290

AC CORROSION ON METALLIC PIPELINES DUE TO INTERFERENCE FROM AC POWER LINES

PHENOMENON, MODELLING AND COUNTERMEASURES

Joint Working Group C4.2.02

April 2006

cigré

AC CORROSION ON METALLIC PIPELINES DUE TO INTERFERENCE FROM AC POWER LINES

PHENOMENON, MODELLING AND COUNTERMEASURES

Joint Working Group C4.2.02

Members of the CIGRE/CIRED Joint Working Group C4.2.02:

L.-E. Juhlin (Sweden) *Convener*
R. Bräunlich (Switzerland), J. Diesendorf (Australia), R. Gregoor (Belgium), G. Lucca (Italy),
H.-G. Öhlin (Sweden), Y. Rajotte (Canada), W. H. Siew (United Kingdom),
Dave Thomas (United Kingdom)

Invited Specialists: Gy. Varjú (ITU-T) (Hungary), P. Kiss (Hungary), G. Camitz (Sweden)

Corresponding members: D. O. Campones do Brasil (Brazil), B. Cramer (USA),
Bernard Graux (Belgium), R. Hubbard (South Africa), G.L. Solbiati (Italy)

TABLE OF CONTENTS

Abstract

A.C. corrosion has been of concern for pipeline owners and corrosion specialists for many years [1]. Consequently, there are many documents describing research and results from investigations of the a.c. corrosion phenomenon, see Figure 1.1. A recently published manual in this area is the CEOCOR guide “A.C. corrosion on cathodically protected pipelines - Guidelines for risk assessment and mitigation measures” [2]. The CEOCOR guide deals mainly with the corrosion phenomenon as such. Therefore, one objective of this new guide is to emphasize the causal link with the a.c. power lines, overhead lines or cables. Dealing with a.c. corrosion on pipelines involves two professional areas: a.c. power system engineering and pipeline corrosion protection engineering. The guide is intended to be a bridge between the two disciplines by defining interface points and important factors with reference to a.c. corrosion. The purpose is not to replace the existing Technical Brochure No. 95 “Guide on the Influence of High Voltage A.C. Power Systems on Metallic Pipelines” by Cigré WG 36.02 published in 1995 [3], but to provide supplementary information reflecting today’s knowledge regarding a.c. corrosion.

Influencing factors and conditions for risk of a.c. corrosion are identified. Guidance is given for overall risk assessment. Especially, modelling and relevant calculation and measurement methods are treated in relation to criteria for assessment of the risk of a.c. corrosion. Decisive parameters have been identified for evaluation of countermeasures. The guide also gives an overview of possible countermeasures both for the pipeline and for the a.c. power line. The feasibility, advantages and drawbacks of each countermeasure are broadly analysed to facilitate the selection of a suitable mix of countermeasures. The applicability of a.c. corrosion for cables and other object is also discussed.

Figure 1.1: Two examples of pipeline damage caused by a.c. corrosion.

1. Introduction

1.1. General

In 1995, Cigré WG 36.02 published the Cigré Technical Brochure No. 95 “Guide on the Influence of High Voltage A.C. Power Systems on Metallic Pipelines” [3]. The guide gives a good overview of the phenomenon relating to how pipelines for gas, oil, water etc. are influenced by a.c. power lines. However, the evaluation is related to equipment and personnel safety and not to a.c. corrosion. The present knowledge is that the risk of a.c. corrosion starts at a much lower voltage than that required for the risk of hazard. Therefore, there is a need to supplement the CIGRE guide with information focusing on the a.c. corrosion phenomena.

On the other hand, a.c. corrosion has been of concern for pipeline owners and corrosion specialists for several years. Consequently, there are many documents describing research and results from investigations of the a.c. corrosion phenomenon. A recently published manual in this area is the CEOCOR guide "A.C. corrosion on cathodically protected pipelines - Guidelines for risk assessment and mitigation measures" [2]. This guide deals mainly with the corrosion phenomenon as such and the causal link with the a.c. power lines, overhead lines and cables has to be emphasized.

1.2. Purpose of this guide

The purpose of this guide is to facilitate the communication between the two professional areas: a.c. power system engineering and pipeline corrosion protection engineering in the area of a.c. corrosion of metallic pipelines. It is intended to be a bridge between the two disciplines by defining interface points and important factors with reference to a.c. corrosion. For this reason, terminologies and parameters used with regards to a.c. corrosion and a.c. power line interference are explained in Appendix A.

Influencing factors and conditions for risk of a.c. corrosion are identified. Guidance is given for overall risk assessment: with references to relevant documents for more detailed information. Decisive parameters have been identified for evaluation of countermeasures.

The purpose is also to give an overview of possible countermeasures for pipelines and for a.c. power lines. The feasibility, advantages and drawbacks of each countermeasure are broadly analysed to facilitate the selection of a suitable mix of countermeasures.

Furthermore, this document provides suitable references for a deeper understanding of the subject.

The purpose is not to replace the existing Technical Brochure No. 95 "Guide on the Influence of High Voltage A.C. Power Systems on Metallic Pipelines" by Cigré WG 36.02 published in 1995 [3], but to provide supplementary information reflecting today's knowledge.

1.3. Description of the phenomenon

1.3.1. The corrosion mechanism

Corrosion is defined as the degradation of a metal (or an alloy) and its properties because of reaction with its environment.

The corrosion of concern in this guide is a process which degrades the metal (the metal is turning into rust (metal oxide)) and its mechanical properties (yield strength, …), making it fail and no longer appropriate as a pipeline material for gas or oil transmission.

Corrosion is a natural process. Indeed, most metals are extracted from ores (oxides, carbonates, sulphates, …) by a reduction process, requiring an input of electrical or thermal energy. From that moment on, metals have a natural tendency to return to the ore state (oxides), which involves corrosion or oxidation, releasing the energy absorbed in the reduction process. Reduction reactions consume electrons, oxidation reactions produce electrons. An environment (soil) with oxygen, water, ions and salts makes these reactions possible.

These processes involve chemical reactions and exchanges of electrons and are therefore called electrochemical reactions. They require an electrolyte (aqueous solution with ions), an anode (metal), a cathode (metal) and an electric circuit. The electric circuit is formed by a cable or the metal itself to transmit electrons and by the electrolyte to transmit charges via the ions. The anodes and cathodes are alternating anodic and cathodic elements on the same metal object making a metal object corrode more or less over its entire surface.

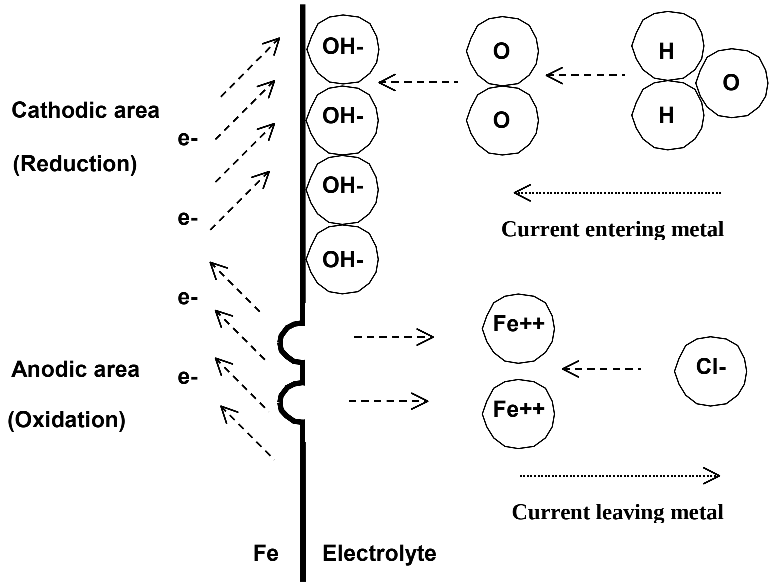


Fig 1.2: Corrosion mechanism

In an electrolyte, the reduction of water or oxygen is the motor behind these reactions. These reduction reactions need electrons, which cannot be found in electrolytes (electrolytes only have ions that have a positive or negative charge) but are found in metals that are in contact with the electrolyte, see Figure 1.2. At the interface between the electrolyte and the metal, the reduction reactions take electrons from the metal. The metal can deliver electrons resulting from oxidizing (corroding) reactions. The metal is dissolving in metal ions and electrons. These metal ions participate in secondary reactions with other ions present in the electrolyte. Corrosion continues as long as the reduction reactions are demanding for electrons.

1.3.2. Corrosion protection

One cannot stop the reduction reactions from requiring electrons, but protection measures against corrosion can be derived based on an understanding of the corrosion phenomenon.

- separate the electrolyte from the metal = apply electrically insulating coating on the metal (primary corrosion protection)
- bring in electrons from an external source to feed the reduction reactions preventing the metal from dissolution (corrosion) = cathodic protection (secondary corrosion protection)

Cathodic protection brings electrons into the metal, using sacrificial anodes or rectifier fed anode beds in the electrolyte in contact with the metal. The electrochemical potential of the metal becomes more negative than the protection potential. The metal doesn’t corrode. A current coming from the anode to the metal is protecting the metal, and current leaving the metal is corroding the metal.

1.3.3. Protection of pipelines

The cathodic protection of pipelines forces current to enter the metallic buried pipeline through the metal surface in contact with soil where the coating is damaged. [4] This current prevents the corrosion process from taking place. In contrast, the corrosion reaction is associated with a current leaving the metal surface.

Corrosion results from an electric current flowing from the metal into the electrolyte, increasing the electrochemical potential above the protection potential. The metal corrodes. This can either be due to the d.c. stray currents leaving the metal or due to the a.c. current anodic half-wave.

1.3.4. A.C. corrosion

When an a.c. voltage is present on a cathodically protected pipeline, current will flow through the metal surface at defects in the coating. This current depends on the impedance of the system. During the positive half wave of the a.c. voltage, current will leave the metal surface if the a.c. potential is sufficiently large. In general this happens when the a.c.-voltage exceeds 1 V. The current leaving the metal surface can cause charging of the Helmholz double layer capacitance, oxidation of hydrogen and reduced corrosion products and oxidation of the pipeline. Since the current leaving the metal surface is feeding several non-corrosive processes, generally higher a.c. voltages, between 4-10 V [5], are required to result in a significant corrosion the pipeline. Various parameters are additionally influencing this process, such as the spread resistance of the defect, the soil composition, the cathodic protection level etc.

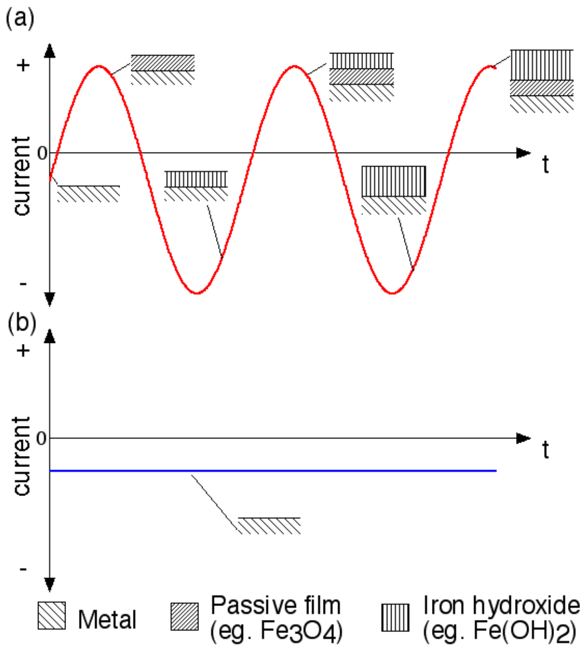
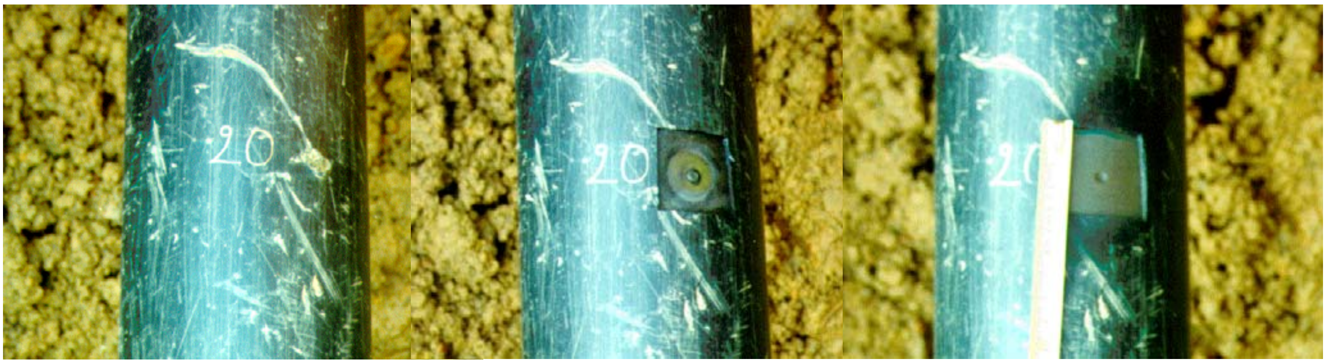


Fig 1.3: Current flow through the metal surface of the pipeline at a coating defect and a schematic representation of the electrochemical processes taking place.

a) Situation with cathodic protection and induced a.c.-voltage.

b) Situation with cathodic protection.

The processes taking place are schematically illustrated in Figure 1.3.a. During the positive half wave the bare metal surface is oxidized resulting in the formation of a passive film. This is due to the current that leaves the metal surface. During the negative half wave, when the current is entering the metal surface this passive film is reduced to iron hydroxide. In the next anodic cycle a new passive film grows. Upon reduction of the passive film the amount of iron hydroxide is increased. Hence, every a.c.-cycle results in some oxidation of the metal. In the long term this can result in a significant metal loss. For comparison, the situation without a.c.-interference is shown in Figure 1.3.b. In this case no metal loss is observed, since the current always enters the metal surface. A case of a.c. corrosion is demonstrated in Figure 1.4.



a) coating defect (15x20 mm) the hole is about a few mm²

b) oxide (40x40 mm) and corrosion product

c) pipeline corrosion (diameter = 5 mm, depth 0,5 mm)

Figure 1.4: Case of a.c. corrosion on a PE coated pipeline at a coating defect (15x20 mm) on top line of the pipeline. The size of the initial hole in the coating is about a few mm².

1.4. Overview of the state of the art

As already mentioned in the introduction to this guide, pipeline operators launched an increasing number of research projects since the nineties to investigate corrosion on cathodically well protected pipelines, subject to interference from a.c. power lines, a.c. traction systems and a.c. power cables.

The results of these research projects were widely communicated at the annual CEOCOR conferences and up-to-date knowledge was published in 2000 in the CEOCOR guide on a.c. corrosion [2]. The research in this area still continues.

These investigations have shown that the risk of a.c. corrosion increases

- with increasing a.c. interference,
- with increasing quality of the pipeline coating,

The interference increases:

- with increasing length of parallelism between the a.c. interfering structure and the interfered structure,
- with decreasing distance between the a.c. interfering structure and the interfered structure,
- with increasing a.c. current densities flowing from an immersed or buried metal structure to the surrounding electrolyte,
- with increasing a.c. voltage on the pipeline ,
- with decreasing section of coating holidays on the interfered pipeline,

The effect of increased coating quality is

- higher coating resistivity leading to higher pipeline voltage
- smaller coating holidays at damages leading to higher current density

Further, the risk of a.c. corrosion increases if specific soil components are present that reduce local soil resistivity in the case of a coating holiday.

There is also a quite good understanding of the phenomenon that cause a.c. corrosion.

All these resulted from field experience on real pipeline networks in operation and from laboratory investigations all over Europe.

The main point is however that no unique and absolute criterion has been found to be applicable.

This is why in this guide and in other publications, there exists a deliberate choice of not imposing strict criteria but of suggesting acceptable levels of interference to limit the risk of a.c. corrosion, staying “on the safe side” in terms of risk management. This has been translated in chapter 7 in the use of spans and wordings like “no risk span”, “low risk span” and “high risk span”, except for 7.3.4. Pipe-to-soil OFF-potential, which confirms the well known d.c. protection potential criterion.

1.5. Design and verification procedures

At the design stage of a new pipeline or a new a.c. power line close to a pipeline, calculations should be made to evaluate the risk of a.c. corrosion. The calculations results should be compared with accepted criteria for risk of a.c. corrosion. Also, when planning for significant countermeasures in existing installation, the effectiveness of the planned countermeasures should be predicted by comparing calculation results with criteria for a.c. corrosion.

After the pipeline or a.c. power line is installed, the risk of a.c. corrosion is verified by measurement. The measurements are verifications of the calculations, including modelling and presumptions. Installation of inexpensive countermeasures may be based on measurement results and experience only, without prediction of the effectiveness by calculation.

The ideal situation is that there is a clear correlation between calculation results and measurement results. However, some of the parameters normally measured for evaluating the risk of a.c. corrosion can not be measured on the pipeline itself, but on separately installed test coupons, and some of these parameters cannot at present be predicted by calculation. In addition, measurement results depend on the conditions at the time of measurement, and some of the condition parameters may be hard to control. These considerations are further discussed in the sections about modelling and calculation, measurements, and criteria.

2. Important parameters

2.1. General

The most significant precondition for a.c. corrosion is the following combination:

- The pipeline is effectively isolated from the surrounding soil.
- A.C. voltage on the pipeline is due to interaction with a nearby a.c. power line, a.c. traction system or a.c. power cable.
- The isolating coating is not perfect, but small holidays in the coating allow local a.c. current to flow between the pipeline and the surrounding soil. That current causes the a.c. corrosion.

The most important parameters are presented below.

2.2. Routing of a pipeline in relation to a.c. power lines

There are three mechanisms of electromagnetic interference between an a.c. power line and a pipeline:

- Inductive coupling
- Conductive coupling
- Capacitive coupling

The voltage due to inductive and conductive coupling is directly proportional to the current in the a.c. power line. The voltage due to capacitive coupling is proportional to the operating voltage.

The distance between the a.c. power line and the pipeline is a very important parameter for the amount of influence of the former on the latter.

The most important mechanism impacting a pipeline is the voltage due to inductive coupling. The closer the a.c. lines are to the pipes and the longer the parallelism is between the a.c. lines and the pipe, the higher is the induced emf per unit length. The inductive coupling must be considered also when the a.c. power line is a cable. This is considered in chapter 3 of the Cigré Technical Brochure No. 95 [3].

When the pipeline is located close to a tower of an a.c. power line or an a.c. power cable, the conductive coupling as described in chapter 4 of the Cigré Technical Brochure No. 95 [3] has to be considered. Points of concern are pipelines located close to earthing points of the cable screen or to earthing points of towers.

In principle, capacitive coupling, as described in chapter 2 of the Cigré Technical Brochure No.95 [3], could cause corrosion due to induced voltages and currents resulting on aerial pipeline sections located in close proximity to a.c. power lines.

However, in practice, risk of corrosion due to capacitive coupling is zero because safety guidelines (touch voltages) recommend:

- the earthing of aerial pipeline sections during the construction phase,
- the installation of isolating joints between the buried and the aerial sections and earthing the aerial section during the operation phase.

Indeed, by such measures, any effect due to capacitive coupling is practically negligible.

2.3. Parameters to be considered.

The following parameters are important to calculate the interference results and the necessary data shall be provided by the pipeline company:

- the location of the pipeline relative to the a.c. power lines,
- the length of the pipeline,
- the depth of the buried pipeline,
- the outer diameter of the pipeline,
- the wall thickness of the pipeline,
- the thickness of the isolating coating,
- the resistivity of the isolating coating,
- the resistivity of the pipeline,
- the soil-resistivity,
- the location and the characteristics of earthings, voltage limiting devices, polarization cells, electrical and/or electronic equipment, cathodic protection devices, metallic structures for shielding, isolating joints and connected apparatus.

Characteristic means description of the electrical behaviour of the equipment under interference.

The chemical reactions due to a.c. currents differ, depending on the type of soil. The characteristic difference is that the a.c. currents may build up a layer of insulating limestone on the metallic surface. For more information, see section B.2 of Annex B.

2.4. A.C. power line configuration

2.4.1. General

The induced voltage depends on the configuration of the phase conductors and shield wires in a tower. This information has to be provided by the a.c. power system operator or owner.

In a double circuit line, the induction may be worse when one circuit is out of operation, depending on the phase conductor configuration. Furthermore, a shield wire may worsen the induction, as it introduces a zero sequence current, see section 3.2.1.2 and Figure 3.7 of the Cigré Technical Brochure No. 95 [3].

How the induction magnetic field depends on the a.c. power line configuration is described in TF C4.2.04: “Guidelines for Mitigation Techniques of Power-Frequency Magnetic Fields” [6].

The configuration of the line must be checked along the complete length influencing the induction in the pipeline. In particular, any point of transposition must be considered.

The configuration of a.c. power cables close to a pipeline must also be checked because the a.c. power cables may be located much closer to a pipeline installation than the conductors of an overhead power line.

2.4.2. Discontinuances in a configuration

As conductive coupling may also be the cause of a.c. corrosion, any discontinuance in the configuration of earthed shield wires, phase conductors and counterpoises are of importance, as discontinuances cause earth currents.

Examples where discontinuances occur are:

- phase transpositions,
- corner towers,
- change of earth shield configuration,
- change of counterpoise configuration,[1]
- earthing points of stay wires.

Even if the earth current in most cases may be insignificant, discontinuances in configuration must be considered in the evaluation.

3. Considerations arising from a.c. power lines

3.1. Load variations

The load currents in a.c. power lines may vary significantly and is a combination of daily variations, weekly variations and seasonal variations. Normally the load is higher during the day than during the night; and higher during the weekdays than during the weekends. Seasonal variation depends on the type of loads served by a.c. power lines.

In addition to the periodic variations, the load currents in a.c. power lines also depend on actual system configuration. During outage of an a.c. power line, the load on other lines will be higher. Another variation, not depending on loading variation, is power transition due to power market conditions. This can result in fast and large load variations, especially on lines that cross borders.

As a result of load variations, measurements of phenomena related to induction from a.c. power lines may be inconsistent, unless the measurement results are correlated to the present load for the most important lines. For evaluation of the measurement results, the present loading should be

[1] Copper counterpoises normally are connected to the towers via spark gaps to avoid bimetallic corrosion. Different countries have different practice and design.

compared with maximum loading, normal loading and loading during other measurements: conditions which are well known by the a.c. power line operator.

3.2. Fault currents

3.2.1. Fault current in the line

During a fault in the power system, high unbalanced fault currents may flow in the a.c. power lines causing quite high induced voltages and currents. This phenomenon is dealt with in section 3.2 of Technical Brochure No. 95 [3]. However, as these fault currents are of short duration (much less than 1 second), they will not impact the a.c. corrosion, but they must be considered for safety of people and equipment.

3.2.2. Fault current to earth

Of much more concern is the case when an earth fault occurs at a tower close to a pipeline. Due to the limited conductivity of the soil, the potential of the tower and surrounding earth may rise significantly compared to the potential of remote earth, especially in areas with high earth resistivity. The phenomenon is treated in Appendix F and in chapter 4 of Technical Brochure No. 95 [3].

The significance of earth potential rise due to nearby earth faults, with respect to a.c. corrosion, is that the high voltage may cause or worsen a damage of the pipeline coating. Also all types of countermeasures have to be designed with the earth fault currents considered.

3.3. Lightning transients

With a lightning stroke to the top of a tower, the tower and surrounding earth will have a high transient potential. If a metallic pipeline is installed close to a tower exposed to a lightning stroke, the lightning might result in a puncture of the coating. As the lightning stroke to the top of the tower may cause a back flashover across an insulator, due to a potential rise of the tower, the lightning stroke current may be followed by a fundamental frequency fault current for a few cycles.

A scenario with relevance to a.c. corrosion is that the lightning transient punctures the coating of a pipeline, the follow-on fault current of fundamental frequency causes a significant holiday in the coating and the end result is that the continuously induced a.c. voltage corrodes the pipeline.

The earth potential rise (EPR) due to lightning strokes and earth faults can be approximated by a potential cone, with the apex of the cone representing the EPR of the tower. The EPR depends on tower earthing arrangements and soil resistivity. As a rule of thumb, the area within 50 m from a tower can be seen as a zone of high risk. The earth potential will also rise along earthing wires or counterpoises.

3.4. Continuous earth current

3.4.1 General

As a.c. corrosion may occur at quite low induced voltages and currents, it is important to consider continuous earth currents from an a.c. power line. They may also cause a.c. corrosion due to conductive coupling, even if those currents are rather low. Unbalanced currents are often the source of earth currents induced in earthed shield wires. Induced currents in counterpoises (buried earth wires following the a.c. line for reducing the footing resistance of the towers) may also result in earth currents even when the counterpoises are connected to the towers via spark gaps.

The highest earth currents occur at end-towers for earthed shield wires or counterpoises. In addition, there may also be significant earth currents at towers where the a.c. power line configuration changes, such as transposition towers, because the total induced current in the two directions of a line differs as the position of the phase conductors is changed. Earth currents may also be induced in stay (guy) wires of an a.c. power line tower.

Correspondingly, earthing points at the ends of screens of a.c. power cables can be a cause of continuous earth current. Transposition of cables may also result in some earth current in the closest earthing points of the cable screen.

