

iv. Earth wire;

v. Earth wire material and diameter;

vi. Tower (pylon) earthing;

vii. Electrical operating characteristics;

— Maximum loads;

— Average loads;

— Fault probabilities.

i) Conformity and compliance requirements;

1) Standards;

2) National regulations.

I.3 Model specification

Specifying the model is something that should be done in collaboration with the end-user and the modelling expert. It is important to select a modelling expert team that has specific experience in the fields of transmission line electrical modelling, cathodic protection, earthing and electrical principles.

The modelling expert will consider and make decisions on

— identifying meaningful pipeline segments for the circuit analysis, and

— location of electrical nodes.

I.4 Model methodology

A valid methodology is to

a) break the pipeline down into segments that can be considered as having substantially identical electrical characteristics,

b) calculate the impedance for the segments, taking into account the effect of the coating and soil conditions, and

c) resolve the values of the voltage nodes.

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I.5 Model validation

If there is no validation available by way of auditable previous experience, then other methods will be required.

Although it will be impossible to validate the entire model, since that would require a complete re-modelling, it is possible to check some isolated features.

This can be done as follows:

a) An engineer with specialist knowledge of cathodic protection can establish whether the current and potential distribution is in general accordance with simple calculated current demand requirements;

b) Smaller sections can be checked by

   1) conventional electric field calculations can be carried out to verify the anode spacing. This can be accomplished using standard field distribution formulae,

   2) calculating the AC induced voltages over a sample length using the formulae in Annex F or equivalent formulae, and

   3) calculating the effects of induced geomagnetic induced voltages using the formulae in Annex D or equivalent formulae.

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Annex J
(informative)

Assessment of the corrosion risk for steel in concrete or for cathodically protected structures under time variant interference conditions

The following data are required from the most critical location of interference and over a period that covers the most critical interference conditions, e.g. highest anodic interference.

a) In case of steel in concrete structures:

   — Long term recording results of the potential, E

b) In case of cathodically protected structures

   — Long term recording results of the on potential, E_{on}, or

c) In case of coupons

   — long-term recording result of the magnitude and direction of the coupon current (I_{cpn}) from which the coupon current density (J_{cpn}) can be calculated.

A reference potential, E_{ref}, (for Method 1) or a reference current density J_{ref} (for Method 2 in case of coupon measurements) that determines whether the present interference is cathodic or anodic, needs to be defined by the operator.

Whenever the potential and current density value is more anodic than J_{ref} and/or E_{ref} then this period of interference is considered to be anodic. Based on the longest anodic period $T_{a,max}$ is determined.

In the absence of interference E_{ref} is the on-potential, E_{on}, of the structure required for effective cathodic protection.

In the case of coupons J_{ref} is defined as the current density that is required to achieve the protection potential. The commonly used values in Table J.1 should be considered.

Table J.1 — Examples of reference levels

	Examples of reference levels	Comments
Cathodically protected structures buried in soil (i.e. particle size smaller than medium gravel as defined in ISO 14688-1) or immersed in water with increased hardness (total hardness exceeding 1,3 mmol/l)	E_{ref} = –1,0 V_{CSE} J_{ref} = 0,02 A·m^{-2}	The assessment becomes more conservative with the E_{ref} value being defined more negative or with the J_{ref} value being defined higher (more cathodic)
Cathodically protected structures buried under exceptional bedding conditions, i.e. soft flowing groundwater (total hardness below 1,3 mmol/l) in combination with coarse bedding material (e.g. medium gravel, as defined in ISO 14688-1).	E_{ref} is the on-potential, E_{on}, of the structure required for effective cathodic protection; In the case of coupons J_{ref} is defined as the current density that is required to achieve the protection potential	E_{ref} can be evaluated from operational data, or from theoretical considerations, e.g. taking into account conservative assumptions for the protection potential $E_{IR\text{-}free}$, the protection current density (a minimum of 0,2A/m^2 should be considered), the geometry of a coating defect and the soil resistivity.

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Table J.1 *(continued)*

	Examples of reference levels	Comments
Steel in concrete	The reference potential E_{ref} should be evaluated from the potential recording when the interfering source is out of operation	

The anodic and cathodic intervals, T_a and T_c, with reference to E_{ref} for Method 1 are identified from analysis of the recording results of on potentials (E_{on}) made over a representative period of time (as specified in 7.3.6).

The data shall be recorded using a constant sampling rate (see 7.3.1) for the duration (T).

The E_{on} average value is calculated by dividing the sum of E_{on} by the number of data measurements (N) over time t.

$$E_{on,avg} = \sum E_{on}/N$$

Subtract E_{ref} from all data points. Replace all negative values by zero, and this gives E'. Take the average of all these data points and this will produce $\Delta E_{a,avg} = \sum E'/N$.

Subtract E_{ref} from all data points. Replace all positive values by zero, and this gives E''. Take the average of all these data points and this will produce $\Delta E_{c,avg} = \sum E''/N$.

The average anodic potential shift ($\Delta E_{a,avg}$) during anodic interference ($E_{on} - E_{ref} > 0$) and the average cathodic potential shift ($\Delta E_{c,avg}$) during cathodic interference ($E_{on} - E_{ref} < 0$) according to Method 1, are proportional to the average anodic charge $|Q_a|$ and cathodic charge, $|Q_c|$.

Correspondingly according to Method 2 $|Q_a|$ and $|Q_c|$ can be evaluated directly from current density values (J_{cpn}) derived from current measurements on coupons and taking into account J_{ref}. The difference between J_{cpn} and J_{ref} ($J - J_{ref}$) provides anodic and cathodic current densities. Their time integral results in Q_a and Q_c.

Subtract J_{ref} from all data points. Replace all negative values by zero, and this gives J'. Take the average of all these data points and multiply it by the time (t) and this will produce Q_a.

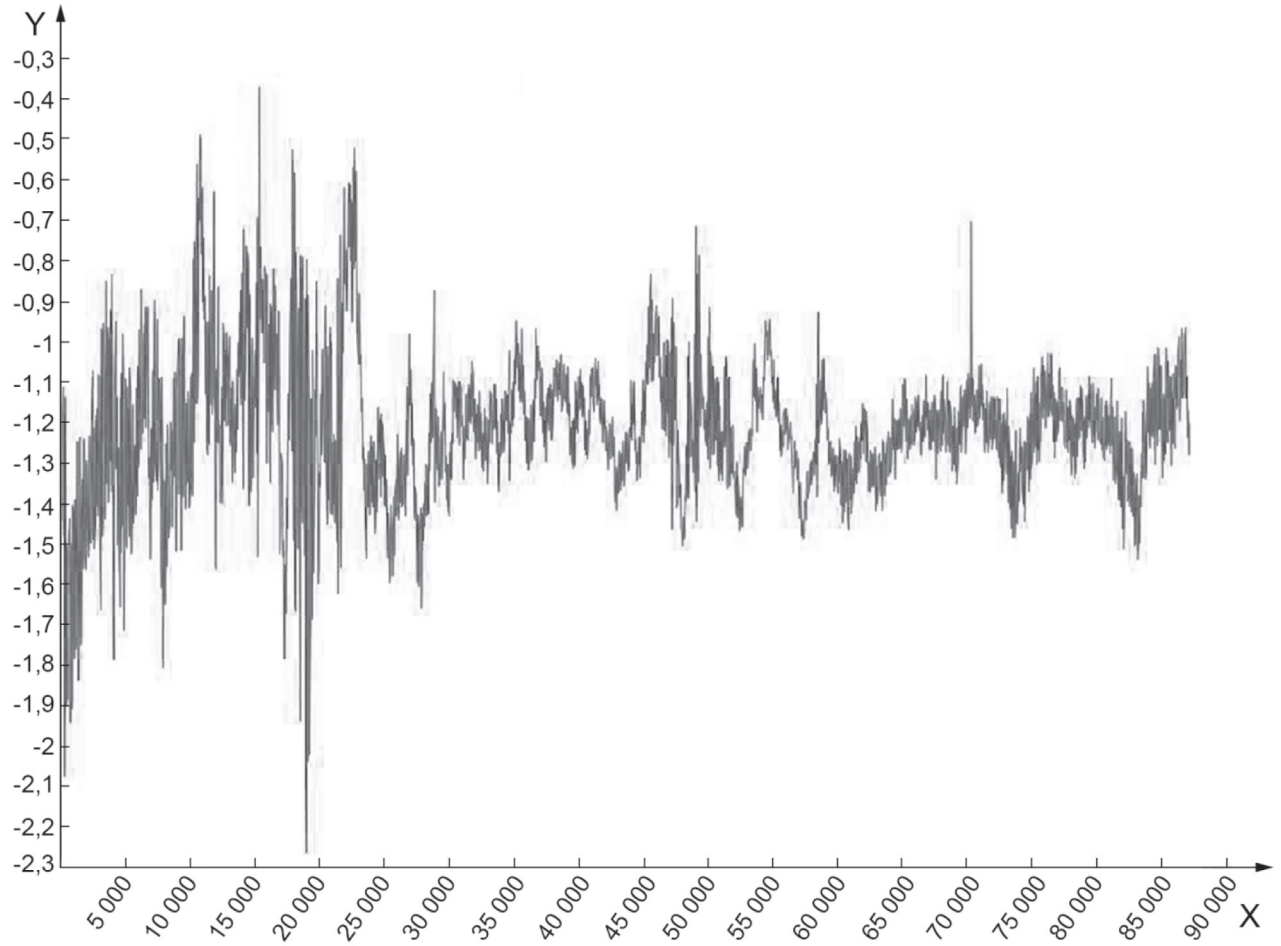
Subtract J_{ref} from all data points. Replace all positive values by zero, and this gives J''. Take the average of all these data points and multiply it by the time (t) and this will produce Q_c.