3.4.2 Zone of influence

The zone of influence for earth currents is defined separately for inductive and conductive coupling.

Inductive coupling:

Zero sequence currents in an a.c. power line contribute to increase significantly the induced voltages at large distances. If the line is provided with earth wire(s), the induced current in the latter can reach up to 10% of the phase currents (see section 3.2.1.2 of Technical Brochure No. 95 [3]). The current in the earth wire typically ranges between 5 A and 50 A depending mainly on the line configuration and load current. Voltages on the pipeline in the order of 10 V may cause corrosion (see section 1.3.4). An induced emf per unit length of 0.1 V/km is considered significant since it can lead to induced voltages of 10 V for a length of exposure of a few kilometres under normal operating conditions. An induced emf per unit length of 0.1 V/km corresponds to a distance between the a.c. power line and the pipeline of approximately $20\sqrt{\rho}$ m (with ρ, the soil resistivity expressed in Ω·m)- see Figure C.2 in Appendix C of Technical Brochure No. 95 [3]. The value $20\sqrt{\rho}$ m is a reasonably good approximation for both 50 and 60 Hz. More information can be found in Appendix C of [3].

Conductive coupling:

The current flowing in a tower footing produces a potential rise of the “electrode” and of the neighbouring soil relative to remote earth. The potential is inversely proportional to the distance for a hemispherical electrode in a homogeneous soil. The radius of the hemispheric equivalent for tower footings is usually in the range of 1 to 10 m and their zone of influence is therefore typically less than 100 m. The shield wire distributes the earth current between towers. In certain soil conditions, the conductive coupling between towers cannot be neglected and the zone of influence of the line may reach distances significantly higher than 100 m (see Appendix F and Appendix G). The presence of a counterpoise also contributes to increase the zone of influence of the line.

4. Considerations regarding pipelines

4.1. General.

For the evaluation of a.c. interference on pipeline systems, the configuration of a metal pipeline and connected equipment has to be considered from an electrical point of view. All parameters that determine the electrical behaviour of the metal pipeline with respect to the interfering infrastructure must be taken into account. They apply to the electrical behaviour of the pipeline to the environment (coating, soil, earthing, etc and to the electrical behaviour between different parts of the pipeline (equipotential bonds, isolating joints, etc).

Characteristics and routing of pipeline sections and connected equipment should be considered as design conditions, including all the mounted safety devices. The pipeline company shall provide all information about the configuration (built-up) of the pipeline system.

4.2. Pipeline coating

4.2.1. General

Pipeline coating is the primary and passive corrosion protection for pipelines. The protection by the coating is combined with cathodic protection: a technique that actively protects the steel in coating holidays (i.e. holes in the coating). This combination allows for an efficient protection of buried or immersed steel pipelines against corrosion.

4.2.2. Types of coating and characteristics

Until the mid seventies, pipeline coating consisted of coal tar or oil-derived bitumen. Since then, plastic coatings became the standard, be it polyethylene, polyurethane, epoxy or a multilayer system composed of a mixture of these.

Coatings can be applied in the factory or applied in the field, the latter being always the case for coating of the welding zone between pipeline tubes.

Coal tar or oil-derived bitumen coatings have reasonably good electrical insulating characteristics. It however degrades with time by water adsorption and cracking. The coating resistivity decreases and this is why cathodic protection systems need to supply higher d.c. currents to obtain the required protection level. On the other hand, this lower coating resistivity is also the reason why induced a.c. voltage due to a.c. power lines is relatively low and almost never exceeding the acceptable levels, even without particular mitigation measures. The system behaves as a continuous earthing along the pipeline.

Plastic coatings can easily have 1.000 times the coating resistivity of tar or bitumen coatings, leading to much lower cathodic protection currents. But due to the good insulation characteristics, the induced a.c. voltages are also much higher, thus requiring mitigation measures to keep it within acceptable levels.

4.2.3. Damage to coating

Although coatings are subject to Standards on application and long-term behaviour, coatings become damaged (punctured) during their lifetime, due to many reasons, and they cannot be avoided:

- handling in the factory,
- transportation to the field,
- handling on site,
- rocks or stones in the backfill,
- external aggression during operation,
- earth potential rises due to lightning strokes,
- earth potential rises due to a.c. power line earth faults,
- and others…

4.2.4. Effects of damaged coatings

Coating faults will not only result in higher d.c. current consumption for cathodic protection but also concentrate all a.c. effects (a.c. currents to earth) on very small surfaces (high current densities) of the pipeline, thus leading to a.c. corrosion when the acceptable levels are exceeded.

4.2.5. Coating fault location

Coating holidays on an existing pipeline can be located from aboveground by various measurement techniques.

These techniques are enhanced by signal processing

- detection of cathodic protection current voltage gradients (DCVG),
- detection of voltage gradients generated by multiple frequency signals applied to the pipeline.

Because disbonded coatings, without an open holiday, often disturb the electric currents, cathodic protection currents and electrical signals for coating fault location can be interrupted, which results in corrosion (no cathodic protection underneath the coating) and undetected coating faults.

5. Modelling and prediction

5.1. Introduction

The purpose of this chapter is to present a numerical method to forecast the quantities that, according to the contents of chapter 7, are considered meaningful in order to estimate the risk of a.c. corrosion i.e.:

- the pipeline voltage to remote earth;
- the current density between a buried pipeline and the soil through holidays present in the insulating coating of the pipeline.

The method is based on the classical transmission line theory, which has been successfully applied to power frequency electromagnetic interference problems. A lot of publications exist on this topic but in particular one may refer to [3], [7], [8]. Nevertheless, one should distinguish between the voltage prediction and the current density prediction.

In fact, if one wants to predict the voltage, nothing new has to be added to a "classical interference calculation" that is formulated to address safety problems for personnel and/or damages to apparatus. If one wants to predict the current density instead, some additional steps are required. Therefore, part of this chapter is devoted to provide some details about the current density prediction.

5.2. Current density prediction

It is necessary to point out that the algorithm described is based on two different hypotheses: structural or contingent.

- **structural hypothesis**: it is related to the nature of the model itself; in fact, as shown in the following sections, the model is purely electric; that is the electrochemical reactions[2] occurring at the coating holiday location are not taken into account; therefore, the parameters involved in the model are expressed only in terms of the physical and geometrical quantities (e.g. soil resistivity, thickness of the insulating covering, radius of the coating holidays etc.);
- **contingent hypothesis**: it is related to the lack of or even impossibility of knowledge of certain input data; in fact, in many cases, the values of certain parameters are not known (e.g. holidays radii and/or their locations) and so have necessarily to be assumed (this is true in particular at the design stage when the plant is not existing); nevertheless, field experience may help in assuming typical or average values for certain input data.

In spite of these difficulties, the use of a prediction method, based on a conservative hypotheses (*worst case condition*), can be helpful for predicting at least the order of magnitude of the current density.

Most of the information presented here is taken from [9].

An alternative approach based on a probabilistic method could also be adopted; in this case, the result of the calculation gives the probability that a certain value of current density at a given pipeline section is exceeded. This second approach will not be presented in this chapter and one can refer to [10] for more information.

Appendix I of this Guide presents some probabilistic concepts for voltage prediction.

[2] Generally, such electrochemical reactions produce salts and corrosion products in the region closest to the holiday and so modifying the electric conductivity of the soil [2].

5.3. Short description of the model

5.3.1 Basic electric circuit to model a pipeline

According to [3], [11], when dealing with electromagnetic interference problems produced by a.c. power lines or electrified railway lines on pipelines or telecommunication cables, the plant that is subject to such interference may be suitably modelled, from the electrical viewpoint, by a chain of an adequate number of elementary circuits (cells) as shown in Figure 5.1.

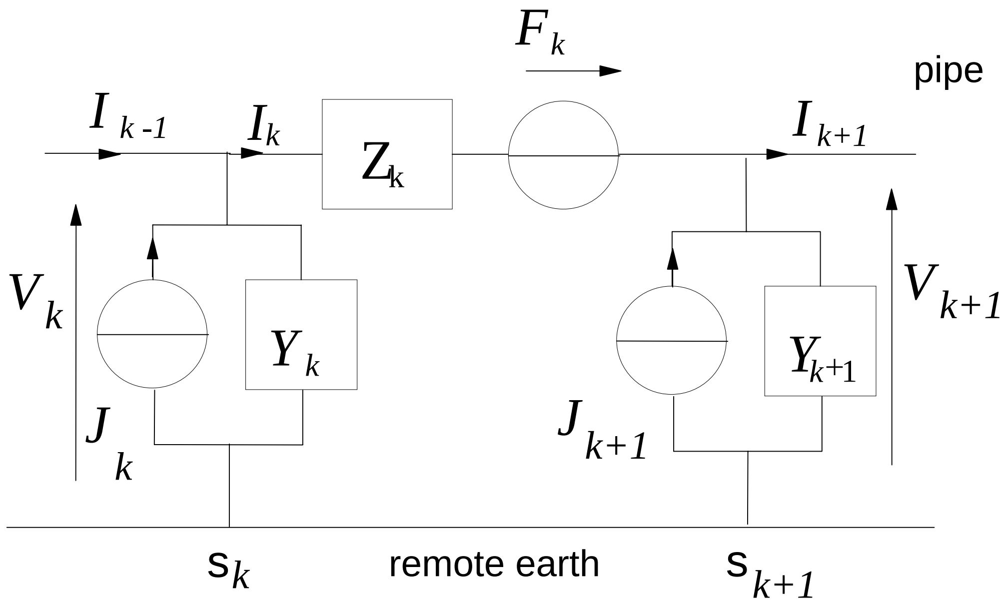


Figure 5.1: k-th cell of the circuit pipeline with earth return

The generic k-th cell, located between abscissas s_k and s_{k+1}[3], is described by means of the following electrical parameters:

- Z_k : the impedance of the circuit formed by the pipeline with earth return;
- Y_k , Y_{k+1} : the admittances to remote earth of the pipeline;
- F_k : the ideal longitudinal voltage generator describing the inductive influence of the line-source on the pipeline;
- J_k , J_{k+1} : the ideal transverse current generators describing the conductive influence of the line-source on the pipeline.

By adopting this model, one can realize that, when dealing with the exchange of current between pipeline and soil, a very important role is played by the admittance to earth (or, equivalently, transverse impedance to earth).

The ideal case of a coating with no defects is described in Appendix G of [3]; reference is made to it for all the information concerning the electrical parameters of the pipeline per unit length (i.e. longitudinal impedances and transverse admittances). As it is important to describe the effect of holidays in the coating, the next paragraph will be devoted to their modelling from the electric point of view in terms of earth resistance.

[3] The layout of the pipeline is represented by a broken line and s is the curvilinear abscissa defined on it. (See Appendix C for some examples).

5.3.2. Earth resistance (spread resistance) of a coating holiday

The model considers a buried pipeline with a coating of thickness d in which a single holiday is present at a given location along the pipeline. The coating holiday is represented by a small cylindrical vacancy in the coating, having a cross section A and the same height d as the coating thickness (see Figure 5.2) and filled with soil.

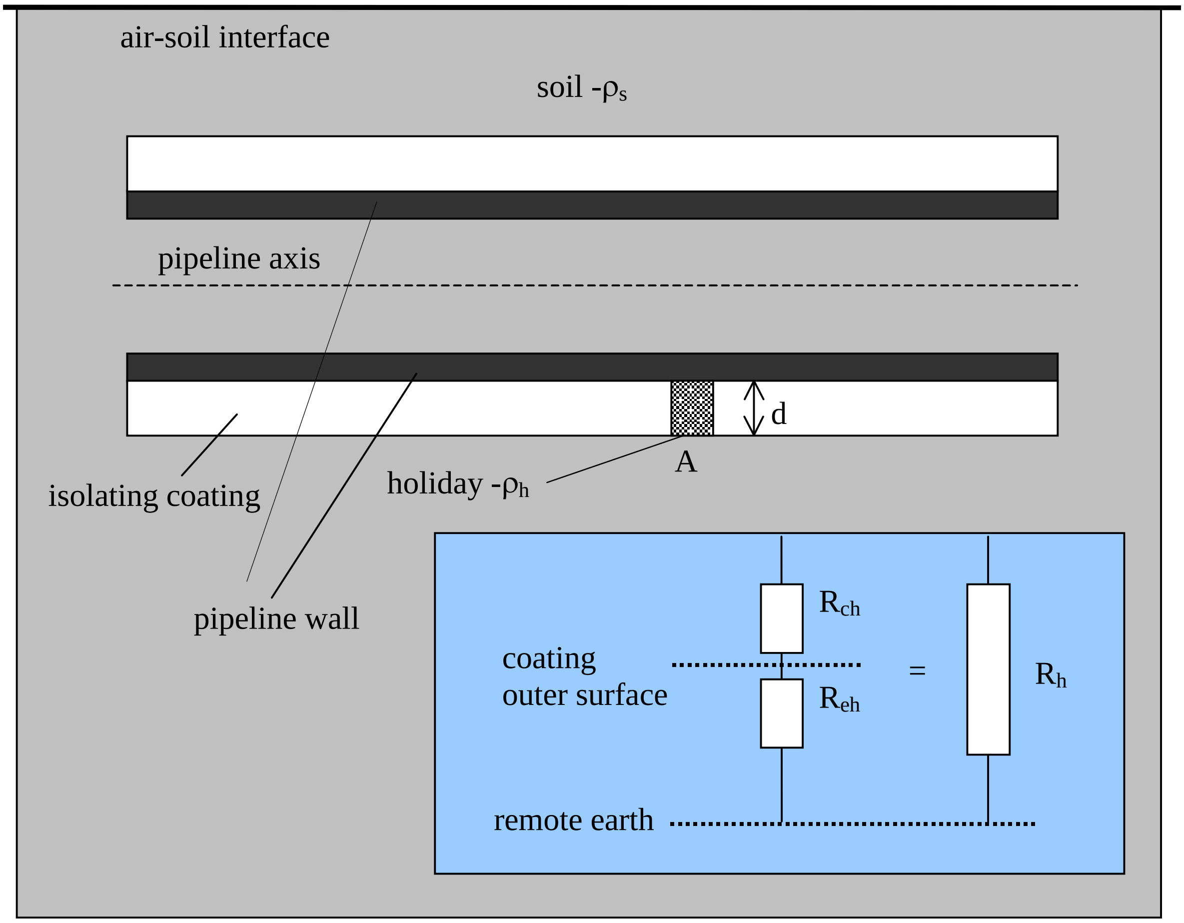


Figure 5.2: Coating with single coating holiday.

Moreover, according to field measurements [12], the value of the soil resistivity measured in points very close to the coating holidays can be very different from the soil resistivity measured at a certain distance from the pipeline. Therefore, two different values for the resistivity are taken into consideration: ρ_h for points inside the coating holiday and ρ_s elsewhere.

The resistance of the pipeline to remote earth R_h through the coating holiday is given by the sum of two elements (see Figure 5.2.) [13]:

The first, indicated by $R_{ch,}$ represents the resistance relevant to the small cylinder inside the coating and is given by:

$$R_{ch} = \frac{\rho_h d}{A} \tag{5.1}$$

Such a contribution can be considered as the voltage drop in the coating holiday with respect to the earth at the outer surface of the coating.

The second contribution, indicated by R_{eh}, represents the earth resistance with respect to the remote earth of the coating holiday. It can be evaluated as the earth resistance of a disk of area A, placed on the soil surface. Hence,

$$R_{eh} = \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}} \tag{5.2}$$

Consequently the total coating holiday resistance R_h is given by:

$$R_h = \frac{\rho_h d}{A} + \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}} \tag{5.3}$$

It is useful to remark that R_h is generally known as the *spread resistance* in books and papers on corrosion.

Typical values of the coating holiday resistance versus the coating holiday area for different values of soil resistivity are shown in Figure 5.3; it can be seen that R_h attains very high values (some hundreds of Ω) even with very large values for coating holiday area A and for low values of soil resistivity ρ_s.

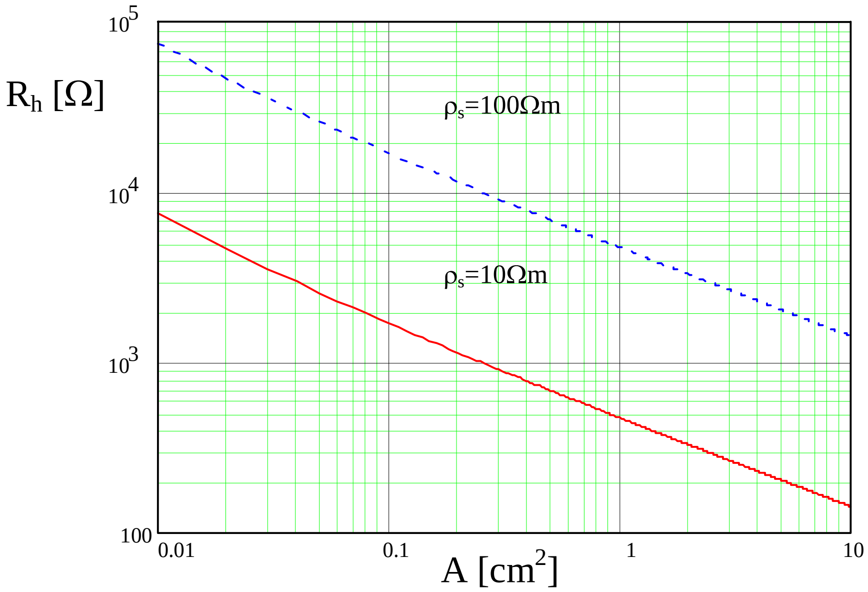


Figure 5.3: Holiday resistance versus holiday area for different values of soil resistivity.

As far as the induced voltage prediction is concerned, the main consequence of this is that, in most of the situations, the presence of coating holidays in the equivalent circuit of the pipeline can be neglected. Hence, only the earthing resistance (whose typical value lie in the range between some ohms to some tens of ohms) has to be taken into account.

5.3.3. Voltage and current density prediction

The prediction of induced voltage and current density on the pipeline should proceed according to the following three steps:

- determination of the currents flowing in the a.c. power line;
- determination of the ideal electromotive force (emf) and current generators to represent the influence of the a.c. power line on the pipeline[4];
- modelling of the pipeline under consideration by means of a suitable equivalent electric circuit and solution of the circuit itself.

All the details of this mathematical procedure can be found in [3], [7], [8], [11] (The last reference is relevant to a pipe network). If K is the number of cells chosen to properly describe the equivalent circuit of the pipeline, the results of the mathematical procedure previously mentioned are the voltages to remote earth V_k calculated at boundary points s_k (k=1,2, ..., K+1) of each cell and the longitudinal currents I_k (k=1,2, .., K) relevant to each cell. The voltage at a generic abscissa s in the k-th cell between s_k and s_{k+1} can be calculated by means of linear interpolation, that is:

$$V(s) = \frac{V_{k+1} - V_k}{s_{k+1} - s_k}(s - s_k) + V_k \qquad s \in [s_k, s_{k+1}] \qquad (5.4)$$

If a coating holiday of area A is located along the pipeline in a point with abscissa s, by applying (5.3), the current density is given by:

$$J(s) = \frac{V(s)}{\rho_h d + \frac{\rho_s}{4}\sqrt{\pi A}} \qquad (5.5)$$

This formula allows for a straightforward calculation of the current density starting from the voltage distribution along the pipeline; it can be noticed that the shape of the function J(s) is the same as the function V(s) and they are related through the factor Ψ given by:

$$\Psi = \left(\rho_h d + \frac{\rho_s}{4}\sqrt{\pi A}\right)^{-1} \qquad (5.6)$$

It can be concluded from (5.5), that, for a given value of voltage V(s), the current density J(s) increases with decreasing values of ρ_h or A.

It is worthwhile to determine the voltage to earth at the outer surface of the coating, which according to Figure 5.2, is the voltage drop U between the pipeline and the soil just outside the coating holiday, (i.e. the voltage drop between the two bases of the small cylinder modelling the holiday).

The voltage U is given by:

$$U(s) = J(s)\rho_h d \qquad (5.7)$$

In order to evaluate the relative weight of the voltage to earth at the outer surface of the coating with respect to voltage to remote earth, the ratio r given by (5.8) is introduced:

[4] Under normal operating conditions, except in particular situations, only inductive coupling between a.c. power line and pipeline has to be taken into account. Hence, with reference to the basic circuit of Figure 5.1, only the longitudinal electromotive force generator has to be considered.

$$r = \frac{U(s)}{V(s)} = \frac{d}{d + \frac{\rho_s}{\rho_h}\frac{\sqrt{\pi A}}{4}} \quad (5.8)$$

Values of r close to 1 mean that the voltage to earth at the outer surface of the coating is practically the same as the voltage to remote earth; this is equivalent to saying that, practically, the entire voltage drop occurs inside the holiday and that the remote earth is very close to the outer surface of the coating. Conversely, values of r close to 0 mean that the voltage drop in the holiday channel is practically negligible and the entire voltage drop occurs outside the holiday.

Figures 5.4a and 5.4b show the plot of r versus the holiday area A for different values of d and of the ratio $\lambda = \rho_s/\rho_h$, (between soil resistivity and holiday resistivity).

The relative weight of the voltage to earth at the outer surface of the coating increases (i.e. tends to 1) for increasing values of the coating thickness d and for decreasing values of the coating holiday area A or the ratio λ.

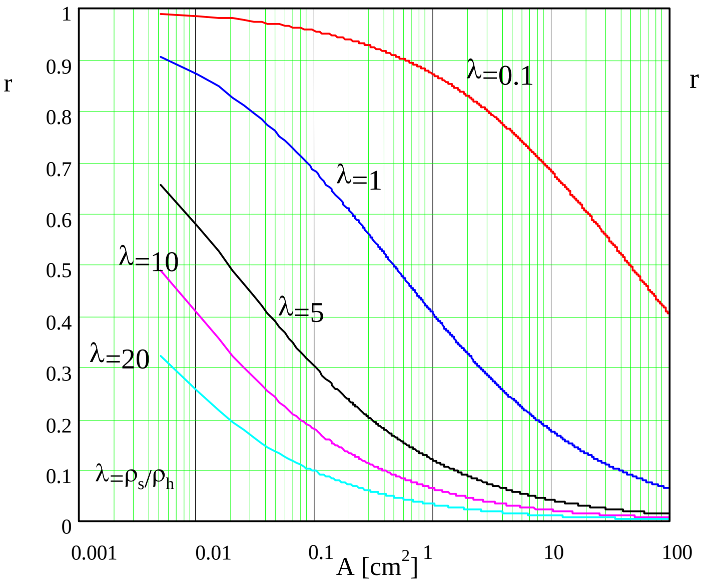


Figure 5.4a: Ratio of the voltage to earth at the coating outer surface with respect to the voltage to remote earth versus holiday area A plotted for different values of λ; d=1mm.

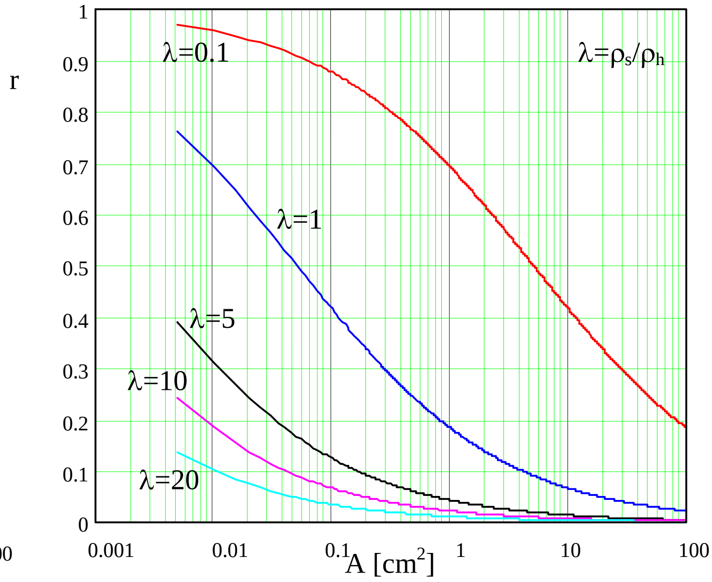


Figure 5.4b: Ratio of the voltage to earth at the coating outer surface with respect to the voltage to remote earth versus holiday area A plotted for different values of λ; d=3mm.

5.4 Equivalent generators representing the interference

5.4.1 General

According to the contents of section. 5.3.1, some information on the determination of the ideal equivalent generators representing the electromagnetic influence from a power line on a pipeline are given here.

With reference to Figure 5.1, distinction has to be made between the longitudinal emf generator F_k due to inductive coupling and the transverse current generator J_k due to conductive coupling.

For convenience the two different coupling mechanisms are treated separately.

5.4.2 Inductive coupling

In order to deal with the inductive coupling, reference is made to chapter 3 of [3], to chapter 4 of [7], or to [11].

This calculation step defines the value of the longitudinal emf generator relevant to each cell.

5.4.3. Conductive coupling

In order to account for the conductive coupling, it is necessary to know the value of the potential in the earth that, for the purpose of this guide, can be calculated according to the contents of Appendices F and G.

In particular, since s is the curvilinear abscissa along the pipeline route, and x(s), y(s), z(s) are the coordinates of a generic point in the soil corresponding to it, the potential in the earth at the pipeline location will be identified by means of the notation V_e(x(s), y(s), z(s)).