Figure J.1 shows typical data from an interfered structure over a period of 87 121 s (approximately 24 h) with an E_{ref} value of –1,0 Volt.

Protection against stray current corrosion is assessed from the approximation given in Formula J.1, which has been derived from practical experience.

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Key

X time, in s

Y pipe to soil potential, in V

Figure J.1 — Complete data set

From this data it is possible to determine:

$E_{on,avg}$ –1,216 V_{CSE} $\Delta E_{a,avg}$ 0,009 V $\Delta E_{c,avg}$ 0,225 V

$T_{a,max}$ 1 150 s

The ratio $Q=(|Q_c|-|Q_a|)/|Q_a| = (E_{ref} - E_{on,avg})/\Delta E_{a,avg}$ is a measure for the excessive cathodic charge over the measuring period.

Protection against stray current corrosion can also be assessed from the approximation given in Formula J.1:

$$Q > 0{,}004\ s^{-1} \bullet T_{a,max} \tag{J.1}$$

Where $T_{a,max}$ is the duration of the longest continuous maximum anodic interference interval in seconds in this example, $Q = (E_{ref} - E_{on,avg})/\Delta E_{a,avg}$

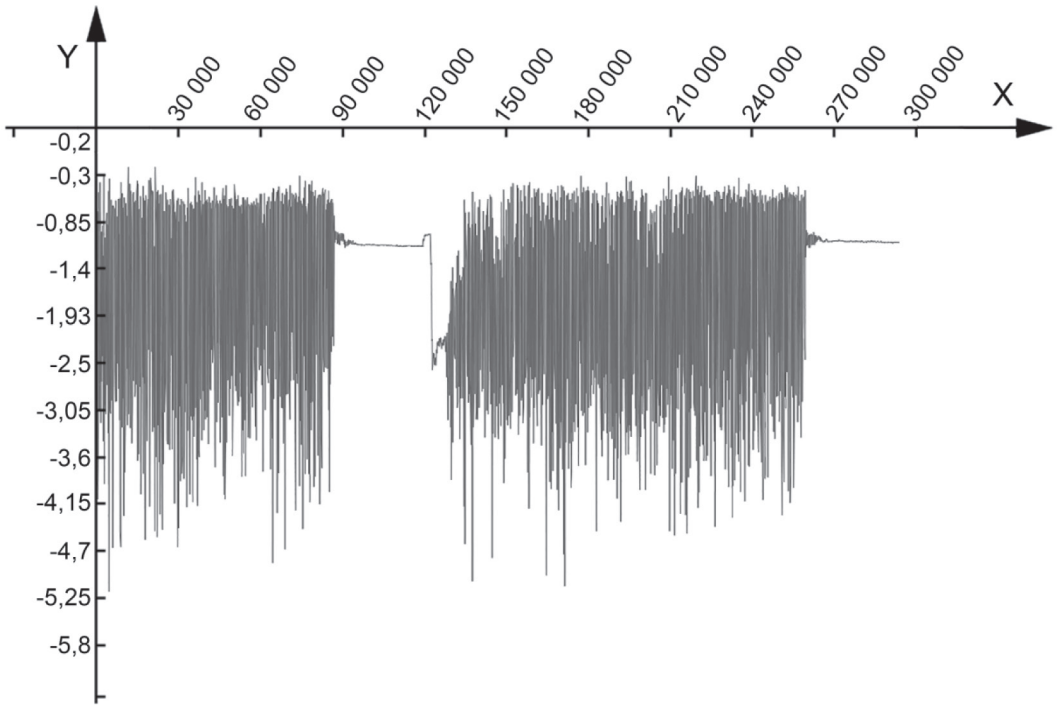
$$\text{Factor} = 0{,}004\ s^{-1} \bullet T_{a,max} = 4{,}6$$

The calculated Q value of 25,369 is greater than the required factor of 4,6 and therefore protection against stray current corrosion has been achieved.