The generic current generator J_k assumes different expressions depending on the absence or presence in the k^{th} cell of coating holidays. The two cases are:

a) If holidays are not present in the k-th cell, the expression for the admittance Y_k is directly derived by applying the formulae presented in Appendix G of [3]; with Y_k' denoting the admittance of a coating without holidays. Y_k is defined by:

$$Y_k = Y_k' \tag{5.9}$$

b) If holidays are present in the k-th cell (only one is considered for simplicity), the total admittance is incremented because it is necessary to take into account the holiday earth resistance contribution given by formula (5.3). In this case Y_k is defined by:

$$Y_k = Y_k' + \frac{1}{R_h} = Y_k' + \frac{1}{\frac{\rho_h d}{A} + \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}}} \tag{5.10}$$

Consequently, the expression for the current generators is given, according to [11], by:

$$J_k = \begin{cases} \int_{s_k}^{\frac{s_k+s_{k+1}}{2}} \left(\frac{Y_k}{\frac{s_{k+1}-s_k}{2}} \right) V_e\big(x(s), y(s), z(s)\big) ds & k = 1 \\ \int_{\frac{s_{k-1}+s_k}{2}}^{\frac{s_k+s_{k+1}}{2}} \left(\frac{Y_k}{\frac{s_{k+1}-s_{k-1}}{2}} \right) V_e\big(x(s), y(s), z(s)\big) ds & k = 2, .. K \\ \int_{\frac{s_{k-1}+s_k}{2}}^{s_k} \left(\frac{Y_k}{\frac{s_k-s_{k-1}}{2}} \right) V_e\big(x(s), y(s), z(s)\big) ds & k = K+1 \end{cases}$$

Where K is the number of discrete cells used in order to form the equivalent transmission line representing the pipeline.

Equation 5.11 shows that the conductive coupling is not only directly related to the influence of the power line through the potential in the soil V_e, but also to the characteristics of the coating (material and possible presence of holidays) through the admittance Y_k.

5.5. How to use the model

Despite the approximations, the model can have practical uses in different situations:

- when the a.c. power line and/or the pipeline are at the design stage, the algorithm can be used to evaluate the corrosion risk in terms of induced voltage and/or J_{max} (i.e. the maximum value of the current density calculated under worst case conditions); moreover the knowledge of the voltage V(s) and current density J(s) profiles along the pipeline can provide useful information about the more exposed zones;
- when both the a.c. power line and the pipeline are already existing, the algorithm can be a useful tool to test and verify field measurements and to increase the knowledge about a.c. corrosion due to electromagnetic induction.

In the first case (i.e. at the design stage), a mathematical method is the only tool to assess a possible risk of a.c. corrosion.

In Appendix C some examples of calculations based on real cases are presented.

6. Measurements

6.1. General

Some general aspects to be considered regarding measurements are:

- measurements may be difficult in heavily populated areas as there are many other metallic objects in the earth together with the pipeline (the subject of measurements);
- measurement results seldom reflect worst case interference. Therefore measurement results require to be adequately elaborated in order to allow for a meaningful comparison with the calculated values and the criteria.

When measurement results are compared with calculation results it is important to check and verify the assumptions used in the calculations with the conditions at the time of the measurements.

6.2. Measurement of the induced a.c. voltage

A.C. interference can be determined by measurement of the pipeline a.c. voltage.

A high input impedance a.c. rms voltmeter is connected with one pole to a reference electrode (e.g. copper/copper sulphate)[5], which is placed on the soil above the pipeline, and with one pole to the pipeline at a test post (junction box with terminal of cable welded to the pipeline). The voltmeter indicates the instantaneous rms value of the induced a.c. voltage on the pipeline.

Note: for long-term evaluation, a data recorder instead of a voltmeter may be used.

[5] For pure a.c., the material of the reference electrode has no impact on the measurement. However, often the same reference electrode is used both for a.c. and d.c. measurements.

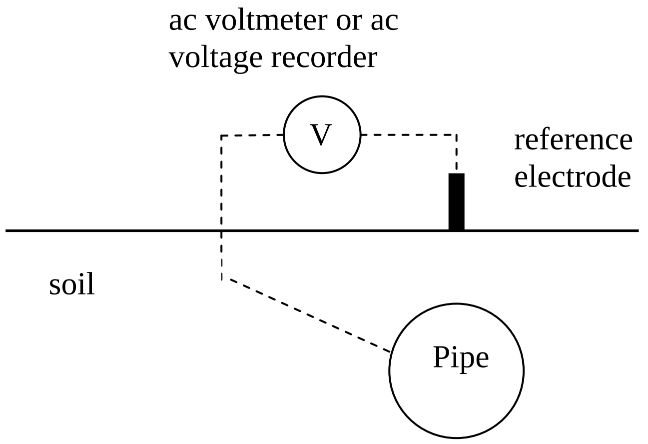


Figure 6.1: Measurement of induced a.c. voltage along the pipeline

Note: locating the reference electrode above the pipeline (as is advised to measure the d.c. potential) is also acceptable to measure the a.c. voltage between pipeline and reference electrode. Indeed, field experience and calculations (see Appendix J) showed that for distances between pipeline and reference electrode exceeding 10 times the coating holiday diameter, the voltage measurement is not interfered by voltage gradients around the pipeline.

6.3. Measurements of a.c. current density

Measurement of the a.c. current density cannot be performed on the pipeline itself. Instead a separate bare steel test coupon with a known area (preferably 1 cm^2) is buried close to the pipeline and connected to the pipeline in a test post, acting as a coating holiday. The a.c. current in the connection wire between the pipeline and the test coupon is measured and divided by the area of the test coupon (see Appendix K).

However, the measurement of a.c. current density is a bit uncertain. The first thing is that it is uncertain if the contact between the test coupon and the soil is representative of the contact between the pipeline and the soil. A second uncertainty is that in a soil with high lime content, the test coupon may be partly covered by isolating limestone, thus significantly reducing the effective test coupon area and consequently the a.c. current and the recorded a.c. current density.

When comparing the current density measurement result with the calculation result, it must also be noted that the electrochemical process can significantly influence the soil resistivity very close to the test coupon or to a coating holiday.

6.4 Measurement of the OFF-potential

To measure the OFF-potential without interference from a.c. or d.c. sources, a bare steel test coupon with a known area (preferably 1 cm^2), acting as a coating holiday, is buried close to the pipeline and connected to the pipeline in a test post, see Appendix K. A reference electrode, installed close to the test coupon measures the potential of the test coupon immediately after disconnecting the test coupon from the pipeline. The measurement is called OFF-potential because it refers to a test coupon disconnected from the pipeline, thus without interference from a.c. and/or d.c. currents. [14]

No method for prediction of the OFF-potential by calculation is available at present.

6.5 Long term monitoring

The measurement techniques mentioned above are most frequently short-term measurements, i.e. measurements done during minutes, sometimes hours. Practice however shows that currents in a.c. power lines vary during time due to changing energy demand (cooking, heating, exchange of electrical energy between operators during shut down, spot markets, …). Consequently interference and influence of the a.c. power lines on pipelines also vary with time. Worst-case conditions are therefore difficult to monitor based on short-term measurements. Also varying soil characteristics due to cathodic protection and a.c. interference might not be seen during short-term measurements.

To monitor interference during longer periods (typically 24 or 48 hours), data recorders can be used to record the electrical signals (pipeline a.c. voltage, current in a coupon). Data can be downloaded to computers for subsequent evaluation and comparison of the registered information with the results of calculations using the a.c. power line parameters at the time of recording.

More and more continuous monitoring of the interference is done using remote monitoring technology. Electronic equipment in remote terminal units reads voltages and currents and compares them online to pre-programmed limits. If a limit is exceeded, an alarm message is generated and transmitted to a central terminal unit, using cellular phone, public switched telephone lines or radio links. Periodically (typically once a week or once a month) data is transmitted for logging and archiving purposes.

7. Acceptable levels for limiting the risk of a.c. corrosion

7.1. General

As the acceptable levels for limiting the risk of a.c. corrosion are often used as contractual conditions, it is important that the considered parameters can be accurately verified by measurements and preferably also predicted using mathematical analyses.

However, the a.c. corrosion process is complex and there are no clear relations between corrosion rate and other parameters. This is illustrated in Appendix E by the statistical analyses of results from a test circuit described in Appendix D. It can indeed be seen from Appendix D that the spread resistance of a coating holiday (total resistance between holiday steel surface and surrounding earth) changes with time due to initial polarization and with seasons.

7.2. Parameter recommended for risk assessment

7.2.1. Pipeline a.c. voltage

The parameter, which seems to have the best correlation between measurement and risk of a.c. corrosion, is the induced a.c. voltage on the pipeline. This parameter can be estimated and measured (see chapter 5 and 6 respectively).

The a.c. voltage between the pipeline and the reference electrode placed above the pipeline should not exceed [5];

- 10 V_{rms} if soil resistivity is higher than 25 ohm·m,

- 4 V_{rms} if soil resistivity is equal to or lower than 25 ohm·m,

at any point of the pipeline under normal operating (non-fault) conditions of the a.c. power system.

In addition, probabilistic evaluations, as presented in Appendix I, can help to assess the risk of a.c. corrosion.

7.3. Complementary parameters

7.3.1. General

In sections where a.c. voltages exceed the values mentioned in 7.2.1. or where the voltages along the pipeline show variations toward lower values, indicating possible a.c. leakage currents[6], specific measurements in the field should be performed.

Some specific measurement techniques with associated criterion are:

- a.c. current density
- pipe-to-soil OFF-potential

As already mentioned in 1.4, instead of strict limits for evaluating the risk of a.c. corrosion, spans are proposed and each of these could be characterised as either a no risk span; a low risk span; or a high risk span.

7.3.2. A.C. current density

The pipeline is considered to be protected from a.c. corrosion if the rms a.c. current density of the metallic surface in contact with the soil is lower than 30 A/m^2.

Practically, there are several levels for corrosion-evaluation:

- $J_{a.c.}$ lower than 30 A/m^2 : no risk,
- $J_{a.c.}$ between 30 and 100 A/m^2 : medium risk,
- $J_{a.c.}$ higher than100 A/m^2 : high risk. [15]

The a.c. current density criterion is not recommended as a general risk assessment criteria because it is difficult to accurately verify by measurements, see also section 6.3.

7.3.3. Pipe-to-soil OFF-potential

A.C. corrosion phenomenon is linked to the switching between immunity and passivity conditions, and vice versa (see 1.3.4.). More negative OFF-potentials increase the pH at the pipeline-soil interface, thus decreasing the leakage resistance and increasing the risk of a.c. corrosion (due to the switching between immunity and passivity).

Therefore, a pipeline is considered to be protected from a.c. corrosion if the coupon-to-soil OFF-potential is at any moment more negative than, and as close as possible to, the protective potential, which is -850 mV for iron or steel in aerobic or -950 mV in anaerobic soil containing sulphate-reducing bacteria, with reference to a $Cu/CuSO_4$ electrode [16], [17].

The pipe-to-soil OFF-potential is not recommended as a general risk assessment criterion because it cannot be predicted by mathematical evaluation and the measurement procedure needs special equipment and expertise.

8. Countermeasures for planned pipelines

8.1. Routing

As the distance between a pipeline and an a.c. power line is one of the main parameters governing capacitive, inductive and conductive coupling, a.c. interference on a planned pipeline can be reduced by increasing the distance between the a.c. power line and the pipeline. Re-routing of a planned pipeline, and which is only possible during the design stage of the pipeline, is therefore an efficient way to reduce a.c. interference on a pipeline.

---

[6] Some possible reasons for irregular variations of the pipeline ac voltage potential are: discontinuances in the pipeline configuration, including earthing points, discontinuances in the ac power line configuration, or a major local damage of the coating.

8.2. A.C. earthing of pipelines

Earthing the pipeline is a classical method to reduce induced a.c. voltage due to capacitive and inductive coupling.

A.C. earthing of a pipeline is performed by effecting a low a.c. impedance to earth without affecting the pipeline d.c. voltage. Thus the a.c. voltage is decoupled without impacting the function of the cathodic protection.

The method is very effective for the reduction of the capacitive influences on above-ground pipelines (assembly of pipeline during construction or permanent above-ground pipeline sections). Earthing electrodes should not be too close to towers to prevent the influence of ground potential rises during a.c. power line earth faults.

A.C. earthing of the pipeline is also an effective way to reduce induced voltages. In less critical situations, this can be done by earthing the pipeline at the two points corresponding to the extremities of the parallelism. In practice and certainly in the case of long zones of influence, more low resistance a.c. earthing systems will be necessary to achieve the required low earthing resistance. A.C. earthing of the pipeline in different earthing systems will cause undesirable circulating currents. The copper cross-section should be chosen accordingly.

Direct earthing of the pipeline will increase the cathodic protection current required to achieve an adequate protection level. This can be avoided by using zinc electrodes (ribbons) as earthing electrodes and/or by using a d.c. decoupling device (capacitors, diodes, …) between pipeline and earthing.

8.3. Insulating joints or flanges

As the induced voltage due to inductive coupling is a function of the length of parallelism, insulating joints or flanges can be used to subdivide the pipeline in shorter sections in order to lower the induced voltage. These insulating joints or flanges must be able to withstand the potential difference due to earth faults to avoid a flashover between the pipeline sections. Self-restoring surge arresters connected to the pipeline sections at both sides of the insulating joints or flanges can avoid damage and their destruction in case of lightning strikes.

Although insulating joints or flanges are often used to divide pipelines in sections with separate cathodic protection systems, it should be noted that this technique can cause severe corrosion in case of heavy d.c. stray current interference (tramway, railway, HVDC power lines, …). Indeed, d.c. stray currents, prevented from following the pipeline because of the insulating joints, will leave the pipeline through coating holidays, causing corrosion at those locations.

8.4. Enhanced insulation of pipelines

Enhancement of the pipeline insulating coating can be used to avoid problems due to conductive coupling in the vicinity of a tower.

This can be achieved by increasing the coating thickness over a certain length of pipeline.

Installing the pipeline inside an insulating sheath could create cathodic protection problems and should be applied with care.

8.5. Full compensation of induced a.c. voltage

Under ideal conditions a complete reduction of induced a.c. voltage may be achieved by introducing controlled a.c. voltages E_1 and E_2 into the connection between pipeline and earth electrodes R_{a1} and R_{a2} respectively (see Figure 8.1) having a phase shift φ=180° compared to the a.c. voltage pipeline/soil at the location of installation.

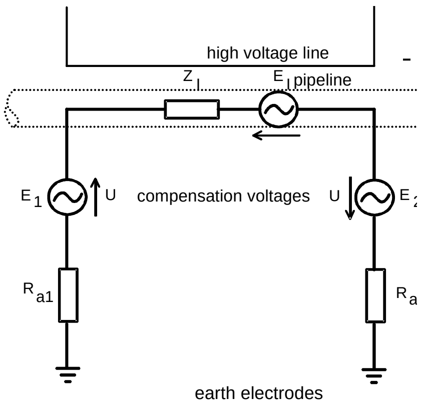


Figure 8.1:

Equivalent circuit (simplified) of an a.c. interfered pipeline with equipment for a.c. voltage compensation

The required power increases proportionally to the square of the induced a.c. voltage and also increases with decreasing impedance per unit length.

In ideal cases a complete compensation of induced a.c. voltage along the complete pipeline - i.e. also outside the section of parallel routing - is possible. However, in practice, the geometry of proximity generally does not correspond to these ideal assumptions. Therefore, one must take into account that a complete compensation will not be achievable. Furthermore the power required will be extraordinarily high in the case of a short but highly-interfered pipeline sections.

Compensation systems are difficult to settle, and installation and operation costs are very high.

8.6. Partial compensation of induced a.c. voltage

The difficulties of high power consumption may be overcome if the compensation compartments are connected to the pipeline via diodes as shown in Figure 8.2.

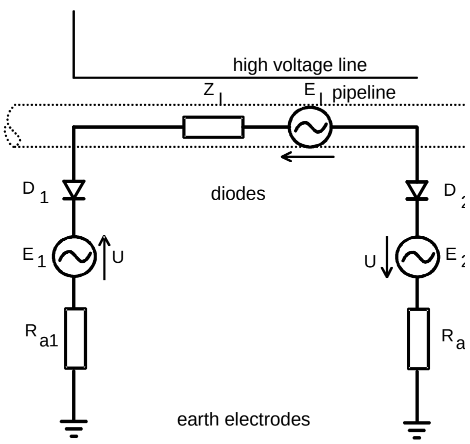


Figure 8.2:

Equivalent diagram (simplified) of an a.c. interfered pipeline with compensation compartments and diodes to compensate the positive part of induced a.c. voltage

Under these conditions the positive cycle of the induced a.c. voltage is exclusively compensated, thus the consequence will not be a reduction of a.c. current density in a coating holiday. This method therefore works under the assumption that the positive part of the a.c. voltage causes corrosion exclusively. This principle corresponds to the considerations mentioned in chapter 7.3.4, where it had been assumed that a.c. corrosion is successfully mitigated if the IR-free potential of the coating holiday at no time exceeds the protection potential U=-0.85V ($Cu/CuSO_4$).

The power consumption of the compensation compartments now corresponds to a simple rectifier, which is adjusted to give an output voltage yielding an on-potential of the order of the induced a.c. voltage.

The disadvantage of this method clearly is the more negative ON-potential which is established on the pipeline and which is now fluctuating with the induced a.c. voltage. Especially in the case of bitumen-coated pipelines, this has to be considered from the d.c. interference point of view.

Compensation systems are difficult to settle, and installation and operation costs are very high. In addition, the effect during a.c. power line faults has to be considered.

8.7. Shielding

A bare conductor laid along a pipeline in the whole zone of influence is a method to shield the pipeline from induction by the a.c. power line. For more information, see section E.5, Appendix E of the Cigré Technical Brochure No. 95. [3])

9. Countermeasures in existing pipelines

9.1. A.C. earthing of pipelines

A.C. earthing of a pipeline as described in section 8.2 is applicable also for an existing pipeline.

9.2. Insulating joints or flanges

It is possible to install insulating joints or flanges also in an existing pipeline, see section 8.3 for more information.

9.3. Compensation of induced a.c. voltage

The two methods for compensation of induced a.c. voltage that are described in sections 8.5 and 8.6 have the same pros and cons when applied to existing pipelines.

9. 5 Shielding

To install a bare conductor laid along a pipeline in the whole zone of influence is a method that can be used to shield the pipeline also from induction by an existing a.c. power line. For more information, see section E.5, Appendix E of the Cigré Technical Brochure No. 95. [3]

10. Countermeasures in planned a.c. power lines

10.1. Routing

Principally, the most straightforward way to avoid interference from an a.c. power line on a pipeline is to avoid routing the a.c. power line close and parallel to the pipeline. Any crossings should preferable be performed at right angles at mid-span, i.e. between towers, of the a.c. power line. This is the ideal countermeasure for minimizing interference, and should be considered during the planning stage.

10.2. Configuration

In a planned line it may be possible to select a conductor configuration minimizing the induction from the line. This is also a favourable aspect regarding the magnetic field environmental. For further information see TF C4.2.04: “Guidelines for Mitigation Techniques of Power-Frequency Magnetic Fields” [6].

However, measures that reduce the magnetic field due to the currents flowing in the symmetrical three phase conductors do not necessarily reduce the common mode field. The common mode field due to the zero sequence current, and hence the current in the earth wire, is in many cases higher than the field due to the three phase currents. For the induction in pipelines, see also section 2.4.1.

10.3. Transposition

Normally transposition of the a.c. power line phase conductors is an effective way to reduce interference from the a.c. power line due to inductive, and also capacitive, coupling. However, with the low induction level required for causing a.c. corrosion, additional transpositions are hardly a realistic countermeasure. The distance between consecutive transposed points has to be unrealistic short. However, it is necessary to take into account the fact that transposition towers introduce a substantial earth potential rise due to earth current and corresponding conductive coupling, see section 10.6 below.

10.4. Shielding

There are techniques for magnetic shielding of an a.c. power line by active or passive loops. This will be described in the guide TF C4.2.04: “Guidelines for Mitigation Techniques of Power-Frequency Magnetic Fields” [6].

10.5. Tower earthing

The potential of the tower’s earthing wires and rods will reach quite a high value during lightning strikes to the tower and earth faults at the tower. Therefore, the tower’s earthing shall be physically separated from the pipeline as far as possible. A low footing resistance for the towers is essential for reducing the potential rise.

10.6. Reducing the risk of tower earth faults

In towers especially exposed to lightning strikes, or at towers where earth fault currents introduce high hazards, it is possible to significantly reduce the risk of flashovers to earth by installing conductor-to-tower arresters. Arresters might also be installed in nearby towers to minimise the risk of a back-flashover.

10.7. Minimising continuous earth current

Any interruption of earthed shield wires or counterpoises should preferably be located at a larger distance from the pipeline than that given by the corresponding zone of influence of the a.c. line, see section 3.4.2 and Appendix F. Otherwise it should be ascertained whether countermeasures are needed.

Transposition of phase conductors or discontinuity of earth wires introduces a substantial earth potential rise due to earth current and corresponding conductive coupling, see Appendix F and Appendix G**.** Adjacent towers will also introduce a large EPR.

The decrease of the EPR from the transposed tower is dependent on the soil resistivity. If the resistivity is very high, the EPR can reach tenths of volts at a distance of more than 1 km from the power line.

If transposition towers or other discontinuities are located such that a pipeline is within its zone of influence, it should be evaluated if further actions are needed.

A way to reduce the earth current in a transposition-tower is to isolate the shield wires in towers with high EPR close to the pipeline. Then the earth current will be shared between the closest towers with earthed shield wires.

A way to eliminate transfer of EPR via lines crossing the transposed line is to isolate the shield wires of the crossing line at towers close to the crossing point.

Depending on the situation, sectionalizing of the shield wires by series insulators might also be a way to reduce the zone of influence and the conductive coupling.

Earth penetration of current induced in stay (guy) wires can be avoided by shortening that current loop or by insertion of insulators. This is a local phenomenon very close to the tower.

10.8. A.C. power cables

A.C. power cables should not be located too close to a pipeline. The distance between an a.c. cable and a parallel pipeline should preferable be much larger than the phase-to-phase distance of the cable system. Crossing should preferable be at right angles. If the routing is close, it must be evaluated if further actions are needed.

Earthing rods and earthing wires for earthing of cable screens should preferably be located away from the pipeline such that the pipeline is outside the zone of influence from the earthing point, thus catering for at least a continuous a.c. current which can be expected at the earthing point. If a cable earthing point is located closer, it still is important to keep it separated from the pipeline as much as possible. It also must be evaluated if further actions are needed.

11. Countermeasures for existing a.c. power lines

11.1. General

The possibilities for countermeasures to be implemented are much less for an existing line than prior to construction of a new line. However, there might be some options to be considered.

11.2. Shielding

Magnetic shielding might in some cases be possible for an existing a.c. power line, see section 10.4.

11.3. Tower earthing

It may be realistic to relocate some of the tower earthing equipment if located too close to the pipeline. The tower earthing system should be reviewed according to section 10.5 above.

11.4. Minimising earth current

Minimizing earth current in accordance with section 10.7 may be realistic.

11.5. A.C. power cables

Minor rerouting of cables might be possible. Reduction of the induction from cables by passive loops might be realistic for a short distance.

Cable screen earthing points should be reviewed considering section 10.8 above.

12. Factors to be considered for selection of countermeasures

12.1. Countermeasures on pipelines

12.1.1. Location

Installing a planned pipeline at a greater distance from an a.c. power line is certainly an efficient way to lower the risk for capacitive, inductive and conductive couplings. This is however not always feasible because environmental pressures and governmental rules have increasingly required that public utility transport systems share a common corridor, which in dense populated areas is rather narrow.

12.1.2. Earthing of pipelines

Earthing of a planned or existing pipeline is an efficient way to reduce induced voltage due to capacitive and inductive coupling. The costs are very low (earthing system, d.c. decoupling device, …) and the solution is almost always feasible.

12.1.3. Insulating joints or flanges

Installing insulating joints or flanges to subdivide a planned or existing pipeline in shorter sections is, from an electrical point of view, certainly an efficient way to reduce the induced voltage due to inductive coupling. However, the countermeasure requires taking the pipeline out of operation and the required equipment is costly. After installation, insulating joints or flanges are weak points in the network that affect transport reliability. Although feasibility is high, overall efficiency is rather low.

12.1.4. Enhanced insulation of pipelines

Enhancement of insulating coating for a new pipeline is almost the only way to avoid problems due to conductive coupling in the vicinity of a tower. Touch-voltage for people who may come in contact with the bare steel of a pipeline or pipeline equipment is a safety issue and the limits are therefore very stringent. This mitigation measure is very often combined with the installation of equipotential grounding mats further along the pipeline. The solution is very effective and almost always feasible.

12.1.5. Earth conductors along pipelines

A bare conductor laid along a planned pipeline in the whole zone of influence is a rather costly and not very efficient solution because it will almost always require supplementary mitigation measures. Feasibility however is high as shown in section E.5, Appendix E of the Cigré Technical Brochure No. 95. [3]

12.1.6. Compensation of induced a.c. voltages

Compensation of a.c. voltage by voltages of opposite phase is a feasible but very expensive measure against induced a.c. voltages. For a short length of parallelism the price is high, and for long parallel sections the required power and the complexity of the systems are too high.

12.2. Countermeasures on a.c. power lines

12.2.1. Location

Installing a planned a.c. power line at a greater distance from a pipeline is certainly an efficient way to lower the risk for inductive and conductive coupling. This is however not always feasible for a planned pipeline because of environmental pressures. Increasingly, governmental rules impose public utility transport systems to share a common corridor, which in dense populated areas is rather narrow. Besides, the cost impact may rule out relocation.

12.2.2. Transposition

Transposition of a.c. power lines is very costly and not efficient for reducing the a.c. corrosion risk. Thus, additional transposition for reducing the a.c. corrosion is not a realistic measure.

12.2.3. A.C. power line configurations

An improved a.c. power line configuration is an effective way to reduce the inducing magnetic field to a certain degree. However, it is costly and this countermeasure can only be an alternative for a planned line if the reduced a.c. magnetic field is also motivated by environmental reasons. The addition of passive or active loops for reducing the inductive coupling is too costly to be a cost effective option.

12.2.4. Isolation of shield wires

Isolation of the shield wires in towers with high EPR, see section 10.7, close[7] to the pipeline is an effective way to reduce earth current and at relatively low cost. Thus, it is normally both feasible and cost effective if continuous earth current is a problem in such cases.

Isolation of the shield wires may also be an option if the shield wires are terminated close to the pipeline.

[7] When the earth resistivity is high, “close” can mean within a distance of some km.

12.2.5. Reducing the risk of tower earth faults by means of arresters

Even if the cost of a few arresters is moderate, the maintenance aspect restricts the use of arresters in a.c. power lines. Besides, if used in many towers, the arresters cost will be high. Thus, installation of arresters in a tower is only used for towers that are frequently exposed to lightning strikes.

12.2.6. Enhanced tower earthing

Depending on the local conditions, especially the soil resistivity, it may be possible to reduce the earth potential close to a tower by reducing the resistance of the tower earthing. However this is a measure to be evaluated and/or combined with measures on the pipeline, see section 12.1.4.

13. A.C. corrosion of cables

Metallic pipelines are long conducting objects covered with an isolating coating. For pipelines there is a risk of a.c. corrosion at coating holidays in the presence of an induced a.c. voltage. The natural question is whether there are other objects with similar conditions that may also be exposed to a risk of a.c. corrosion. One answer is that the conditions are similar for cables with a coated metallic sheath and for coated pipelines.

A.C. corrosion has been reported regarding underground concentric neutral URD cables [18]. In those cables, the concentric neutral conductor consists of bare copper or tin plated copper conductor in contact with the surrounding soil.

So far, JWG C4.2.02 is not aware of any report regarding observed a.c corrosion on cables with an outer isolating sheath. This is an indication that cables with an isolating sheath may be less vulnerable to a.c. corrosion when compared with coated pipelines. An hypothesis is that the corrosion process may be different for cables because cables have another design and may be made of other material than pipelines, Besides, the smaller diameter of the cables may make it less vulnerable to physical damages of the isolating cover.

The basic preconditions, leading to a risk of a.c. corrosion, are the same for cables and for pipelines and it may take a long time before a.c. corrosion in cables lead to noticeable consequences. Therefore, in case there is an observed corrosion damage on a metallic cable sheath, a.c. corrosion has to be considered as a probable cause.

Also for other metallic objects, which can have high local a.c. potential between the metallic surface and a surrounding electrolyte, a.c corrosion has to be considered in cases of observed corrosion damage. It must also be noted that metals with a protective oxide film, such as aluminium and stainless steel, may be more sensitive to a.c corrosion than normal steel, in terms of a.c. current density.

14. Conclusions

Background information regarding the a.c. corrosion phenomenon has been given with reference to relevant and important parameters and conditions. The state of the art is described.

Influencing factors and conditions for risk of a.c. corrosion are identified. Guidance is given for overall assessment of the risk. Modelling and relevant calculation and measurement methods are treated in relation to criteria for assessment of the risk of a.c. corrosion. Decisive parameters have been identified for evaluation of countermeasures.

Possible countermeasures both for the pipelines and for the a.c. power lines are discussed. The feasibility, advantages and drawbacks of each countermeasure are broadly analysed to facilitate the selection of a suitable mix of countermeasures.

A number of appendices give deeper knowledge in areas related to a.c. corrosion. References are given to relevant documents for more detailed information.

15. References

[1] *D.K. Kim, J.H. Bae and D Scantlebury: "AC Induced Corrosion – Summary of AC Corrosion Cases" Cathodic Protection Conference at UMIST, February 10-11, 2003, Published in JCSE, The Journal of Corrosion Science and Engineering, Volume 4, Paper 16. Available at: www.jcse.org/ViewPreprint.asp?vol=4&pap=16*

[2] *CEOCOR: A.C. Corrosion on cathodically protected pipelines. Guidelines for risk assessment and mitigation measures. Published by APCE Association for the Protection against Electrolytic Corrosion, 2001. Available at: CEOCOR, www.ceocor.lu.*

[3] *CIGRE: " Guide on the Influence of High Voltage A.C. Power Systems on Metallic Pipelines ", Cigré WG 36.02, Cigré Technical Brochure No. 95, 1995.*

[4] *EN12954:2000, "Cathodic protection of buried or immersed metallic structures – General principles and application for pipelines". Subclause 4.2 "Criteria for cathodic protection". European Committee for standardisation, Brussels, December 2000.*

[5] *M. Büchler, F. Stalder and C.-H. Voûte : "Evaluation of techniques for the determination of the corrosion risk caused by induced AC-currents on cathodically protected pipelines". CEOCOR Plenary Days, Zürich, Switzerland, 2-4 Octobre 2002. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[6] *CIGRE: "Guidelines for Mitigation Techniques of Power-Frequency Magnetic Fields originating from Electric Power Systems" (The guide is under preparation by Cigré TF C4.2.04 within SC C4 and will be published as a Cigré Technical brochure).*

[7] *ITU-T: "Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines", Vol. II, ITU-T, (Former CCITT) Geneva 1989.*

[8] *ITU-T: "Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines", Vol. III, ITU-T, (Former CCITT) Geneva 1989.*

[9] *G. Lucca, M. Moro: "A.C. interference from a power line on a buried pipeline: evaluation of the current density", Proceedings of CEOCOR meeting, Zurich, October 2-4, 2002. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[10] *G. Lucca, L. Di Biase, M. Moro: "A. C. corrosion on buried pipelines: a probabilistic approach", Proceedings of 6th CEOCOR International Congress, May 13-16 2003, Giardini Naxos, (Sicily) Italy. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[11] *G. Lucca: "Electromagnetic interference produced by power or electrified railway lines on metallic pipe networks ", L' Energia Elettrica, vol. 76, n. 2, 1999.*

[12] *L. Di Biase: "Corrosione da corrente alternata su tubazioni metalliche interrate: stato dell'arte e prospettive", Atti del II^{o} Convegno Nazionale APCE, Roma, November 21-22 1996. (In Italian[8]).*

[13] *E. D. Sunde: "Earth Conduction Effects in Transmission Systems", Ch. 6, Van Nostrand Company Inc., 1949.*

[14] *EN13509 "Cathodic protection measurement techniques." European Committee for standardisation, Brussels December 2000.*

[15] *Wechselstromkorrosion – Beurteilung der Verhältnisse bei Stahlrohrleitungen und Schutzmassnahmen. AfK-Empfehlung Nr. 11 Januar 2003, Herausgegeben von der*

[8] The English version of such a paper can be found in [2] (in Annex 2).

Arbeitsgemeinschaft DVGW/VDE für Korrosionsfragen (AfK) (In German.)

[16] *R. Gregoor, A. Pourbaix and Ph. Carpentiers: "Detection of a.c. corrosion. (Protectioncriteria, measurement of corrosion rate and pH, using correac system and an electrical resistance probe"). Proceedings of 6th CEOCOR International Congress, May 13-16 2003, Giardini Naxos, (Sicily) Italy. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[17] *H.-G Schöneich: " Discussion of criteria to assess the alternating current corrosion risk of cathodically protected pipelines". CEOCOR Plenary Days, Dresden, Germany, 15-17 June 2004. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[18] *K.C. Compton: Underground corrosion of copper - Particularly concentric neutral of URD cable. Final second year report on Project 265. Dept. of Mechanical and Ocean Engineering. Rosensteil School of Marine and Atmospheric Science. University of Miami. 4600 Rickenbacker Causeway, Miami, Florida 33149, USA. (Published: December 31, 1977)*

[19] *Camitz G & Johansson C & Marbe Å: Alternating current corrosion on cathodically protected steel in soil – A long-term field investigation. CEOCOR 5th International Corrosion Congress, Brussels May 2000. CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[20] *Camitz G & Persson C & Lundberg R: Alternating current corrosion of cathodically protected steel in soil - Field investigation with low constant AC voltage. CEOCOR 6th International Corrosion Congress, Giardini Naxos,Sicily, Italy, 13-16 May 2003. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.*

[21] *F. J. Sollerkvist and Gy. Varju: "A general model and numerical method for multiconductor systems in frequency domain". Proc. of the IEEE/KTH Stockholm Power Tech. Conference, Stockholm, Sweden, June 18-22, 1995, pp. 227-232.*

[22] *F. Jonas, L. E. Juhlin and A. Nyman: "Penetration of Harmonics from the Baltic Cable HVDC Station into the Feeding AC System". CIGRÉ Session 1996, Paris, Paper 36-302.*

Glossary

A.C. earthing: a measure giving low a.c. impedance to earth without affecting the d.c. voltage on the pipeline. Thus the d.c. current is blocked and there is no impact on the function of the cathodic protection.

A.C. corrosion: corrosion caused by alternating current, which originates from an external current source.

A.C. discharge device: a device blocking d.c. current but allowing the flow of a.c. current; used in the connection between a cathodically protected pipeline and an earthing electrode.

Anions: ions with positive electrical charge.

Anode (in general within the science of corrosion): the part of a metal surface, in a corrosion cell, which is oxidised, i.e. is attacked by corrosion.

Anode (in conjunction with cathodic protection): electrical electrode of metal, metal oxide or graphite placed in the electrolyte, through which the protection current is fed to the metal surface (cathode) to be protected.

Anode bed: buried anode, which is surrounded by an anode-fill.

Anode-fill: electrically conductive fill material in which an anode is embedded in the ground, in order to lower the earthing resistance of the anode. Coke is often used as fill material for impressed current cathodic protection anodes. Very often, a mixture of pulverised bentonite clay, gypsum and sodium sulphate is used as fill material for sacrificial anodes.

Back flash: the phenomenon that a flashover occurs from the metallic structure of an a.c. power line tower to a phase conductor. The reason is that during a lightning strike to the top of the tower of an a.c. power line, the potential of the top of the tower is suddenly increased substantially while the isolated phase conductors remain close to the pre-strike voltage.

Cathode: the part of a metal surface, in a corrosion cell, where a species (usually oxygen) is chemically reduced. This reduction at the cathode supports the oxidation process at the anode.

Cathodic protection: a type of electrochemical corrosion protection, which involves the electrode potential of the metal to be protected to be lowered from the corrosion potential to the protection potential, when the corrosion is negligible. The lowering of the potential is achieved by causing a current to flow from the anode, through the electrolyte to the metal surface (the cathode). *Impressed current protection (electrochemical protection)* means that the protection current is fed from an external direct current source, usually a mains-operated transformer/rectifier. In the last few years also solar cells are being used as a current source. *Sacrificial anode protection (galvanic protection)* means that the protection current is generated in a galvanic way by a magnesium, a zinc or an aluminium anode.[9] [10]

Cations: ions with negative electrical charge.

Coating holiday: defect in the electrically isolating pipeline coating, allowing contact between the steel of the pipeline and the surrounding electrolyte.

---

[9] Cathodic protection doesn't protect the metal underneath the coating.

[10] Cathodic protection doesn't protect from a.c. corrosion.

Coating holiday detection method: methods (Pearson, DCVG) for localising coating holidays on pipelines from the ground surface.

Corrosion cell: a type of electrochemical cell on a metal surface, in which corrosion can take place. The cell consists of an anodic surface, a cathodic surface and an electrolyte. On the anodic surface an oxidation process takes place (dissolution of the metal = corrosion) and on the cathodic surface a species (usually oxygen) is chemically reduced. Positive current flows through the electrolyte from the anodic surface to the cathodic surface. A prerequisite for the oxidation of the anodic surface is that the reduction takes place on the cathodic surface. If the reduction process on the cathodic surface is hindered then also the oxidation process on the anodic surface is hindered.

Corrosion rate: the rate of corrosion (metal dissolution). Corrosion rate is expressed as weight loss per unit of metal area and unit of time (g/m^2 and year) or as loss of metal thickness per unit of time (μm/year = 0,001 mm/year). Weight loss can be recalculated into loss of metal thickness. The rate of localised corrosion is usually expressed as depth penetration per unit of time (μm/year).

Corrosion potential: the electrode potential of a freely corroding metal surface, e.g. the steel surface in a coating holiday on a buried pipe, which is <u>not</u> cathodically protected. The corrosion potential may either be a *resting potential* (also called *free corrosion potential*) or a *polarised potential*.

Counterpoise: buried wires following an a.c. power line from tower to tower. The counterpoise arrangement is often used for reduction of the tower footing resistance in areas with high soil resistivity. Copper or galvanised steel can be used as counterpoise material. When made of copper, the counterpoise may be connected to the towers via spark gaps to avoid galvanic corrosion.

Coupon: a small piece of steel plate buried in the soil close to and electrically connected to a pipeline for corrosion and potential measurements.

Current density (on metal surface): current per unit metal surface area, usually expressed as A/m^2 or mA/cm^2.

D.C. decoupling device: device for blocking d.c. current but allowing passage of a.c. current; used in the connection between a cathodically protected pipeline and an earthing electrode.

DCVG: abbreviation of D.C. Voltage Gradient, see Voltage Gradients

Depolarisation (cathodic): reduction of cathodic polarisation, e.g. as a result of reduced or interrupted feeding of D.C. current to the metal surface.

Earth megger: a 4-pole alternating current instrument for measurement of resistances, e.g. in soil. With an earth megger the resistance measurement can be made according to the two-, the three- or the four- point method.

Earthing: dispersion of current into the earth via an earthing electrode.

Earthing electrode: a metallic electrode, usually in the shape of a rod, a plate or a wire, in low-ohmic contact with the soil, used for earthing.

Earthing resistance: the electrical resistance between a metal surface (e.g. the steel surface in a coating holiday on a buried pipe, or an earthing electrode or a a.c. power line pole foundation) an remote earth.

Electrical continuity: unbroken electrical (metallic) conductivity, e.g. longitudinally in the pipe wall in a metallic pipeline or in the metal sheath in a metal sheathed cable.

Electrical separation: interruption of the electrical continuity between two metal structures or between two parts of a metal structure. In pipelines, isolating joints or isolating couplings are used for electrical separation between two pipe sections.

Electrode: a metallic or another type of electric conductor, which is in contact with an electrolyte, and through which electric current can flow into or can leave the electrolyte. The metal surface of a buried pipe is an electrode. An electrode may also be a measuring electrode, e.g. a reference electrode. Non-metallic electric conductive materials are e.g. graphite and certain types of coke.

Electrode potential: the potential difference between an electrode and the surrounding electrolyte. It is measured by means of a reference electrode, which is placed in the electrolyte. Cf. *Corrosion potential* and *Protection potential.*

Electrochemical potential: same as *Electrode potential*.

Electrolyte: a medium, which can transport current by means of ions, e.g. water, wet soil and wet concrete.

Electrolytic corrosion: corrosion of a metal surface caused by electric current, which originates from a foreign current source, and which is flowing out of the metal surface into the electrolyte. Both d.c. current and a.c. current may cause electrolytic corrosion. Electrolytic corrosion requires an external electric energy source, while galvanic corrosion produces electric energy.

Earth Potential Rise (EPR): the increased potential of an a.c. tower earthing point and the surrounding soil due to earth currents, especially the high fault current at a phase-to-earth fault in an a.c. power line tower. The potential rise may also be caused by a lightning strike to the tower, and which may result in a phase-to-earth fault. The EPR is a function of the a.c. tower earthing and the soil resistivity. [11]

External corrosion test probe: an *external potential test probe* used for assessment of the efficacy of the cathodic protection by weight loss measurement. The weight of the metal coupon has been measured before the burial of the probe. After a certain time, e.g. one year, the coupon can be excavated and its weight loss can be measured in order to assess the cathodic protection efficiency.

External potential test probe: permanent installation in the ground close to the cathodically protected structure, comprising a reference electrode with an associated small metal coupon that is connected to the structure. The distance between the reference electrode and the coupon is very small to provide a voltage-potential measuring facility without IR-drop due to currents in the ground.

Faraday's law: a physical law which, simplistically expressed, gives how many grams of a metal that dissolves (corrodes) at a certain anodic direct current and during a certain influencing time period, that is the period when the current is leaving the metal surface. Thus, with the aid of Faraday's law the corrosion rate can be calculated. Faraday's law can be used in conjunction with electrolytic corrosion in such a way that if the current and the influencing time period are known, then the corrosion that is caused by the direct current can be calculated. This law was first described by the English physicist and chemist Michael Faraday in the beginning of the 19^{th} century.

Free corrosion potential: a corrosion potential, which is not influenced (polarised) by electric currents (also called *Resting potential*). See also *Corrosion potential*.

Galvanic cell (bi-metal type): a special type of corrosion cell in which the anode and the cathode consists of two different metals. The cathode consists of a noble metal (stainless steel, copper, silver etc.) and the anode consists of a less noble metal (magnesium, zinc, aluminium, iron, low alloyed and carbon steel, lead, tin etc.). The anode and the cathode are immersed in the same electrolyte and in metallic contact (either in direct contact or via a metal cable or another type of

[11] There may also be steady state earth potential rise due to conductive coupling from steady state earth current. A.C. power line transpositions are typical sources of such earth currents.

lead) with each other. The cathode has a more positive potential than the anode, and this potential difference results in a flow of a galvanic current from the anode to the cathode.

Galvanic corrosion: corrosion of a metal (the anode) caused by metallic contact with another, more noble metal surface (the cathode). One example is corrosion of steel or cast iron in contact with copper, where the cast iron or the steel becomes anodic and corrodes whilst the copper becomes cathodic and thereby protected against corrosion. In practice this could be a buried cast iron or a steel pipeline in contact (intentionally or unintentionally) with a copper earthing-electrode. In cathodic protection with galvanic (sacrificial) anodes the less noble galvanic anode is exposed to galvanic corrosion, as a result of the connection to the more noble structure, which is to be protected. Galvanic corrosion takes place in a *galvanic cell.*

Galvanic current: the current, which is flowing between the anode and the cathode in a *galvanic cell.*

General corrosion: corrosion, which is taking place at roughly the same rate all over the corroding surface. Cf. *Localised corrosion*.

Grounding resistance: same as *Earthing resistance.*

Guy wires: wires used for keeping a.c. power line towers in position when the towers are not self-supporting.

Holiday (i.e. coating holiday): a small hole or defect in the pipeline coating leaving a small steel area open and exposed to corrosion.

Instantaneous OFF- potential: same as *OFF- potential*.

Instantaneous ON- potential: same as *ON- potential*.

IR- drop (in conjunction with cathodic protection measurement): voltage drop in the electrolyte, which is caused by the cathodic protection current and which undesirably is included in the potential of the protected objective if the potential is measured when the cathodic protection is working. The expression is derived from I for current and R for resistance. During measurement the IR- drop is added to the potential in such a way that the measured potential will be more negative than the true potential of the protected object. Other currents in the electrolyte in addition to the cathodic protection current can give rise to IR- drop in the ground, e.g. stray current from D.C. installations and galvanic current.

In coarse soils such as sand, gravel and moraine (which have a high soil resistivity) the IR- drop can be high whilst the IR- drop usually is less in wet clay (which has a low soil resistivity). In seawater (which has a very low resistivity) the IR- drop is so small that it can be neglected.

Isolating coupling: a device, which interrupts the electrical continuity between one pipeline section and another pipeline section. The coupling can be a flanged coupling (so called isolating flange) with isolating plastic washers. The coupling can also be an isolating piece of a pipe, which is welded into the pipeline.

Isolating joint: same as *Isolating coupling*.

Local earth: a region in the soil that is too close to the electrode, or the object, under investigation for it to be considered as *remote earth*. Current from the electrode, or current in the object, under investigation influences the potential.[12] Cf. *Remote earth*.

Local earthing point: a local earthing electrode arrangement.

Localised corrosion: corrosion, which takes place at a high rate at local areas on the corroding metal surface. Cf. *General corrosion* and *Pitting corrosion*.

[12] In practice, *local earth* for a pipeline coating holiday is a region in the soil close to the holiday. The distance is in the same order of magnitude as the diameter of the holiday (outside the outer surface of the coating).

OFF- potential: cathodic protection potential, which is measured a fraction of a second after the interruption of the cathodic protection current (but before the cathodic depolarisation starts) with the purpose to exclude the IR-drop in the electrolyte from the measured protection potential. The expression is derived from the fact that the potential is measured when the cathodic protection is off. Cf. *ON-potential*.

ON- potential: cathodic protection potential, which is measured when protection current is flowing. The ON-potential includes, apart from the true protection potential, an IR-drop. The expression is derived from the fact that the potential is measured when the cathodic protection is on. Cf. *OFF-potential*.

Pipe current: current, which is flowing in the pipe wall.

Pitting corrosion: corrosion, which results in an attack with small extension but with considerable depth.

Polarisation (anodic): change in the electrode potential of a metal surface in the positive direction. Increased anodic polarisation is a result of increased anodic current density on the metal surface.

Polarisation (cathodic): change in the electrode potential of a metal surface in the negative direction. Increased cathodic polarisation is a result of increased cathodic current density on the metal surface.

Polarisation cell: a device that blocks D.C. current at low voltage and provides a low resistance path for a.c. current at higher voltage between a structure and an electric earthing installation. It can be used e.g. for lightning or fault current discharge.

Polarisation probe: same as *External potential test probe.*

Polarised potential: a potential, which is shifted in the positive direction (as a result of a d.c. current leaving the metal surface) or shifted in the negative direction (as a result of a d.c. current entering the metal surface). Cf. *Free corrosion potential*.

Pourbaix diagram: A diagram showing the reaction on a metallic (steel) surface in an electrolyte as a function of the acidity (pH-value) of the electrolyte and the electrical potential between the electrolyte and the metallic surface.

Protection anode: same as *anode* used for cathodic protection.

Protection potential: the electrode potential at which cathodic protection is achieved, i.e. the potential at which the corrosion is negligible.

Protection current: the D.C. current, which is fed from the anode, through the electrolyte to the metal in order to achieve cathodic protection of the metal surface.

Reference electrode: an electrode, which cannot be polarised and which is designed for the measurement of electrode d.c. potentials of metal objects. Reference electrodes for use in soil are usually of saturated copper/copper sulphate ($Cu/CuSO_4$). Reference electrodes for use in water are usually of silver/silver-chloride (Ag/AgCl). All types of reference electrodes have a certain fixed potential in the Standard Hydrogen Electrode (SHE) potential scale. This means that a potential, which has been measured with respect to one type of reference electrode, can be recalculated to a potential with respect to another type of reference electrode.

Remote earth: a region in the soil sufficiently far away from the electrode or the object under investigation so that the current from the electrode or the object under investigation has negligible influence on the potential; thus, the points in this region may be considered as a reference for voltage measurements and calculations. The distance to remote earth depends on the structure and resistivity of the soil and the size of the electrode/object of interest. [13] [14]

Resting potential: same as *Free corrosion potential*.

Soil corrosion: corrosion of a buried metal structure caused by the chemical and the physical properties of the soil.

Soil resistivity: specific resistance of a soil to carry electric current. Soil resistivity is expressed in Ω·m (earlier in Ω·cm). The lower the soil resistivity, the easier it is for electric current to flow through the soil. Fine-grained soils with water holding capacity (clay, silt, peat etc.) usually have low resistivity, whilst coarse grained and water draining soils (sand, gravel, till etc.) usually have a high resistivity. The water and salt content of the soil have a large influence on the resistivity. A high water and a high salt content results in a lower resistivity. Road de-icing salt, which is drained through the soil, lowers the soil resistivity.

Spread resistance: total coating holiday resistance, between the pipeline and remote earth through the coating holiday. Cf. *Earthing resistance*.

Stay wires: same as *Guy wires.*

Stray current: d.c. current which flows in another path from the anticipated path in an electrolyte (water, soil, concrete etc) and which originates from an electric installation with one conductor in contact with the electrolyte. Stray current originating from a d.c. source can cause stray current corrosion. Stray current was named vagabonding current in earlier literatures.

Stray current corrosion: corrosion caused by a d.c. stray current.

Transformer-rectifier: mains-operated electric unit, which feeds cathodic protection current to the anode bed. The unit consists of a transformer which reduces the mains voltage down to a lower value and a rectifier which transforms the alternating current to direct current. There are two different types of these units: a) unit with constant, but adjustable, output-voltage and varying output-protection current, and b) unit with varying output-voltage and constant, but adjustable, output-protection current.