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Figure J.2 shows typical data from a structure showing railway interference over a period of approximately 48 h with a measurement taken every 0,5 s. The two non-operational periods of the railway system are apparent.



Key

X time, in s

Y pipe to soil potential, in V

Figure J.2 — Complete data set

From this data it is possible to determine:

$E_{on,avg}$ –1,59 V $\Delta E_{a,avg}$ 0,02 V $\Delta E_{c,avg}$ 0,61 V

$T_{a,max}$ 104,5 s

E_{ref} –1 V

In this example Q = |0,61|– |0,019 5|/|0,019 5| = 30,226 9

Factor = 0,004 s^{-1} • $T_{a,max}$ = 0,418

The calculated Q value of 30,226 9 is greater than the required factor of 0,418 and therefore protection against stray current corrosion has been achieved.

The Q_a and Q_c values are determined as follows:

a) Calculate the potential difference between the anodic and cathodic excursions with respect to the reference potential E_{ref}. These values are ΔE_a and ΔE_c respectively and expressed in V. Expressed mathematically, if $E_{on} < E_{ref}$, $\Delta E_a = E_{on} - E_{ref}$.

   If $E_{on} > E_{ref}$, $\Delta E_c = E_{ref} - E_{on}$.

b) Analyse the data to establish the longest continuous period of anodic excursion expressed in seconds. This will be $T_{a,max}$.

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c) Calculate the sum of the ΔE_a values and divide by N. This produces $\Delta E_{a,avg}$, which is proportional to Q_a.

d) Calculate the sum of the ΔE_c values and divide by N. This produces $\Delta E_{c,avg}$, which is proportional to Q_c.

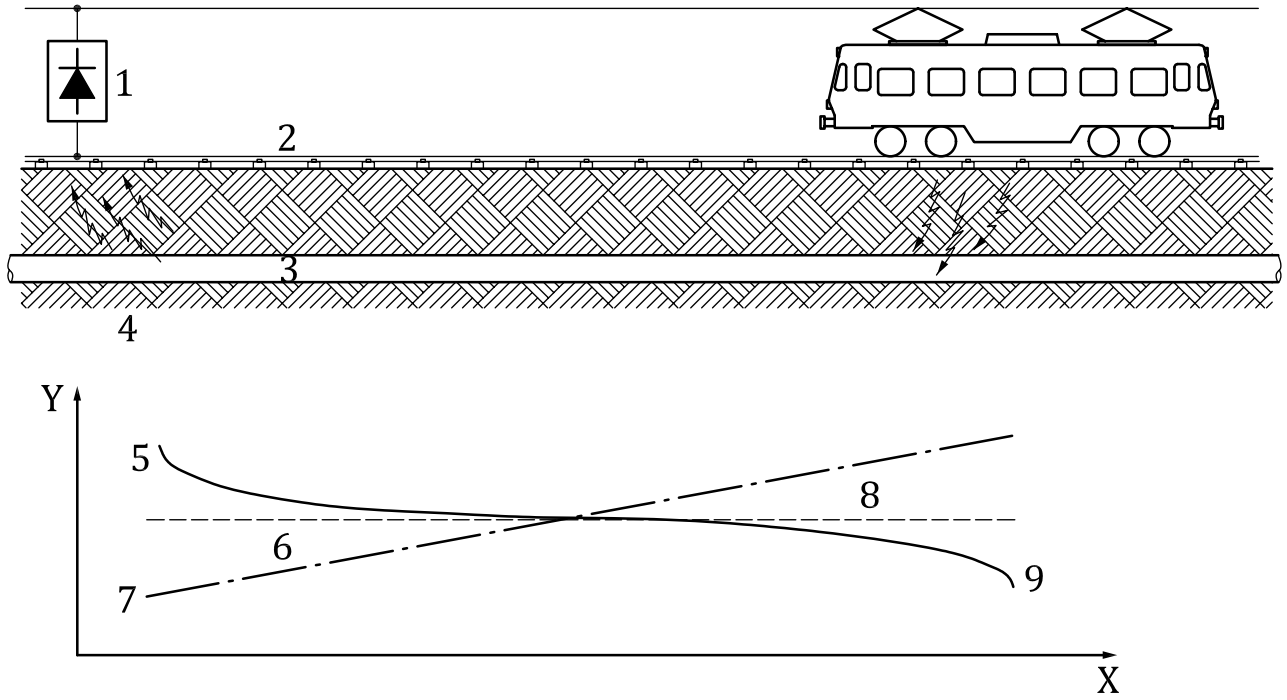
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Annex K
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Principles of anodic and cathodic interference