Transposition: the physical location where the phase conductors are altered or transposed. In one third of the a.c. power line the phase position is U-V-W. In another third of the line the phase position is W-U-V and in the last third of the line the phase position is V-W-U. The reason is that the impedance of a phase conductor depends on the location related to the other phase conductors, earth and shield wires. Resulting from the transposition, the total power frequency impedance of the line will be, in principle, the same for all three phases.

Vagabonding current: same as *Stray current*.

Voltage gradients (in the ground): potential difference between two separate points in the ground caused by a current, e.g. the cathodic protection current.

Close to the cathodic protection anode, the cathodic protection current density in the ground is high, thus giving a high voltage drop. The farther away from the anode the lower is the current density and the lower is the voltage drop. If the voltage drop is measured at the ground surface from the position of the anode and farther on from the anode, it will be observed that the voltage drop per meter (the voltage gradient) is largest at the first few metres and that the voltage drop per meter diminishes with distance from the anode.

---

[13] When investigating corrosion phenomenon, the *remote earth* is a reference point for the voltage between the metallic surface and the surrounding soil, and is unaffected by corroding currents. As shown in Appendix J, the reference electrode can be located as close as the soil surface above the holiday. If the reference electrode is located more remote than necessary, other objects and stray currents may disturb the measurement.

[14] For large earthing systems such as power substation grids or a.c. power lines, the *remote earth* can be located at distances ranging from a few hundred metres to several kilometres as shown in Appendix F.

The same condition is prevalent close to the steel surface in a coating damage on a cathodically protected steel pipeline (the cathode), where the protection current is concentrated and the voltage drop is large, whilst the current density in the ground and the voltage drop per meter is lower in regions farther away from the pipeline.

If the voltage drop is plotted against the distance in a diagram the resulting curve will take the shape of a cone. Therefore, voltage gradients in the ground also are named *voltage cone.*

Zone of influence: the zone around an a.c. system where it is a risk for a.c. corrosion due to inductive and/or conductive coupling.

Appendix B

A.C. Corrosion Chemistry – A description of the phenomenon

B.1. Introduction

In this appendix the phenomenon of a.c. corrosion chemistry is described in greater detail.

B.2. Soil characteristics (electrical and chemical)

The a.c. current density at a coating holiday is essentially determined by the induced a.c. voltage on the pipeline and the spread resistance of the holiday. Generally low spread resistance is observed in soil with low specific electrical resistivity resulting in a higher risk for a.c. corrosion for a given a.c. voltage. Additionally, the size of the holiday has a critical influence on the a.c. corrosion risk. A decreasing diameter results in an increasing current density resulting in higher probability for a.c. corrosion to occur.

The specific soil resistivity is controlled by the amount of soluble salts and the water content. Therefore, significant differences in spread resistance can be observed if the pipeline is above or below the ground water level. Additionally the spread resistance is strongly influenced by the electrochemical processes taking place on the metal surface in the coating holiday due to the cathodic protection current. The electrochemical reduction of oxygen or the evolution of hydrogen results in an increase of the pH value adjacent to the metal surface of a coating holiday. Typically, the pH value is above 11 and can reach up to 14 or more.

The cathodic protection current results in a migration of cations to the coating holiday, which interacts with the locally increased pH-value. Depending on the predominant composition of the soil the spread resistance can either increase or decrease.

Ions of alkaline earth metals such as Ca^{2+} and Mg^{2+} form hydroxides with relatively low solubility. With increasing pH, precipitation will take place near the holiday. The reaction of these hydroxides with CO_2 present in the soil results in the formation of a chalk layer. If a dense chalk layer is formed directly on the metal surface in the coating holiday, the spread resistance is significantly increased by up to a factor of 100.

While the earth alkaline ions generally increase the spread resistance, the alkaline cations Na^+, K^+ and Li^+ result in the formation of highly soluble hygroscopic hydroxides. As a consequence, the spread resistance is reduced due to the attracted water and high ion concentration. This process can decrease the spread resistance of the coating holiday by up to a factor of 60.

The current density of the coating holidays is therefore depending on the size of the holiday, the specific soil resistivity, the ratio of alkali to alkaline earth ions and the amount of hydroxides produced due to the cathodic protection current.

Voltage and current density calculation
Examples

C.1. Introduction

This appendix gives two typical examples of the calculation of induced voltage and current density flowing through a coating holiday [15]. The situations described are real; the first one represents a case, still at the design stage, characterized by a low level of induction while the second one is relevant to two existing plants and is characterized by a high level of induction.

Based on the previous remarks about the coating holiday resistance to remote earth (see section 5.3.2), it can be concluded that in the typical range of values for the soil resistivity ρ_s (from 10Ωm to 10000Ωm) and for the holidays area A (from 0.01cm^2 to 10cm^2), the induced voltage on the pipeline does not depend on the characteristics of the holiday (A, ρ_h, d) and can be calculated by considering an ideal coating (i.e. no holidays); therefore, from this point of view, the induced voltage profile V(s) along the pipeline layout is a well-defined characteristic determined solely by the characteristics of the a.c. power line and pipeline involved in the calculation and their proximity.

After calculating the induced voltage, the current density may be calculated by making some assumptions concerning the characteristics of the coating holiday:

- assumed values of the parameters A and ρ_h;
- assumption about the location of the coating holiday along the pipeline - in particular, in order to consider the worst case condition, the coating holiday is assumed to be located at the point where the induced a.c. voltage is maximum.

C.2. Case I (Low induction)

The pipeline, whose length is about 24 km, is laid close to a single circuit a.c. power line (150kV, 50Hz) for most of its length (see Figure C.1.). The main data of the pipeline and power line are summarised in Table C.1.

Table C.1: Most relevant data for the pipeline and the a.c. power line (Case I)

pipeline length	**24km**
pipeline burial depth	**1.5m**
pipeline thickness	**15mm**
pipeline diameter	**1200mm**
pipeline coating thickness (polyethylene)	**5mm**
pipeline earthing points	**11 earthing points (20Ω at extremities and about 7Ω at inner points)**
pipeline insulating joints	**1 joint located at s=4.235km**
soil resistivity	**200Ωm**
a.c. power line (150kV-50Hz): single circuit with one shield wire; unbalanced currents	
conductor 1 coordinates (-3, 16) m	**current I_1: -142A $\angle 180^0$**
conductor 2 coordinates (3, 14) m	**current I_2: 142A $\angle 0^0$**
conductor 3 coordinates (-3.5, 12) m	**current I_3: 0A**
shield wire coordinates (0, 19.5) m	**current I_{sw}: 2.8 A $\angle 37^0$**

[15] For simplicity, only one coating holiday along the total pipeline route is considered.

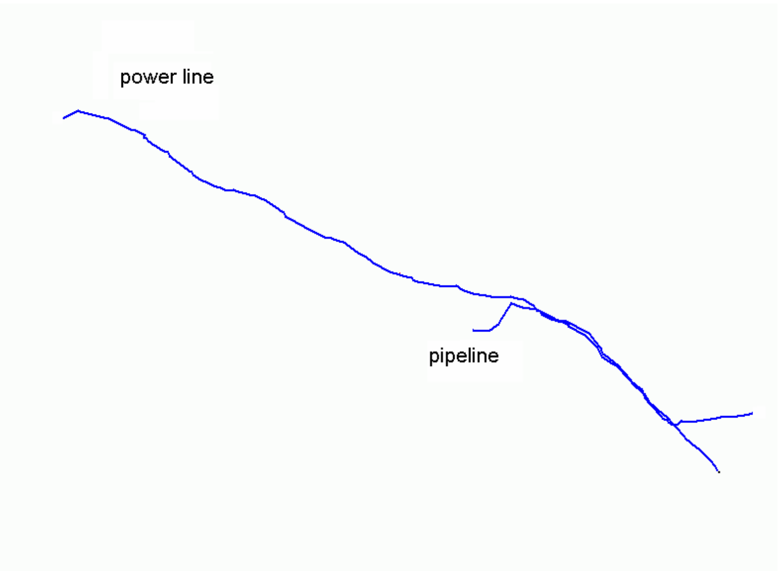


Figure C.1: Layout relevant to the plants (Case I); scale 1:200000

A meaningful quantity characterizing the level of inductive influence from the a.c. power line is the induced electromotive force f per unit length versus the location along the pipeline route, described by the abscissa s. This is shown in Figure C.2.

The induced a.c. voltage along the pipeline route is shown in Figure C.3.

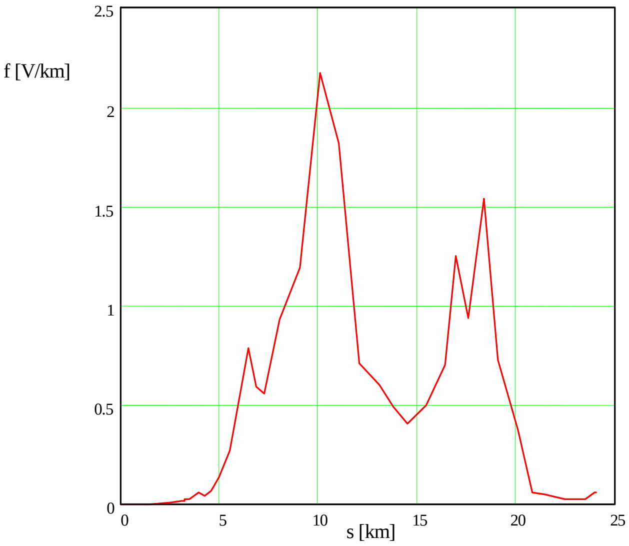


Figure C.2: Induced emf per unit length versus pipeline abscissa.

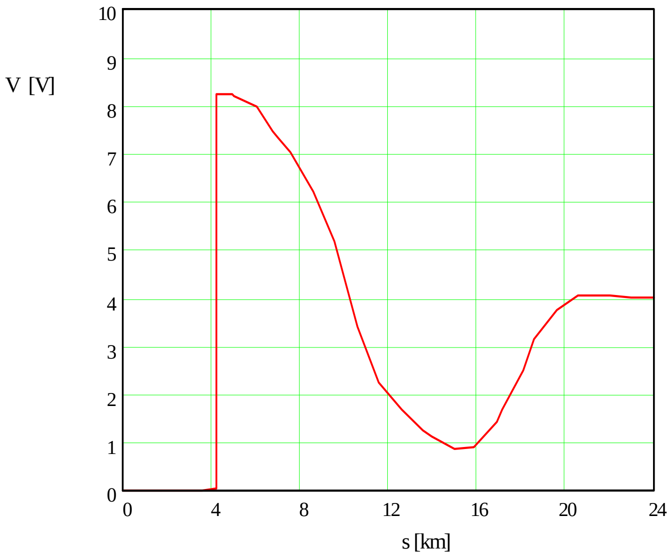


Figure C.3: Induced a.c. voltage along the pipeline route.

The induced a.c. voltage in the interval [0km, 4km] is practically nil; this is due to the presence of the insulating joint and to the low values of the induced emf in this interval (see Figure C.2).

When the induced a.c. voltage V(s) is determined, the current density through the coating holiday on the pipeline is calculated: in order to consider the worst case, the coating holiday is assumed to be located where the induced voltage is maximum: V=8.2V at s=4.95km.

In Figure C.4 the current density J is shown versus the holiday area A for different values of the resistivity ρ_h of the electrolyte inside the coating holiday.

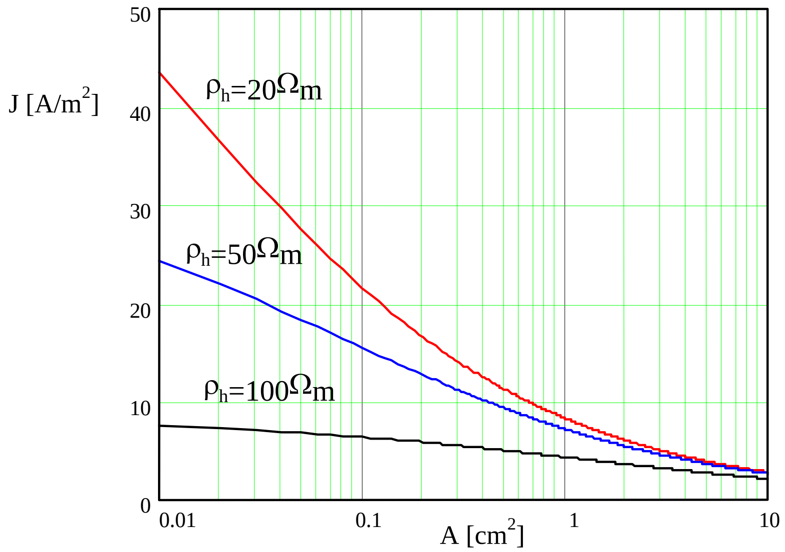


Figure C.4: Current density versus the coating holiday area A for different values of ρ_h.

Figure C.4 shows that for very small holidays a current density of some tens of A/m^2 is exceeded for low values for ρ_h.

C.3. Case II (High induction)

In this second example, both the pipeline and power line already exist and a.c. corrosion has occurred in the field. The pipeline is 28.5km long and is installed close to a single circuit a.c. power line (380kV, 50Hz) for most of its length (see Figure C.5). The relevant data for the facilities are reported in Table C.2.

Table C.2: Most relevant data for the a.c. power line and the pipeline (Case II)

pipeline length	**28.5km**
pipeline burial depth	**1.5m**
pipeline thickness	**17mm**
pipeline diameter	**1200mm**
pipeline coating thickness (polyethylene)	**3mm**
pipeline earthing points	**11 earthing points (5Ω at extremities and 100Ω, 5Ω, 2Ω at inner points)**
pipeline insulating joints	**2 joints located at s=9km and s=19km**
soil resistivity	**100Ωm**
a.c. power line (380kV, 50Hz): single circuit with two shield wires; balanced currents	
conductor 1 coordinates (-7.5, 11) m	**current I_1: 630A $\angle 0^0$**
conductor 2 coordinates (0, 11) m	**current I_2: 630A $\angle 120^0$**
conductor 3 coordinates (7.5, 11) m	**current I_3: 630A $\angle 240^0$**
shield wire 1 coordinates (-2.5, 20) m	**current I_{sw1}: 5A $\angle 70^0$**
shield wire 1 coordinates (2.5, 20) m	**current I_{sw2}: 5A $\angle -32^0$**

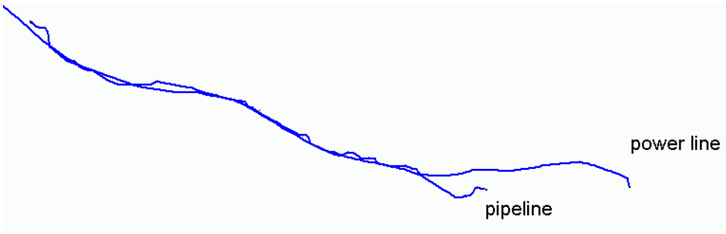


Figure C.5: Layout relevant to the plants (Case II); scale 1:150000

The induced emf f per unit length along the pipeline is shown in Figure C.6; in this case the level of induction is much higher than in previous one. The induced a.c. voltage along the pipeline route is shown in Figure C.7.

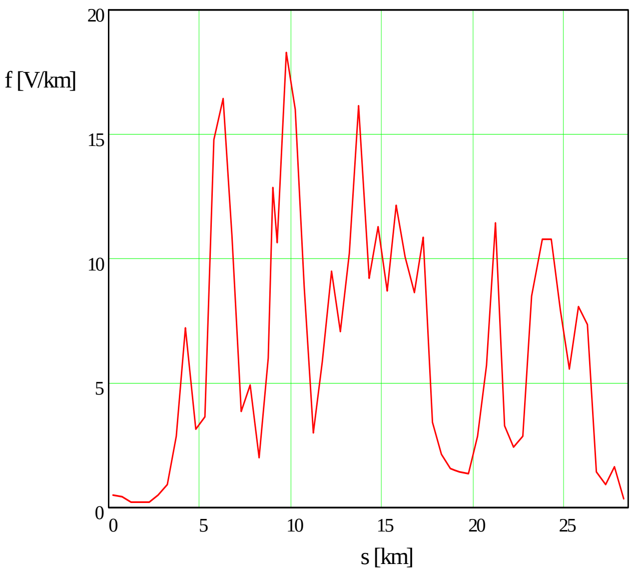


Figure C.6: Induced emf per unit length versus pipeline abscissa.

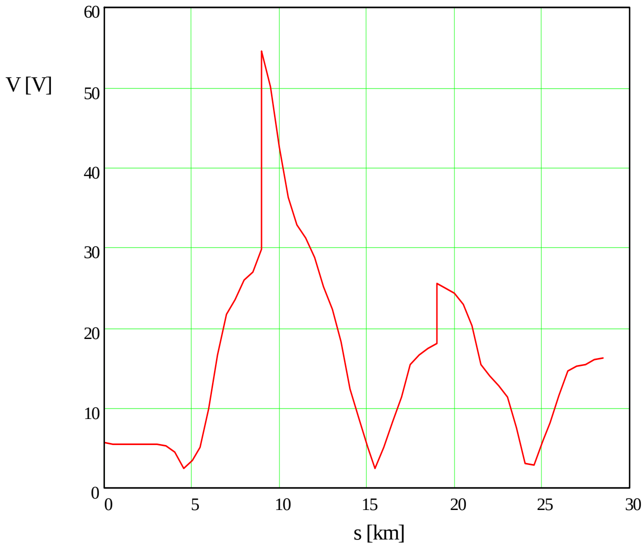


Figure C.7: Induced a.c. voltage along the pipeline route.

As could be expected from Figure C.6, the level of induced a.c. voltage is high despite the presence of the two insulating joints and of the earthing points; in particular, the maximum value is V=54.6V at s=9km. As in the previous case, the current density is evaluated supposing the coating holiday located at the point of maximum induced a.c. voltage. In Figure C.8 the current density J is shown versus the coating holiday area A for different values for ρ_h (the resistivity of the electrolyte inside the coating holiday).

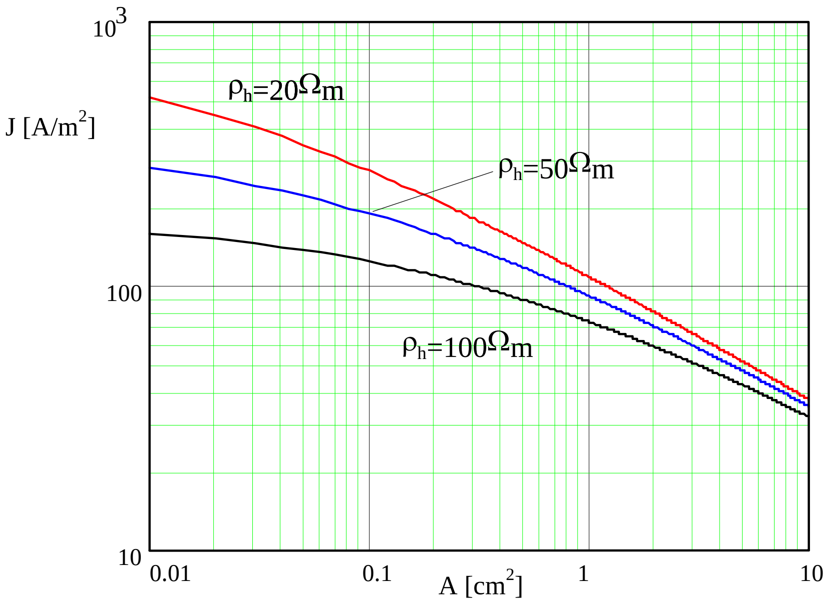


Figure C.8: Current density versus the coating holiday area A for different values of ρ_h.

Figure C.8 shows that the value of 30A/m^2 is significantly exceeded, independent of the resistivity ρ_h and of the holiday area A.

Although the current density calculation has been made with conservative assumptions, it can be expected that significant values for the current density can be reached at many other points of the pipeline (provided that a holiday is present) due to the high value of induced voltage along all of the pipeline route; in fact, as already mentioned, the presence of a.c. corrosion has been actually detected in the field at more than one point along the pipeline.

Alternating Current Corrosion on Cathodically Protected Steel in Soil. Field investigation with 5 V, 10 V, and 30 V constant a.c. voltage.[16]

D.1. Summary

Alternating current corrosion has been systematically studied for holidays of various sizes on steel test coupons in soil. The coupons were provided with cathodic protection and exposed to constant a.c. voltages resulting in a range of a.c. densities. Three series of tests were performed, one with 5 Vac during 1½ years, one with 10 Vac during almost two years, and a third one with 30 Vac during approx. 1½ years. 16 test coupons were used in each test series. In addition 12 reference coupons were used in the 5V-series. This appendix describes the results from the three test series.

The corrosion rates (both average and local corrosion) varied widely between the test coupons in all three test series. The measured average corrosion rates in the 5V-test series were, surprisingly, of the same magnitude as those measured in the 10V-series. The average corrosion rates were clearly higher in the 30V-test series. This relationship was the same for local corrosion pitting in the three series. In the 30V series some very high local corrosion rates occurred. Four coupons showed a local corrosion of 120-285 μm/year. There seemed to be a tendency for the local corrosion rate to increase with higher influencing a.c. voltage. The measured corrosion rates at different and constant a.c. voltages are relevant to the discussion whether a fixed a.c. voltage can be used as a measurement criterion for a.c. corrosion on cathodically protected pipelines.

Despite a constant alternating voltage being used throughout the test series, the grounding resistance and consequently the alternating current density of the coupons varied strongly up and down between different measurement occasions, presumably due to weather and seasonal changes in soil resistivity. Long-term changes in the grounding resistances also occurred and there seemed to be a tendency for grounding resistance to increase and a.c. current density to decrease with time. The increase in resistance and decrease in alternating current appeared to be larger for coupons with small exposed steel areas (0,5 and 1 cm^2). The observed short-term variations and long-term changes in alternating current densities complicate the use of this parameter as a criterion for assessing a.c. corrosion risk on cathodically protected pipelines.

D.2. Introduction and background

Since the end of the 1980s, corrosion damage caused by alternating current to underground steel pipelines has been discovered to an increasing extent in Europe. It concerns primarily natural gas pipelines with well electrically insulating external protective coatings. Corrosion has occurred even though the pipelines were cathodically well protected [2]. In Sweden, two cases of severe corrosion damage were discovered in the early 1990s, caused by high alternating current intensity (50 Hz). Damage was found on two separate natural gas pipelines, both of which were influenced by an alternating voltage due to their proximity to high voltage power lines. One was observed on the gas pipe and the other one on a steel coupon connected to the gas pipe. Both pipelines were provided with cathodic protection: OFF-potential *ca* - 1.0 V *vs* saturated $Cu/CuSO_4$.

The discovery of these instances of corrosion damage led to field trials focusing on alternating current corrosion. Investigations were started with test coupons buried close to and connected to gas pipelines exposed to an alternating voltage and with test coupons in a field test installation, designed especially for the investigation of alternating current corrosion in soil. In the field test installation buried steel coupons were provided with cathodic protection and exposed to constant

[16] Appendix D is based on the CEOCOR article about the test installation [20].

a.c. voltages but to different a.c. densities. Three series of tests were performed, one with 5 Vac, one with 10 Vac and a third one with 30 Vac. More detailed information about the test series is given in [19], [20].

D.3. Experimental procedure

The investigation was carried out in a field test installation, in which cathodically protected steel coupons buried in soil were exposed to constant a.c. voltages but to different alternating current densities. These coupons realistically simulated a steel surface with coating damage on a cathodically protected steel pipeline exposed to an electrical influence for long time from a high voltage source with a 50 Hz alternating voltage.

D.3.1. The field-test installation and the test coupons

The field test installation has a 150 metre long PE coated steel pipe buried to a depth of 1.5 m. See Figure D1. The native soil at the site consists of heavy clay. Close to each end of the pipe, a large and deep pit was dug in the clay soil and filled with sand. The groundwater level varies with the season but lies roughly at the pipe depth for most of the year. Approximately two years after the test pits had been filled with sand, soil samples were taken close to each test coupon both in the clay and in the sand. The sand was refilled before the start of the 5V test series.

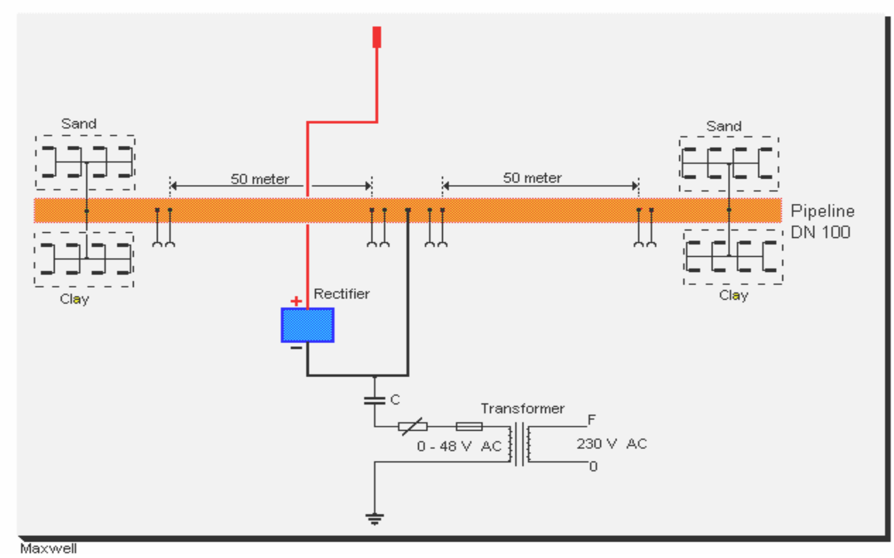


Figure D.1: The field test plant with its electrical installations and buried test coupons. Nota bene: The position of reference coupons is not shown in the figure.