Figure K.1 shows the principle of interference due to DC operated railways.



Key

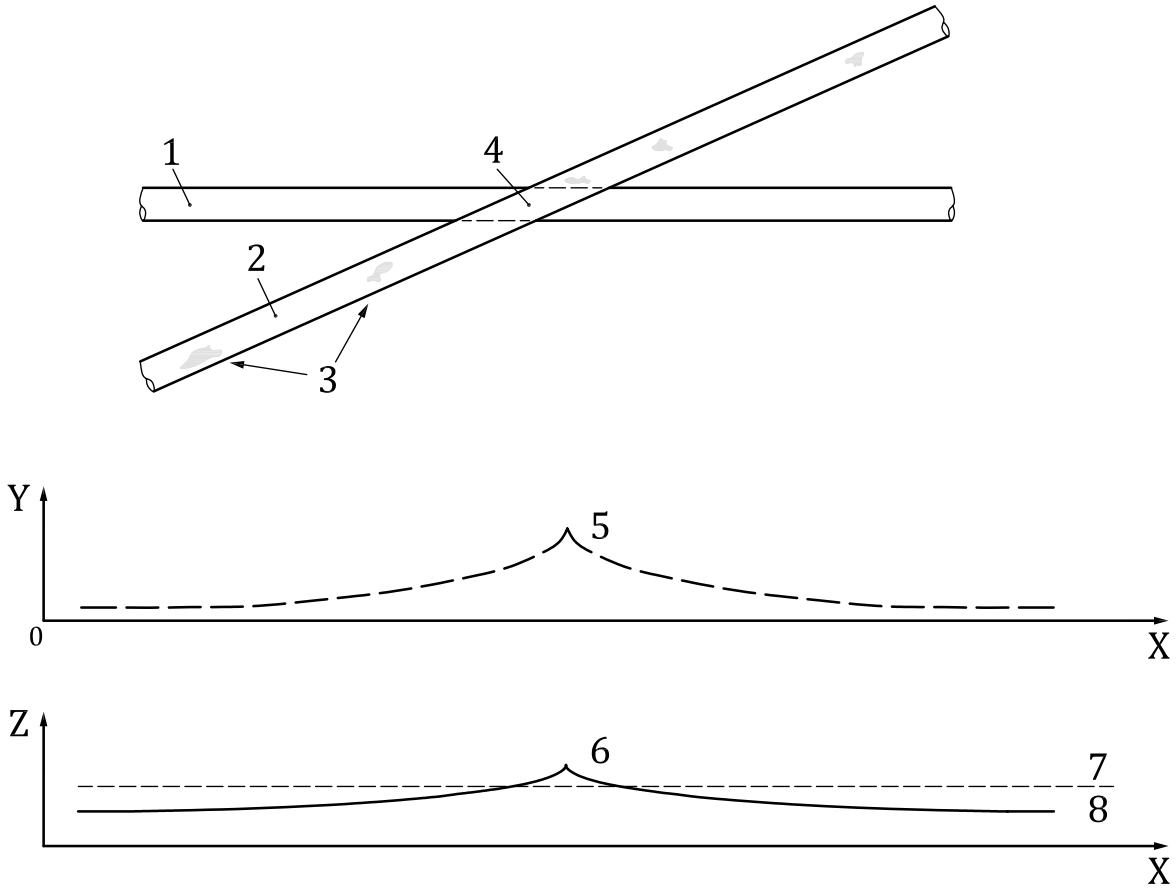
1 subsection
2 rails
3 pipeline
4 area with enhanced corrosion risk
5 potential of pipeline with interference
6 area with anodic interference
7 potential of rails
8 area with cathodic interference
9 potential of pipeline without interference
X length
Y potential (+)

Figure K.1 — Principle of interference due to DC operated railways

Figure K.2 shows the principle of interference due to cathodic potential gradients.

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Key

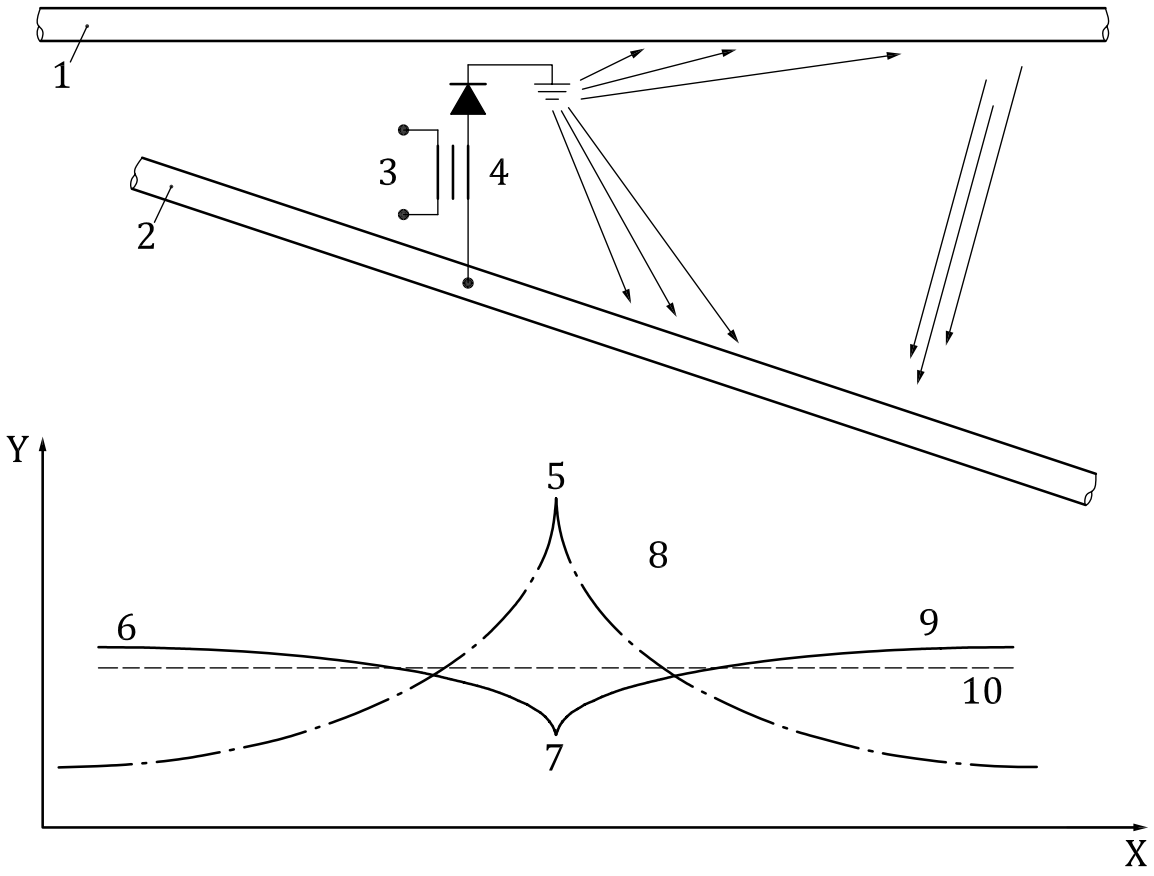
1 cathodically protected pipeline
2 unprotected pipeline
3 coating defect on unprotected pipeline
4 coating defect on protected pipeline
5 potential gradient (measured above ground) of cathodically protected pipeline
6 area of anodic interference measured above the unprotected pipeline
7 potential of unprotected pipeline without interference
8 potential of unprotected pipeline with interference
X Length
Y potential gradient
Z potential (+)

Figure K.2 — Principle of interference due to cathodic potential gradients (anodic interference)

Figure K.3 shows the principle of interference due to anodic potential gradients.

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Key

1 interfered pipeline
2 cathodically protected pipeline
3 power supply
4 c.p. station
5 location of an anode of a c.p. system
6 potential of pipeline with interference
7 area of cathodic interference
8 potential of soil around the anode
9 area of anodic interference
10 potential of pipeline without interference
X Length
Y potential (+)

Figure K.3 — Principle of interference due to anodic potential gradients (cathodic interference)

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