At each end of the pipe, 8 steel coupons were buried at a depth of *ca* 1m and were each connected electrically to the steel pipe by an insulated cable. Half of the coupons were buried in clay and half in sand. In all, 16 coupons were exposed in this manner. Before the coupons were buried, they were carefully weighed and then covered with a thick and strongly adhesive PE- tape. On one side of each coupon, a circular hole was cut in the tape so that a circular steel surface with a given area was exposed.

Four areas of different sizes were used: 5 cm^2, 3 cm^2, 1 cm^2 and 0.5 cm^2. For each area two coupons were exposed in clay and two coupons in sand. The exposed steel surfaces simulated, as already mentioned, a steel surface with coating damage on a buried steel pipeline.

The steel pipe and the connected test coupons were exposed to an alternating voltage in a resistive circuit with the help of an adjustable transformer (50 Hz) connected to the pipe and to a grounding rod. The alternating voltage was held constant during the whole exposure period. The pipe and the coupons were provided with cathodic protection with a dc- current from a constant-current rectifier, so that the protective current could be held constant throughout the exposure period.

Furthermore, 12 reference coupons with 1 cm^2 exposed steel area were buried near the steel pipe. Of these, 4 coupons were freely exposed in the soil without any d.c. or a.c. current, 4 coupons were exposed only to d.c. current (cathodic protection) and 4 with were exposed only to a.c. current. All coupons are listed together with their coupon number and electrical parameters in Table D.2. Reference coupons were not used in the 10V and 30V test series.

D.3.2. Test series

The three test series (exposures) were carried out in sequence. The major difference between them was that the alternating voltage of the pipe and the coupons was 30 V with respect to distant earth in the first test series, 10 V in the second and 5 V in the third. Another difference, which is probably of less importance for the corrosion, was that the exposure times for practical reasons differed by several months for the different test series. The exposure time for the 30V series was 1.4 years, for the 10V series 1.8 years and for the 5V series 1.3 years.

As the coupons had exposed steel areas of different sizes and since the soil resistively closest to the steel surface was somewhat different for the different coupons, the coupons in each test series had grounding resistances ("spread resistances") of different magnitudes. As a consequence of the different grounding resistances, the coupons were exposed to current densities of different magnitudes, in spite of having the same constant alternating voltage.

D.3.3. Evaluation of the corrosion

After being withdrawn, the coupons were inspected visually with respect to corrosion products and adhering soil. Then, the coupons were cleaned through pickling in an acid bath (Clark's solution), after which they were weighed. The weight loss, which had occurred during the exposure, was used to calculate an <u>average corrosion rate</u> in µm/year for each coupon. The steel surfaces were then examined in a microscope and the depth of the deepest local corrosion pit was measured using the microscope focusing method. The corrosion depth was used to calculate a <u>maximum local corrosion rate</u> in µm/year for each coupon. Finally the corrosion attacks were photographed.

D.3.4. Repeated measurements of electrical parameters on the coupons

During the exposure periods, a number of electrical parameters were measured on each coupon at intervals of about one month. The parameters measured were: the alternating current (I_{ac}) from which the alternating current density (J_{ac}) was calculated and the direct current, i.e. the cathodic protection current (I_{dc}), which was expressed in terms of protection current density (J_{dc}). The protection potential of the coupons with and without ohmic voltage drop (E_{on} and E_{off}), alternating voltage (U_{ac}) and grounding resistance (R_{gr}) of all coupons were also measured. In this report the grounding resistance is given in kOhm in the tables.

D.4. Results and discussion

In the following, results from the test series with 5 V a.c. voltage are presented and discussed. A comparison with the results from the 10 V and 30 V test series is also made. All electrode potentials are given with respect to the saturated $Cu/CuSO_4$ reference electrode.

D.4.1. Soil analysis

Results from the analysis of the soil samples are shown in Table D.1. The chemical composition of the clay is typical for clay soils in the region in southern Sweden where the investigation was performed. The pH-value and the cation content of the sand is, however, higher than expected. The sand resistivity is also lower than expected. This is probably due to the fact that the groundwater in the clay, which is the native soil on the site, has penetrated into the test pit with sand, with the result that the chemical composition of the groundwater is reflected in the sand. Also the quite low sand resistivity points in this direction.

Table D.1: Chemical composition of the clay and sand soil at the field test installation.

Soil	pH	K mg/kg	Ca mg/kg	Mg mg/kg	Na mg/kg	Cl mg/kg	Resistivity (Wenner 4-pin) Ω·cm
Clay	7,8 - 8,1	28 - 68	2 400 - 2 500	120 - 230	25 - 37	< 10	1 800
Sand	8,0 - 8,3	10 - 34	660 - 1 300	28 - 65	8 - 21	< 10	19 000

D.4.2. The grounding resistance and alternating current density of the test coupons

Results from the repeated measurements of electrical parameters in the 5V test series are shown in Table D.2**.** Each parameter is given as a mean value of all the single values obtained during the exposure period.

Each single grounding resistance and each single a.c. current density measured over the exposure period are shown in diagrams (one diagram for each size of exposed steel area) in Figure D.2 and Figure D.3 respectively. These diagrams show that, in spite of a constant alternating voltage throughout the exposure, the grounding resistance and therefore also the alternating current density varied upwards and downwards on different measurement occasions. Long-term changes in the grounding resistances, and thus also in alternating current density, also occurred. There seems to be a tendency to increasing grounding resistance, and decreasing alternating current density, with time. This tendency, however, is not equally pronounced for all test coupons. The increase in resistance and decrease in alternating current seems to be larger for coupons with small exposed steel areas (0.5 cm^2 and 1 cm^2).

The electrical parameters were measured at an approximately 3 week intervals. In order to follow the variations more closely, the a.c. currents on some of the coupons were logged during the period between the measurement occasions. It appeared from the logging that the abrupt changes in grounding resistance and a.c.-current density, as they are shown in the diagrams, do not reflect the reality. The logged changes are much more slow and “smooth”.

Table D.2: Mean values of electrical parameters measured on the test coupons at 16 occasions in the 5V-test series.

Coupon no.	Exposed steel area cm^2	Coupon exposed to	Coupon exposed in	Uac V	Jdc A/m^2	Jac A/m^2	Rgr. kohm
333	0,5	DC&AC	sand	5,11	0,06	2,52	63,57
331	0,5	DC&AC	sand	5,13	0,05	1,14	90,42
332	0,5	DC&AC	clay	5,11	0,28	11,30	24,96
334	0,5	DC&AC	clay	5,13	0,05	2,02	40,75
342	1,1	DC&AC	sand	5,11	0,05	1,89	37,55
336	1,1	DC&AC	sand	5,13	0,14	2,93	19,32
348	1,1	DC&AC	clay	5,11	0,19	9,19	13,99
340	1,1	DC&AC	clay	5,13	0,56	23,01	2,21
328	3,1	DC&AC	sand	5,12	0,06	1,80	8,98
326	3,1	DC&AC	sand	5,13	0,09	2,21	8,33
330	3,1	DC&AC	clay	5,11	0,10	4,23	4,45
327	3,1	DC&AC	clay	5,13	0,03	1,18	10,48
324	4,9	DC&AC	sand	5,11	0,06	1,80	5,67
323	4,9	DC&AC	sand	5,13	0,09	1,85	6,15
325	4,9	DC&AC	clay	5,11	0,22	8,33	1,40
322	4,9	DC&AC	clay	5,13	0,21	8,76	1,25
345	1,1	free exp	sand	–	–	–	6,95
335	1,1	free exp	sand	–	–	–	7,51
346	1,1	free exp	clay	–	–	–	1,51
339	1,1	free exp	clay	–	–	–	1,15
349	1,1	only DC	sand	–	0,06	–	31,69
329	1,1	only DC	sand	–	0,06	–	32,11
344	1,1	only DC	clay	–	0,09	–	5,09
338	1,1	only DC	clay	–	0,08	–	6,60
347	1,1	only AC	sand	5,10	–	8,66	5,34
337	1,1	only AC	sand	5,13	–	7,53	6,79
343	1,1	only AC	clay	5,10	–	39,20	1,17
341	1,1	only AC	clay	5,13	–	39,69	1,19

The variations in the grounding resistance may be due to more than one factor. The soil resistivity closest to the steel surfaces may have varied because of weather and seasonal variations in the moisture content of the soil. The formation of, and changes in, corrosion products and calcareous or salt layers on the steel surfaces may also have had an influence.

D.4.3. Corrosion rates

The corrosion rates, expressed as average corrosion and maximum local corrosion, on each coupon (also the reference coupons) in the 5V test series are shown in Table D.3**.** The corrosion rates are also shown in histograms in Figure D.4, where they are ordered from left to right according to increasing average corrosion rate. For comparison the corrosion rates on coupons in the 10V and 30V test series are also shown in Figure D.4. The range of distribution of the corrosion rates in all three test series is shown in Table D.4.

As can be seen in Figure D.4 and Table D.3, the corrosion rates vary widely between the test coupons in all three test series. Somewhat surprisingly, the magnitude of average corrosion is about the same in the 5V and 10V test series. The average corrosion is, however, higher in the 30V test series. This relationship is the same for the local corrosion rates in the three test series. In the 30V-test series some extremely high local corrosion rates were measured. Four coupons showed a local corrosion rate between 120 and 285 μm/year. In Figure D.4 it can be seen that there seems to be a tendency of increasing local corrosion for higher a.c. voltage.

In the European standard EN 12954 [4] it is stated that a criterion for complete cathodic protection is a corrosion rate lower than 0,01 mm/year (10 μm/year). Among all 16 cathodically protected and a.c. influenced test coupons in each of the three test series 10 coupons in the 5V test series, 7 coupons in the 10V test series and only 4 coupons in the 30V test series met this criterion in terms of average corrosion. The rest of the coupons had a higher average corrosion rate than the criterion for cathodic protection.

The reference coupons, which were a.c. influenced but had no cathodic protection, showed an average corrosion of the same magnitude as a.c. influenced coupons with cathodic protection. These two groups of coupons had the same size of exposed area (1 cm^2). It is remarkable that one of the coupons, which was cathodically protected without a.c. influence, showed an average corrosion as high as 20 μm/year. The other three coupons in this group, however, met the criterion for complete cathodic protection, in terms of average corrosion.

Table D.3: Corrosion rates (average and max. local corrosion) on all test coupons, also the reference coupons, in the 5V-test series.

Coupon no.	Exposed steel area cm^2	Coupon exposed to	Coupon exposed in	Corrosion rate: Average corrosion μm/year	Corrosion rate: Max. local corrosion μm/year
333	0,5	DC&AC	sand	11	–
331	0,5	DC&AC	sand	26	51
332	0,5	DC&AC	clay	15	–
334	0,5	DC&AC	clay	8	11
342	1,1	DC&AC	sand	18	–
336	1,1	DC&AC	sand	13	23
348	1,1	DC&AC	clay	17	37
340	1,1	DC&AC	clay	4	30
328	3,1	DC&AC	sand	3	17
326	3,1	DC&AC	sand	5	–
330	3,1	DC&AC	clay	5	27
327	3,1	DC&AC	clay	4	–
324	4,9	DC&AC	sand	5	30
323	4,9	DC&AC	sand	6	38
325	4,9	DC&AC	clay	4	25
322	4,9	DC&AC	clay	4	24
345	1,1	free exp	sand	6	46
335	1,1	free exp	sand	23	68
346	1,1	free exp	clay	13	–
339	1,1	free exp	clay	15	33
349	1,1	only DC	sand	20	32
329	1,1	only DC	sand	8	17
344	1,1	only DC	clay	6	37
338	1,1	only DC	clay	10	–
347	1,1	only AC	sand	14	48
337	1,1	only AC	sand	15	–
343	1,1	only AC	clay	15	–
341	1,1	only AC	clay	17	–

Table D.4: Range of distribution of corrosion rates (average and local corrosion) in the 5V-, 10V- and 30V-test series.

Type of corrosion	Distribution range of corrosion rates in test series		
	5 Vac	10 Vac	30 Vac
Average corrosion, μm/year	3 – 26	4 – 27	4 – 66
Localized corrosion, μm/year	11 – 51	12 – 60	33 – 284

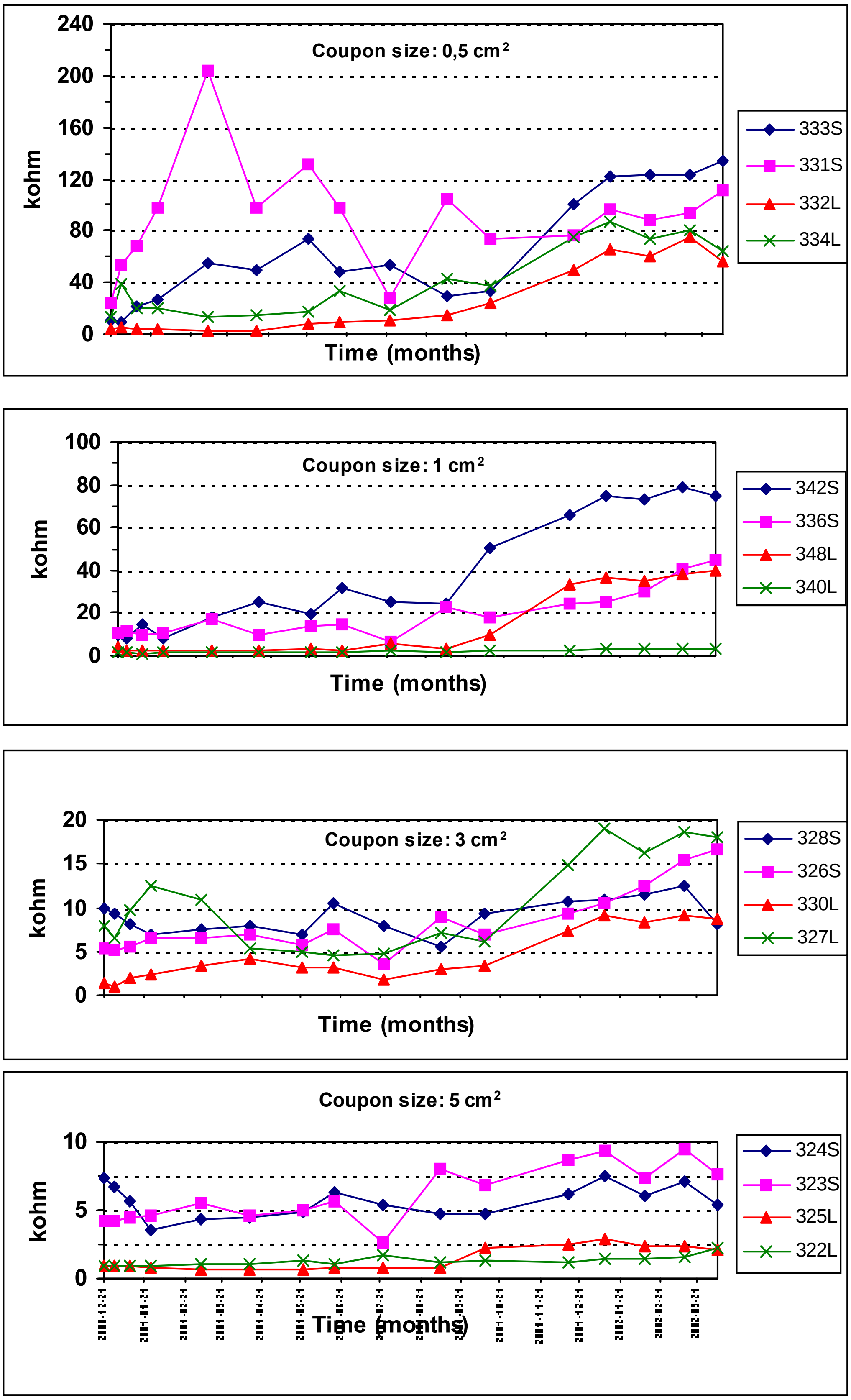


Figure D.2: The grounding resistance (Rgr.), given in kohm, of every single test coupon at the twelve measurement occasions in the 5V test series. One diagram for each size of exposed steel area.

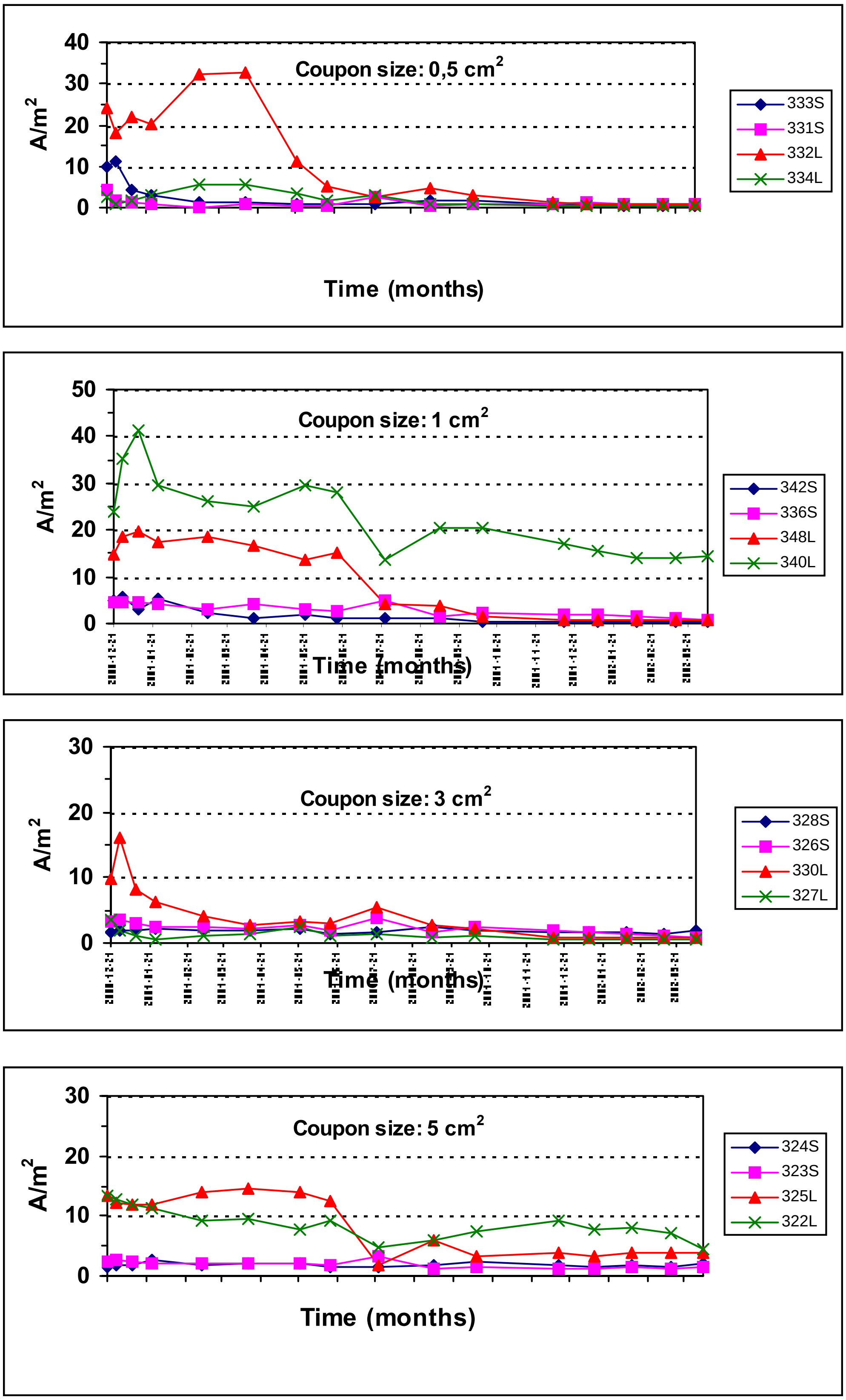


Figure D.3: The alternating current density (Jac), given in A/m^2, of every single test coupon at the twelve measurement occasions in the 5V test series. One diagram for each size of exposed steel area.

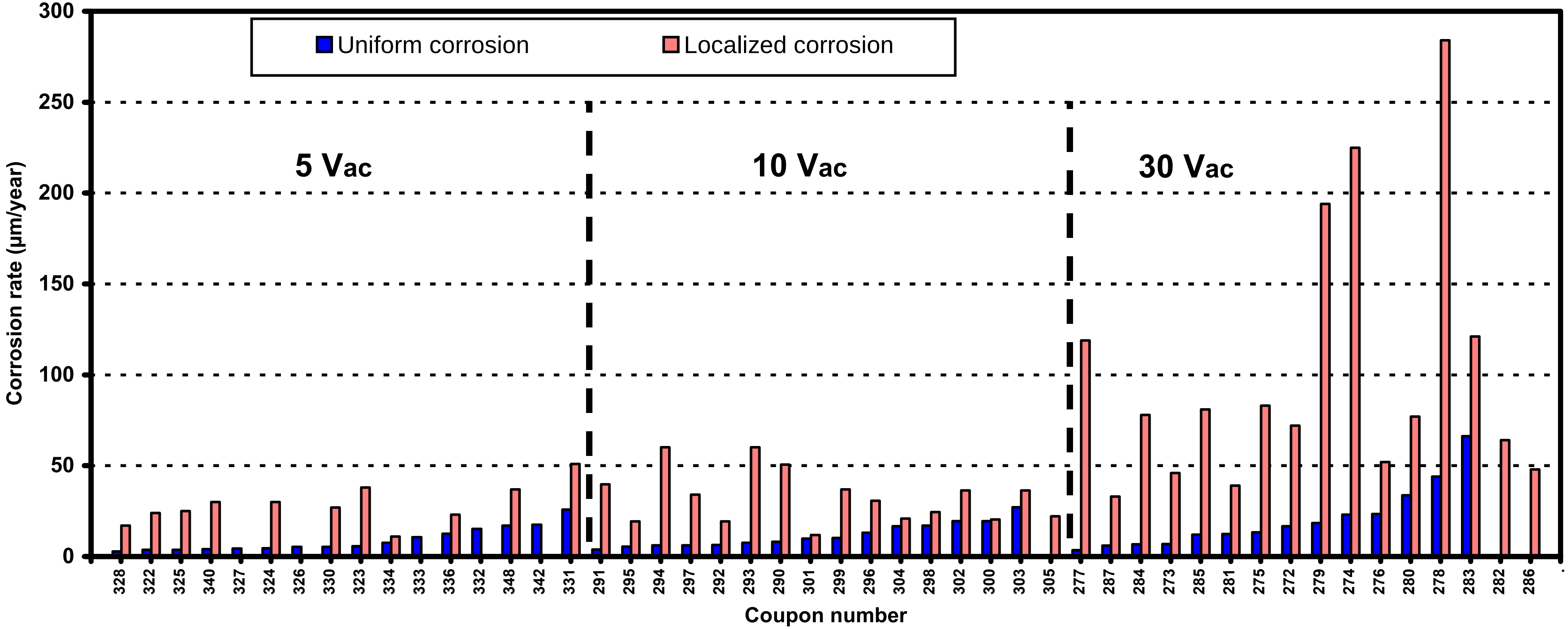


Figure D.4: Average corrosion rate and maximum local corrosion rate of all test coupons in the 5V, 10V and 30V test series. The corrosion rates are ordered from left to right according to increasing average corrosion rate. Average corrosion rate for coupon no. 305 (10V test series), 382 and 386 (30V test series) is false and therefore not given, because of corrosion under the tape cover.

D.4.4. Comparison with other field trials of alternating current corrosion

The alternating voltage on the pipe and the test coupons was kept constant throughout the exposure period, and this investigation differs in this respect from other field trials of alternating current corrosion. In these latter investigations, the corrosion conditions are usually studied on test coupons buried and electrically connected to a pipeline, which is electrically influenced by an alternating current plant, e.g. a power line or the contact line of an a.c. railway. In such field trials, the alternating voltage of the pipes and coupons therefore varies with time in an uncontrolled way, because of operational variations in the electrically influencing high voltage source.

Examples of the diurnal variations in the induced alternating voltage in a natural gas pipeline in southern Sweden in the summer and in the winter are shown in Figure D.5**.** The alternating voltage of the pipeline is induced from a 400 kV a.c. power line, which runs parallel to the pipeline. The alternating voltage of the pipe is highest in the morning and evening and almost twice as high in the winter as in the summer, because the alternating current in the phase conductor of the power line is highest during these periods.

In this field trial, the electrical conditions have thus been more controlled, which may be of importance in attempts to find a relationship between the alternating current corrosion and other parameters and in an attempt to find a suitable measurement criterion for a.c. corrosion on cathodically protected pipelines.

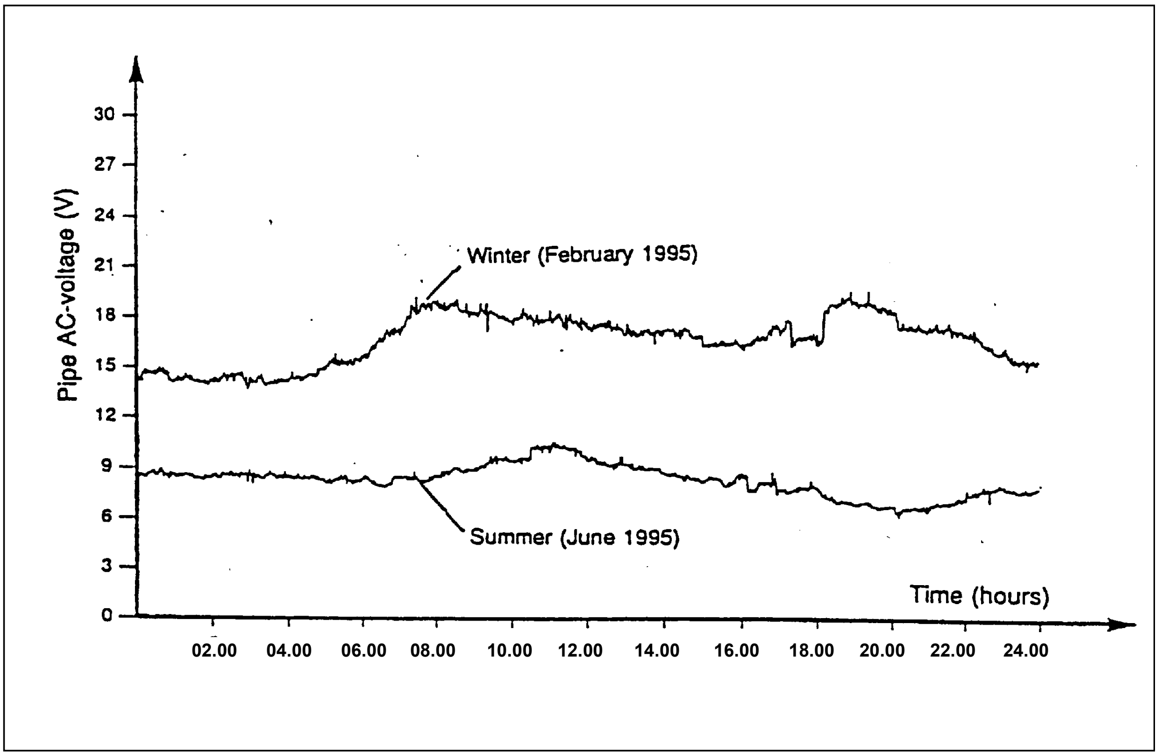


Figure D.5: Diurnal variations in the induced alternating voltage in a natural gas pipeline in the summer and in the winter. The alternating voltage of the pipeline is induced from a nearby and parallel 400 kV a.c. power line.

D.5. Conclusions

From the field investigation of alternating current corrosion on cathodically protected steel in soil, the following conclusions can be drawn:

- Alternating current of high current density can cause corrosion attacks on steel in soil, despite the steel surface being provided with cathodic protection.
- The corrosion rates (both average and local pitting corrosion) varied widely between the test coupons in all three test series. The measured average corrosion rates in the 5V test series were of the same magnitude as those in the 10V test series. The average corrosion in the 5V series was 3-26 μm/year and in the 10V series 4-27 μm/year. However the average corrosion rates were higher in the 30V test series, 4-66 μm/year. This is the same for the local corrosion in the three test series. In the 30V series there appeared some very high corrosion rates. In this series four coupons showed a local corrosion of 120 – 285 μm/year.
- There seems to be a tendency of increasing local corrosion rate with higher influencing a.c. voltage.
- One observation is that for some of the coupons, which were partly covered with limestone, the corrosion was very uneven. One explanation could be a very high local a.c. current density at the parts not covered with limestone.
- The corrosion rates, which were measured in the 5V, 10V and 30V test series, are relevant to the discussion whether a fixed a.c. voltage can be used as a measurement criterion for a.c. corrosion on cathodically protected steel pipelines. This is because of the comparably large number of test coupons and the controlled experimental conditions.
- In spite of a constant alternating voltage throughout the test series, the grounding resistance and thereby also the alternating current density varied strongly on a short-term up and down between different measurement occasions, primarily due to weather and seasonal changes in soil resistivity and in chemical conditions closest to the steel surfaces due to cathodic polarisation.
- Long-term changes in the grounding resistances also occurred and there seemed to be a tendency of increasing grounding resistance, and decreasing a.c. current density, with time. The increase in resistance and decrease in alternating current seems to be larger for coupons with small exposed steel areas (0,5 and 1 cm2).
- The observed short-term and long-term variations and changes in alternating current densities complicate the use of this parameter as a criterion for a.c. corrosion on cathodically protected pipelines.
- In this field investigation, the electrical conditions have been more controlled than has generally been the case in other field investigations of alternating current corrosion, where coupons are connected to a pipeline which is a.c. influenced from a high voltage power line or an electrified a.c. railway.

Statistical evaluation of the results from the a.c. corrosion field tests described in Appendix D.

E.1. General

Appendix D describes a field test site, including results. The large number of results from the a.c. corrosion field tests, which were carried out under well-controlled conditions, is a reasonably good basis for statistical evaluation of any possible correlation of a.c. corrosion with measurable parameters. However, the variations are large, and there seem to be important parameters, which were not controlled. The large variations also mean that a single measured value can have a significant impact on the statistical result. Therefore, the result from the statistical evaluation must be interpreted with care.

E.2. Types of corrosion and corrosion rates

Two types of corrosion have been evaluated on the test coupons, which were exposed to a.c. current in soil. Uniform (or average) corrosion was evaluated by measurement of the weight loss after the exposure period. The weight loss (expressed as g per year and per m^2 steel area) was then calculated to give an anticipated uniform corrosion rate all over the exposed steel area, expressed as µm/year. Maximum local corrosion attack was evaluated by identification of the deepest local pitting and measurement of the depth with a microscope. The depth was then expressed as a maximum local corrosion rate.

E.3. Correlation

The first attempt to evaluate the correlation was to calculate the different correlation factors between corrosion and other parameters, starting from the one suggested as a criterion. However, due to the large variation, all correlation factors were quite low, as seen in Table E.1.

The next step was to test the hypotheses by using the T-distribution for changes in the mean value (average) and the F-distribution for changes in variation. The P-values in Table E.1 indicate the probability that the mean value and the variation respectively of the corrosion depend on the parameters. As a general rule, the P-value should be higher than 95 % to be considered as statistically significant. Anyhow, the P-value gives a reasonable good indication. It should be noted that the changes of the variability are more significant than the changes of the mean value.

Table E1: Correlation factors for the corrosion of all coupons.

Uniform Corrosion Correlation		
Parameter	**Correlation factor**	**P-value [%] (mean/var)**
Jac	0.62	96.7 / 99.9
Jac/Uac	0.53	>99.9 / >99.9
Max Loc Corr	0.52	99.8 / >99.9
Uac	0.40	95.9 / >99.9
Iac	0.36	89 / 95.8
Area	-0.28	79 / 99.8
Jac/Jdc	0.15	46 / 95.7
Soil type	0.04	21 / 87
E_{Off}	0.03	88 /99.9
Resistance	0.02	90.3 / 99.9

Maximum Local Corrosion Correlation		
Parameter	**Correlation factor**	**P-value [%] (mean/var)**
Jac	0.74	>99.9 / >99.9
Iac	0.68	>99.9 />99.9
Uac	0.67	>99.9 / >99.9
Jac/Uac	0.58	99.5 / >99.9
Unif. Corr	0.52	94.9 / 99.9
Jac/Jdc	0.48	98.2 / >99.9
Resistance	-0.28	99.0 / >99.9
Area	0.23	71.5 / 98.2
E_{Off}	0.08	92.3 / >99.9
Soil type	0.05	25.1 / 97.5

In addition to the values in Table E.1, Figure E.1 to Figure E.6 show the variations graphically for some important parameters, a.c. voltage U_{ac}, a.c. current density J_{ac}, and the ratio between a.c. and d.c. current density J_{ac}/J_{dc}. The scale for the corrosion rate is µm/year.

For definition of the different curves in the figures, see section E.5 below.

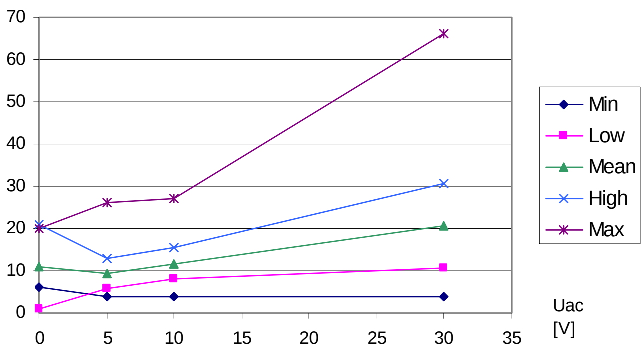


Figure E.1: Uniform corrosion as function of Uac.

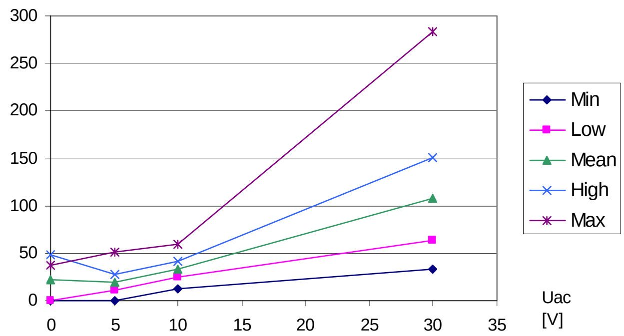


Figure E.2: Max local corrosion as function of Uac.

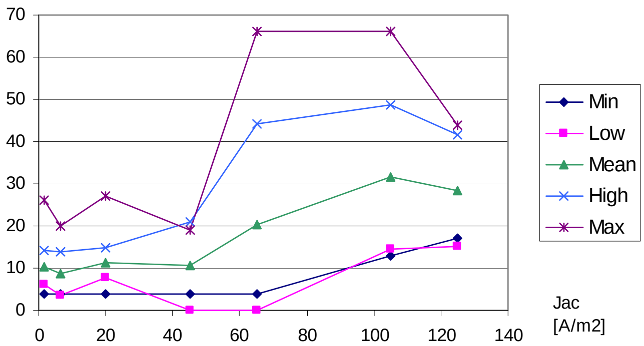
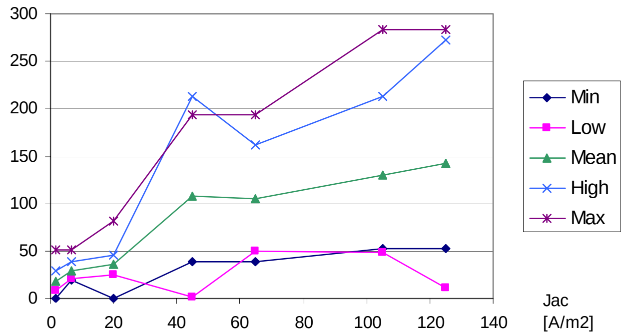


Figure E.3: Uniform corrosion as function Jac.



FigureE.4: Max local corrosion as function of Jac.

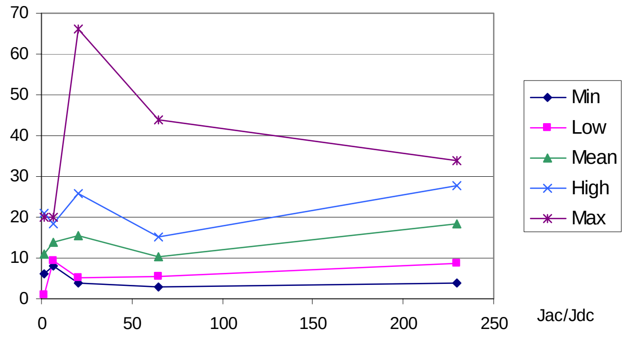


Figure 5: Uniform corrosion as function of JAC/JDC

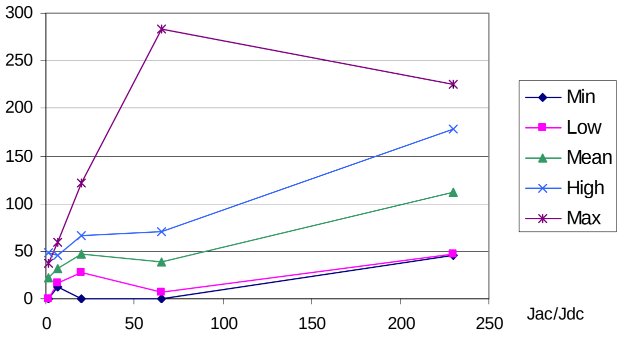


Figure 6: Max local corrosion as function of Jac/Jdc.

E.4. The worst cases

As the worst cases of corrosion are of most importance, the 25 % of the coupons with the worst uniform corrosion and the worst local corrosion respectively, were selected and the correlation factors were calculated, see Table E.2. The correlation factors are much more significant for the individuals with the highest corrosion than for the total set, compare Table E.2 with Table E.1. However, at looking at the detailed distribution in Figure E.7 to Figure E.14, it can be seen that single results impact the correlation factor too much. There are too few values with high corrosion values for giving reliable results. Thus, the result is an indication, but must be interpreted with care.

Table E.2: Correlation factors for corrosion (only the 25 percent of the coupons with the worst corrosion from each test).

Uniform Corrosion Correlation	
Parameter	**Correlation factor**
Uac	0.74
Max Loc. Corr	0.69
Jac	0.65
Jac/Uac	0.54
Iac	0.43
Soil type	-0.37
Area	0.31
Resistance	-0.31
E_{Off}	0.24
Jac/Jdc	0.09

Max Local Corrosion Correlation	
Parameter	**Correlation factor**
Jac	0.94
Iac	0.91
Uac	0.90
Jac/Uac	0.88
Jac/Jdc	0.74
Unif. Corr	0.56
Soil type	0.45
Resistance	-0.29
E_{Off}	0.12
Area	0.09

As a complement to Table E.2 the detailed distributions of corrosion rate for the 25 % worst coupons as function of a.c. voltage U_{ac}, a.c. current density J_{ac}, the a.c. conductance J_{ac}/U_{ac} and the ration between a.c. and d.c current density J_{ac}/J_{dc} are shown in Figure E.7 to Figure E.14. The scale for the corrosion rate is µm/year.

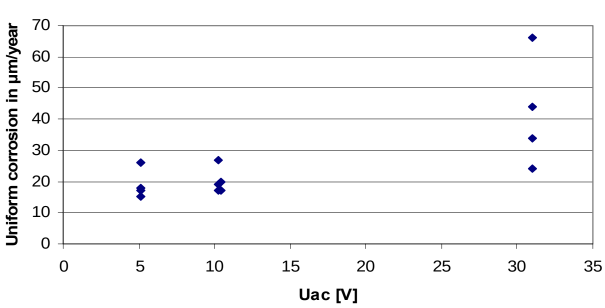


Figure E.7: Worst uniform corrosion related to U_{ac}.

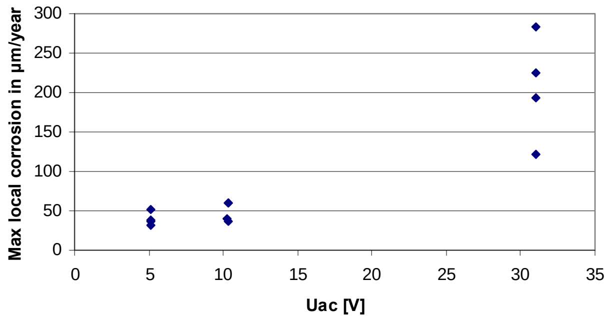


Figure E.8: Worst max local corrosion related to U_{ac}.

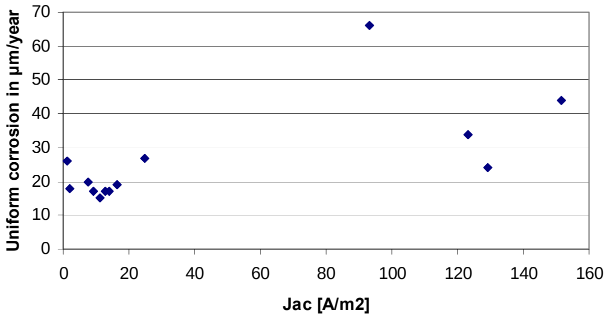


Figure E.9: Worst uniform corrosion related to J_{ac}.

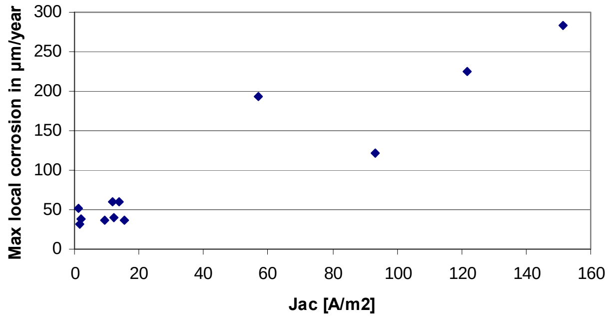


Figure E.10: Worst max local corrosion related to J_{ac}.

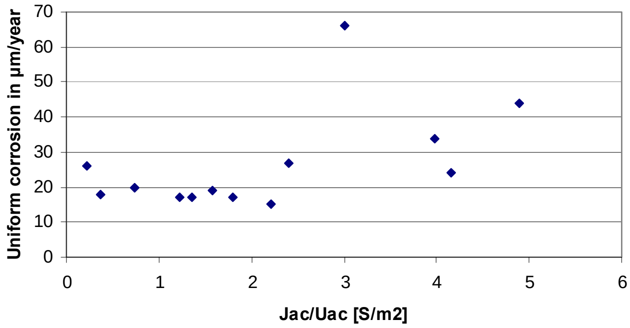


Figure E.11: Worst uniform corrosion related to J_{ac}/U_{ac}.

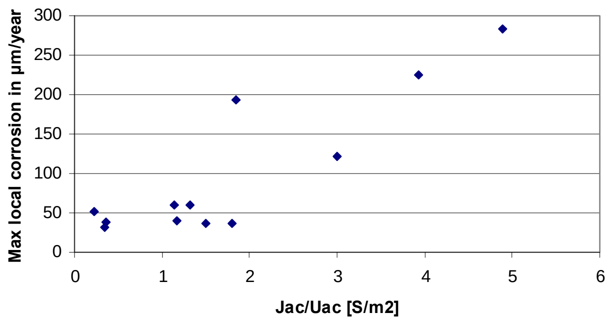


Figure E.12: Worst max local corrosion related to J_{ac}/U_{ac}.

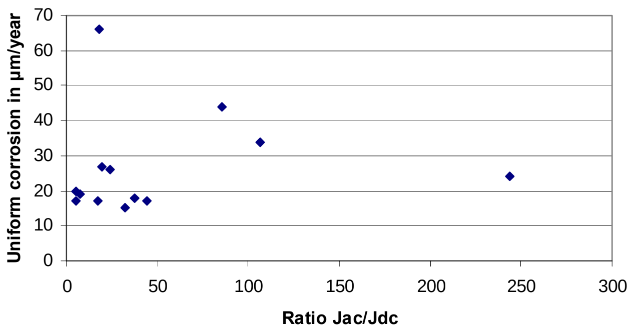


Figure E.13: Worst uniform corrosion related to J_{ac}/J_{dc}.

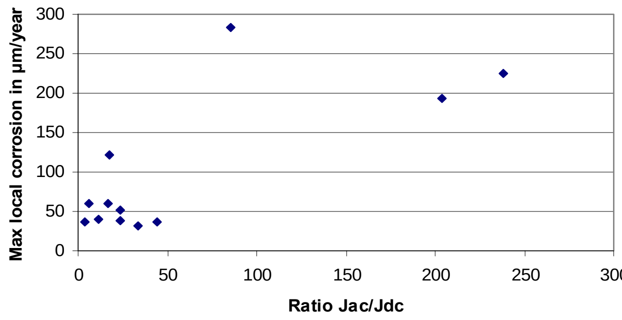


Figure E.14: Worst max local corrosion related to J_{ac}/J_{dc}.

Comments:

The four high values from the 30 V series dominate the picture completely. As an overview, the correlation with a.c. voltage Uac seems to be most reliable. Of the parameters in Figure E.7 to Figure E.14 the ratio between a.c. and d.c. current density J_{ac}/J_{dc} seem to be the least useful.

E.5. Definitions of designations used in the figures

The following designations are used in the figures.

- 97.5 % Statistically 97.5 % of the values should be below this value. This curve is only given in some figures.
- Max Maximum recorded level within the group.
- High Upper 95 % confidence value for the mean value.
- Mean Average of the values within the group.
- Low Lower 95 % confidence value for the mean value.
- Min Minimum recorded level within the group.

The span between “High” and “Low” indicates the uncertainty of the mean value both considering the variation and the number of samples in the group.

The Y-values within the group correspond to the coupons with X-values within the group as defined in Table E.3.

E.6. Correlation with some other parameters

Also the correlation between a.c. corrosion and some other parameters have been investigated graphically. This in addition to the correlation figures in Table E.1 and Table E.2.

E.6.1. Correlation with a.c. current, coupon area, and soil type

The correlation of the corrosion rate with a.c. current, coupon area, and soil type is graphically illustrated in Figure E.15 to Figure E.20. Corrosion rate in µm/year.

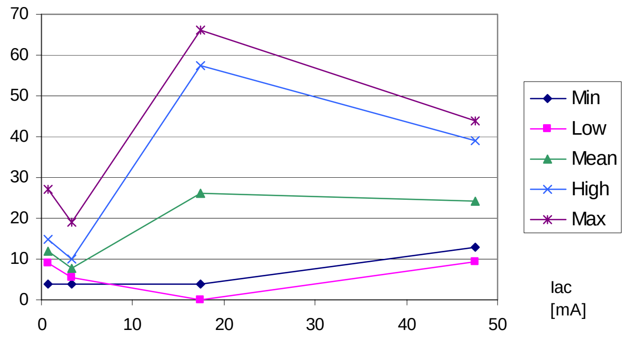


Figure E.15: Uniform corrosion related to I_{ac}.

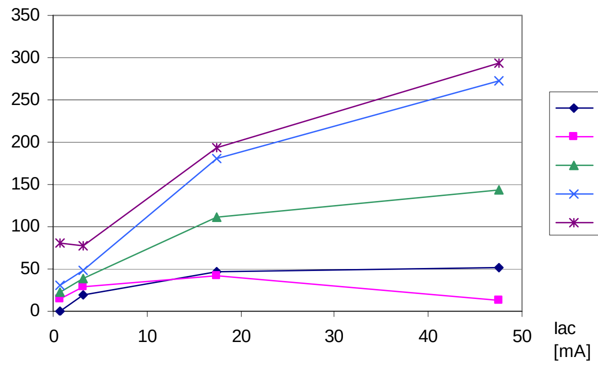


Figure E.16: Max local corrosion related to I_{ac}.

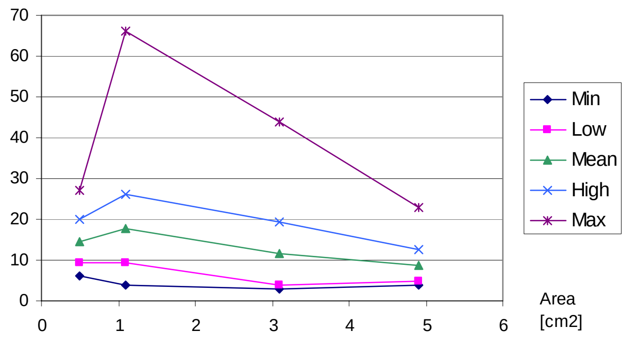


Figure E.17: Uniform corrosion related to area.

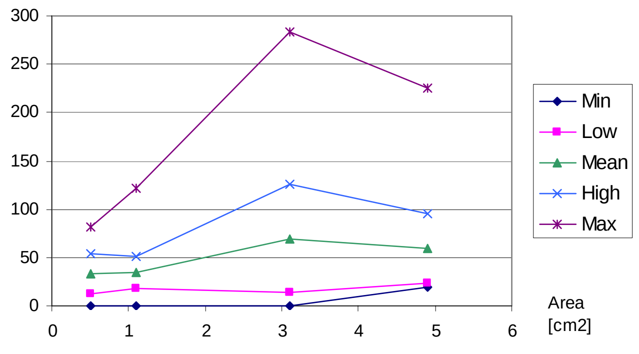


Figure E.18: Max local corrosion related to area.

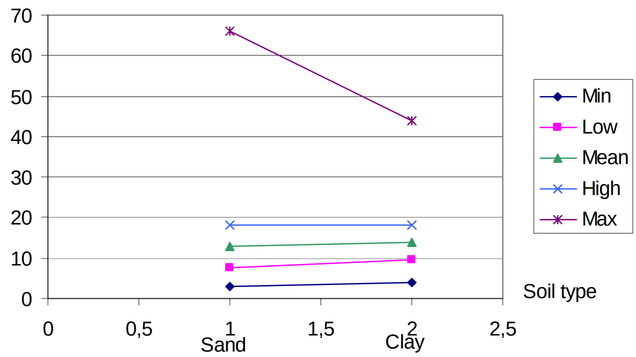


Figure E.19: Uniform corrosion related to soil.

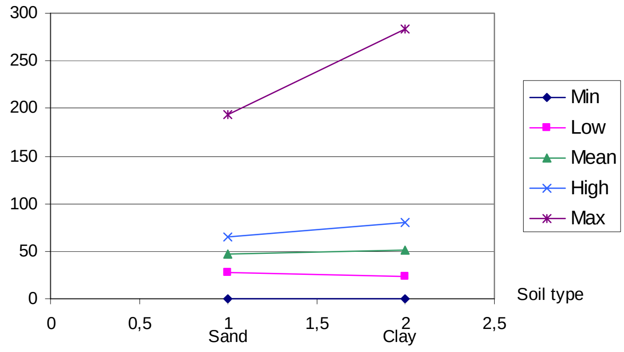


Figure E.20: Max local corrosion related to soil.

E.6.2. Correlation of corrosion rate with E_{OFF}

Figure E.23 and Figure E.24 demonstrates the correlation of uniform corrosion and max local corrosion respectively with the pipe-to-soil OFF-potential E_{OFF}.

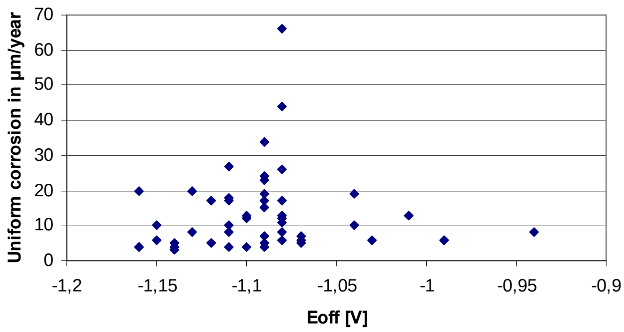


Figure E.21: Uniform corrosion related to E_{OFF}.

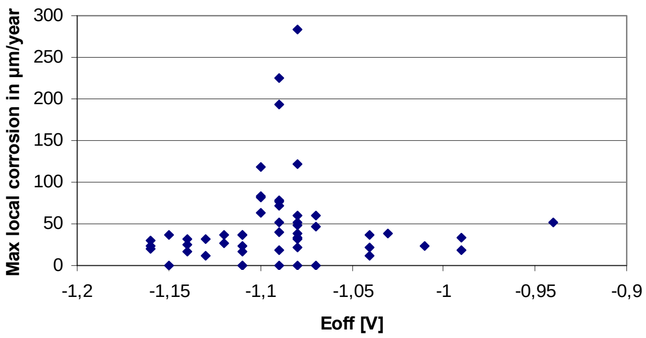


Figure E.22: Max local corrosion related to E_{OFF}.

Comment:

The reason for the high corrosion around E_{OFF} = -1.1 V is that the measured E_{OFF} values from the 30 V series are in the range from –1.10 V to –1.07 V.

Statistically the corrosion depends on the measured values of E_{OFF}. However, the result is a bit confusing.

E.6.3. Correlation of corrosion rate with a.c. conductance

Table E.2, Figure E.9 and Figure E.12 indicate that the corrosion rate for the 25 % worst cases from each test is correlated to the a.c. conductance J_{ac}/U_{ac}. Figure E.25 and Figure E.26 show the correlation for all coupons.

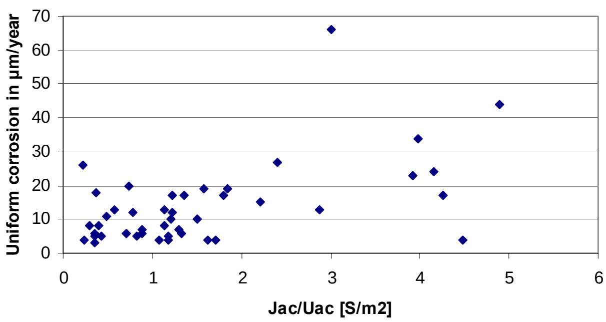


Figure E.23: Uniform corrosion related to J_{ac}/U_{ac}.

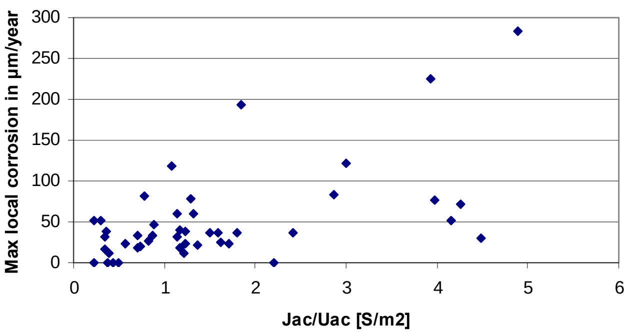


Figure E.24: Max local corrosion related to J_{ac}/U_{ac}.

E.6.4. Correlation of a.c. conductance with soil type and area

A.C. voltage and a.c. current density are both important parameters for evaluation of the risk for a.c. corrosion. As the relation between these two important parameters a.c. conductance it is of interest to study also how the a.c conductance is correlated to some other parameters. Figure E.25 and Figure E.26 show how the current density in S/m^2 depends on the coupon area in sand and clay respectively.

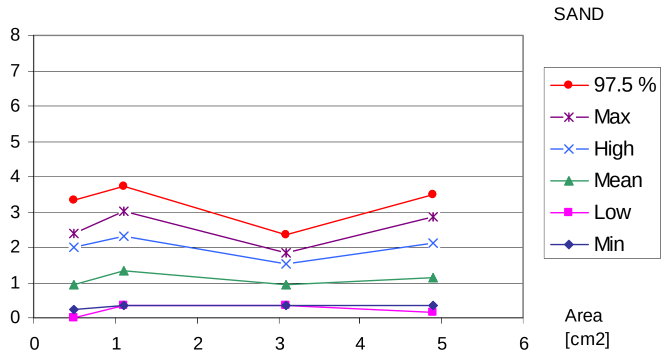


Figure E.25: A.C conductance correlation with. coupon area in sand.

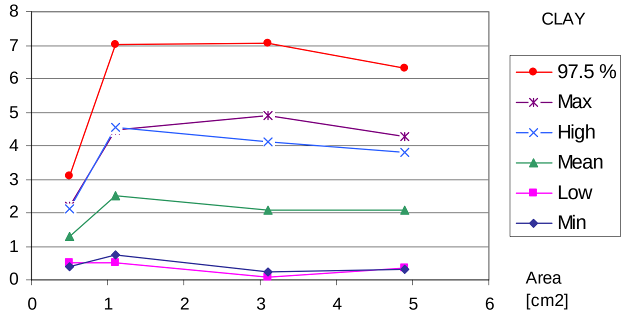


Figure E.26: A.C conductance correlation with coupon area in clay.

Comments:

The a.c. conductance is about twice as high in clay as in sand, which could be expected. Thus, also the mean a.c. current density is twice as high in clay as in sand.

Theoretically the a.c. current conductance/m^2 should decrease with increased area. No such tendency can be found in Figure E.25 and Figure E.26.

The variation of the current density is significant. Thus, the a.c. current is not easy to predict precisely by calculations based on external end geometrical conditions.

E.6.5. Variation of conductance with voltage – it is not linear

Figure E.27 and Figure E.28 indicate that the a.c. conductance varies with the a.c. voltage both in sand and in clay.

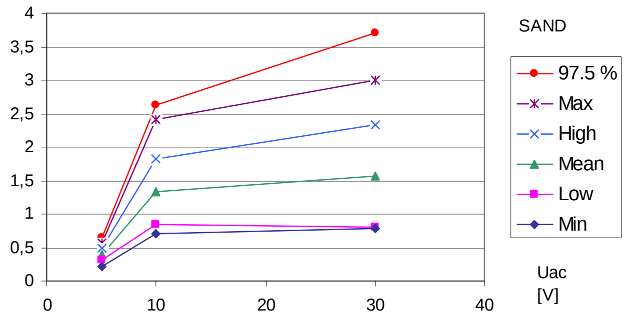


Figure E.27: A.C conductance variation with. a.c. voltage in sand.

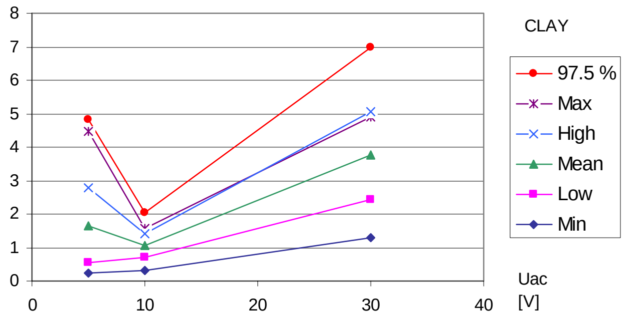


Figure E.28: A.C conductance variation with a.c. voltage in clay.

The a.c. conductance increases with the voltage, most clearly for the sand coupons. This means that the a.c. current is not only determined by the nominal resistivity of the material. It is most likely that the very local electrochemical process is important for the conductance.

E.7. Some interesting findings

If current density should be a better criterion for a.c. corrosion than a.c. voltage, one could expect the corrosion rate to be clearly correlated to the ratio Jac/Uac, which is the a.c. conductance per m^2. Figure E.23 and Figure E.24 do not necessarily support such a conclusion. Besides, section E.6.4 shows that the mean value of the current density is twice as high in clay as in sand, but Figure E.19 and Figure E.20 do not indicate any higher corrosion rate for the coupons in sand. Although the variation is significant, this weakens the importance of the a.c. current density J_{ac}. However, for the 25 % worst cases Figure E.11 and Figure E.12 a better correlation between corrosion rate and a.c. conductivity, at least for maximum local corrosion.

One unexpected observation is that the maximum local corrosion seems have a correlation with the total a.c. current Iac, which is as good as the correlation with the a.c. current density Jac, see Figure E.16 and Figure E.4. For uniform corrosion the a.c. current density seems to be more important than the total current, see Figure E.15 and Figure E.3.

From Figure E.17 and Figure E.18 it can be concluded that the uniform corrosion tends to decrease with increased coupon area while the maximum local corrosion tends to increase. Furthermore, the corrosion rate seems to be independent on soil type, see Figure E.19 and Figure E.20. However, the variation may depend on the soil type.

It is hard to correlate the corrosion rate with the measured E_{OFF}-potential, see Figure E.21 and Figure E.22.

One very interesting finding is that the ratio Jac/Uac increases with increased voltage, see Figure E.27 and Figure E.28. Thus the behaviour is non-linear. Besides, the variation is large. This stresses the importance of the a.c. voltage.

An observation is that the uniform corrosion and the maximum local corrosion are related to each other, but they can have quite different patterns.

There is no clear relation between the a.c. corrosion rate and any of the parameters investigated. Higher a.c. voltage, higher a.c. current density and even higher a.c. current are related to higher mean values and higher variation of a.c. corrosion rate, but the picture is fuzzy. No other criterion seems to be better than the a.c. voltage Uac as a risk criterion. However, the variation is very significant, regardless of applied criterion.

E.8. Conclusion

Although the correlation between corrosion and a.c. voltage and the correlation between corrosion and a.c. current density are of the same magnitude, the practical use of these two parameters as a risk criterion differ essentially in the practicability. For reference see Appendix D. The observed large seasonal and weather dependent variations in earthing resistance of the exposed steel surfaces during the exposure periods, which was reflected in corresponding variations in a.c. current density, makes it difficult to use a.c. current density as a risk criterion in the practice. An instantaneous measurement value could thus be completely misleading. The time period for obtaining a reliable measurement value would be in the order of one year in order to cover seasonal variations. Using a.c. voltage as a risk criterion involves no such problems in the practice. The actual measured a.c. voltage of the pipeline can be recalculated to “the worst case” by comparing the actual loading with the maximum loading of the inducing a.c. power line.

It also should be noted, that due to the large variation, several coupons are needed for establishing the a.c. current and a.c. current density with any reasonable accuracy.

E.9. Detailed information about data used

Table E.3 show how the date was grouped before used in the statistical evaluation.

Table E.3: Definition of groups used in the statistical evaluation. The corrosion is given in [μm/year].

Groups Uac [V]		
Group	Mean	No.
0	0.0	4
5.11-5.13	5.0	16
10.2-10.5	10.0	15
30-31	30	14

Groups Area [cm^2]	
Group	No.
0.5	10
1.1	15
3.1	12
4.9	12

Groups Iac [mA]		
Group	Mean	No.
0.0-1.5	0.75	24
1.5-5	3.25	15
5-30	17.5	5
30-65	47.5	5

Groups Resistance [kΩ]	
Group	No.
0.57-3	10
3-10	15
10-30	12
30-91	12

Groups Jac [A/m^2]		
Group	Mean	No.
0-3	1.5	14
3-10	6.5	8
10-30	20	60
30-60	45	4
30-100	65	6
60-150	105	7
100-150	125	5
Note. Overlapping groups		

Groups E_{Off} [V]	
Group	No.
-1.16;-1.10	21
-1.11;-0.94	28

Groups Jac/Uac [S/m^2]	
Group	No.
0.2-1	17
1-2	16
2-4.9	9

Groups of Ratio Jac/Jdc		
Group	Mean	No.
0-3	1.5	4
3-10	6.5	7
10-30	20	13
30-100	65	18
100-355	227.5	7

Group Uniform Corrosion	
Group	No.
3-5	11
6-9	12
10-15	10
16-66	16

Groups of Soils		
Soil type	Resistivity	No.
1. Sand	190 Ω*m	25
2. Clay	18 Ω*m	24

Groups Max Local Corrosion	
Group	No.
0-19	12
20-50	22
51-285	15

The complete database for the statistical evaluation is shown in Table E.4, which is a summary of the result from the test site described in Appendix D.

Table E.4: Source data for the statistical evaluation. Corrosion is given in [μm/year].

Coupon	Soil	Area	E_{OFF}	U_{ac}	I_{ac}	J_{ac}	J_{ac}/J_{dc}	R	Uniform Corrosion	Maximum local Corr
333	1	0,5	-1,08	5,11	0,13	2,52	71,71	63570	11	0
331	1	0,5	-1,08	5,13	0,06	1,14	23,79	90420	26	51
332	2	0,5	-1,09	5,11	0,56	11,3	32,47	24960	15	0
334	2	0,5	-1,13	5,13	0,1	2,02	43,62	40750	8	11
342	1	1,1	-1,11	5,11	0,21	1,89	37,43	37550	18	0
336	1	1,1	-1,01	5,13	0,32	2,93	28,91	19320	13	23
348	2	1,1	-1,12	5,11	1,01	9,19	44,17	13990	17	37
340	2	1,1	-1,16	5,13	2,53	23,01	45,79	2210	4	30
328	1	3,1	-1,14	5,12	0,56	1,8	36,77	8980	3	17
326	1	3,1	-1,07	5,13	0,69	2,21	28,42	8330	5	0
330	2	3,1	-1,12	5,11	1,31	4,23	35,94	4450	5	27
327	2	3,1	-1,11	5,13	0,37	1,18	33,23	10480	4	0
324	1	4,9	-1,14	5,11	0,88	1,8	33,47	5670	5	31
323	1	4,9	-1,03	5,13	0,91	1,85	23,95	6150	6	38
325	2	4,9	-1,14	5,13	4,08	8,33	35,81	1400	4	25
322	2	4,9	-1,16	5,13	4,29	8,76	48,63	1250	4	24
290	2	4,9	-0,94	10,45	1,53	3,12	26,00	51324	8	51
291	1	4,9	-1,09	10,29	3,75	12,11	11,76	3835	4	40
292	2	4,9	-0,99	10,28	3,57	7,29	48,60	19849	6	19
293	1	4,9	-1,08	10,32	3,62	11,69	6,35	3181	8	60
294	2	3,1	-1,07	10,34	4,25	13,7	16,51	2907	6	60
295	1	3,1	-1,09	10,29	3,75	12,11	11,76	3835	5	19
296	2	3,1	-1,08	10,32	3,62	11,69	6,35	3181	13	31
297	1	3,1	-0,99	10,28	3,57	7,29	48,60	19849	6	34
298	2	1,1	-1,04	10,28	1,79	16,27	7,36	10668	19	36
299	1	1,1	-1,11	10,36	1,72	15,61	4,18	25460	10	37
300	2	1,1	-1,16	10,39	0,85	7,71	5,28	17250	20	20
301	1	1,1	-1,04	10,28	1,37	12,49	5,31	57725	10	12
302	2	0,5	-1,11	10,42	0,64	12,77	4,97	29955	17	24
303	1	0,5	-1,11	10,25	1,23	24,69	19,44	57205	27	36
304	2	0,5	-1,08	10,29	0,7	14,02	17,10	30857	17	21
272	2	4,9	-1,09	30	62,56	127,7	354,72	1570	17	72
273	1	4,9	-1,07	31	13,44	27,4	195,71	6904	7	46
274	2	4,9	-1,09	31	59,56	121,6	238,43	569	23	225
275	1	4,9	-1,1	31	43,56	88,9	78,67	1316	13	83
276	2	3,1	-1,09	31	40	129	243,40	998	24	52
277	1	3,1	-1,1	31	10,33	33,3	175,26	7138	4	119
278	2	3,1	-1,08	31	47	151,6	85,65	1438	44	284
279	1	3,1	-1,09	31	17,67	57	203,57	3305	19	194
280	2	1,1	-1,09	31	13,56	123,3	106,29	3384	34	77
281	1	1,1	-1,08	31	4,18	38	55,07	18191	12	39
283	1	1,1	-1,08	31	10,24	93,1	17,90	2249	66	121
284	2	0,5	-1,09	31	2,01	40,2	25,77	28809	7	78
285	1	0,5	-1,1	31	1,21	24,2	20,51	34865	12	81
287	1	0,5	-1,08	31	1,36	27,2	34,00	57643	6	33
349	1	1,1	-1,13	0	0	0	0,00	31690	20	32
329	1	1,1	-1,11	0	0	0	0,00	32110	8	17
344	2	1,1	-1,15	0	0	0	0,00	5090	6	37
338	2	1,1	-1,15	0	0	0	0,00	6600	10	0

As a complement Table E.5 lists data for some coupons not included in the statistical evaluation.

Table E.5: Data not used in the statistical evaluation

Coupon	Soil	Area	EOFF	Uac	Iac	Jac	Jac/Jdc	R	Uniform Corr	Maximum local Corr
305	1	0,5	-1,04	10,25	0,42	8,5	4,67	33829	NA	22
282	2	1,1	-1,1	31	4,89	44,5	13,69	6094	NA	64
286	2	0,5	-1,08	31	47	940	85,77	33400	NA	48

Note: The coupons listed in Table E.5 were not used in the statistical evaluation as they were corroded outside the defined area, underneath the plastic insulation.

Zone of influence of a high voltage a.c. power line due to conductive coupling

F.1. Introduction

The earthing system of an HV (high voltage) a.c. power line includes earth electrodes at tower footings usually interconnected by one or two shield wire(s) and/or a counterpoise. The injection of current (due to the transposition of phase conductors for example as shown in Appendix G, or due to a power fault) into the earthing system of the HV a.c. power line causes an EPR (earth potential rise) to appear on the tower footings. The EPR and the rate of decrease of the potential at the surface of the soil depend on the soil resistivity and structure. Due to conductive coupling, significant voltages can appear on earthed systems such as an MV (medium voltage) or an LV (low voltage) a.c. power line with multiply earthed neutral conductor, a telecommunication line or a pipeline entering the zone of influence of the HV a.c. power line. This Appendix analyses briefly the impact of the soil resistivity and structure on the zone of influence of an HV a.c. power line due to conductive coupling.

F.2. Description of the circuit

Figure 1 presents the system considered in the calculations. The earthing system of the HV a.c. power line comprises the tower footings interconnected by a steel shield wire. An optional MV a.c. power line perpendicular to the HV a.c. power line is also considered. A neutral conductor connects earth electrodes located 100-m apart. The neutral can be either connected or isolated from the HV a.c. power line earthing system. The resistance of the earth electrodes on both lines varies with the soil resistivity (ρ expressed in Ω·m).

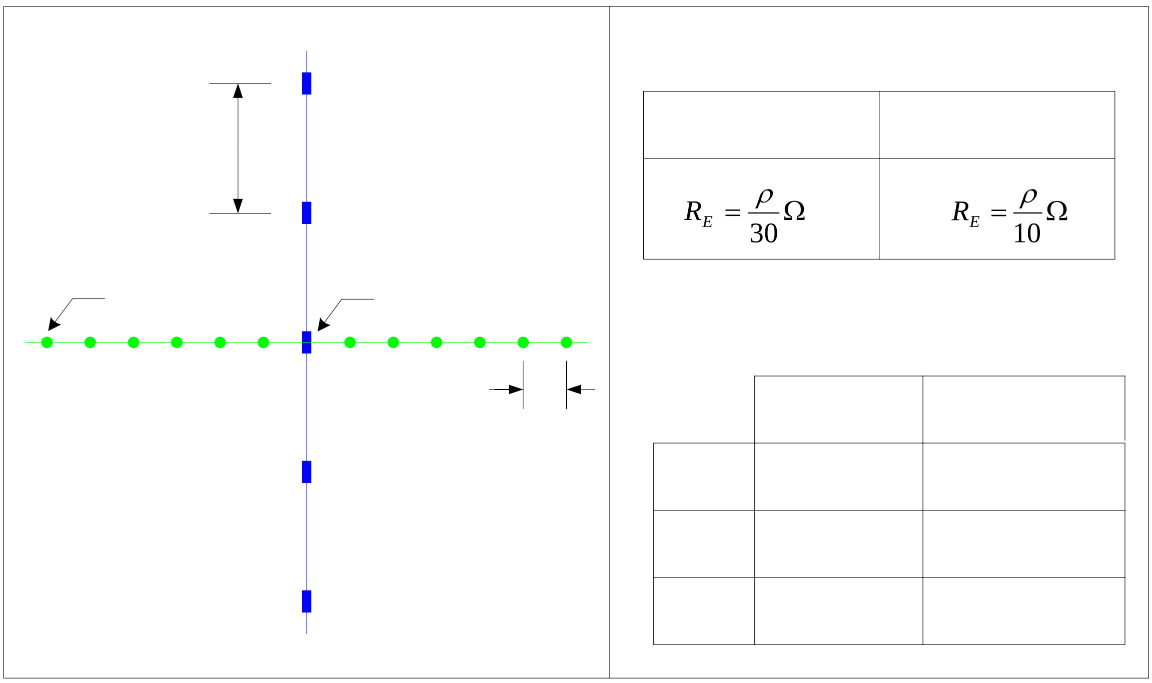


Figure F.1: Schematic of the configuration considered: optional MV a.c. power line perpendicular to an HV a.c. power line

Two soil models are used: homogeneous or two-layer structure (see figure F.2). The current is injected on the shield wire in the middle of the HV a.c. power line. The current distribution between the earth electrodes is calculated taking into account their resistance and the impedance of the earth wires. The conductive coupling between earth electrodes is included in the model. Once the current in the earth electrodes is known, the potential at the surface of the soil in the zone of interest is calculated.

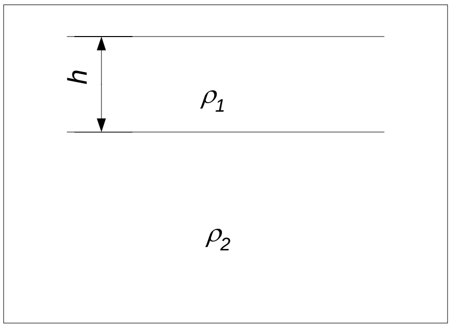


Figure F.2: Two-layer soil structure

Calculated voltages are referred to the current injected in the shield wire at the faulted tower.

F.3. Results

F.3.1. MV line not included in the calculations

Figure F.3 presents the earth potential profile for the case of the HV a.c. power line alone in a homogeneous soil. At 100 Ω·m, the EPR (earth potential rise) at the current injection point is below 1 V/A and most of the injected current is dissipated via the towers located within 1 or 2 km from the faulted tower. Furthermore, the potential at the surface of the soil decreases rapidly and becomes negligible at one or two hundred metres from the faulted tower. The conductive coupling between towers is negligible.

At 3 000 Ω·m, the EPR (earth potential rise) at the current injection exceeds 5 V/A and the injected current is dissipated over several kilometres via the tower footings. Again, the conductive coupling between towers is negligible and the potential at the surface of the soil decreases rapidly. However, a residual potential of 0.25 V/A still exists at 1 km from the faulted tower.

Figure F.4 presents the earth potential profile for the case of the HV a.c. power line alone in a two-layer soil structure. The top layer has a lower resistivity. The 10 m thick 100 Ω·m top layer contributes to reduce the EPR to less than half (from 5.5 V/A in the preceding case to 1.9 V/A). The conductive coupling between towers is significant and the potential at 1 km from the faulted tower reaches 20% of the maximum EPR.

F.3.2. MV line included in the calculations

In figure F.5, the neutral of the MV a.c. power line is not connected to the HV a.c. power line earthing system. The two-layer soil structure is identical to the one used in the previous example (see figure F.4). The potential at the surface of the soil varies between 0 and 0.8 V/A along the MV a.c. power line. This earth potential variation along the neutral forces current to be dissipated via the earth electrodes.

The EPR on the neutral exceeds 0.4 V/A within the zone of influence of the HV a.c. power line that extends for a few kilometres. The voltage drop on electrodes located 100 m from the HV a.c. power line exceeds 0.3 V/A but these voltage drops become negligible for distances exceeding 500 m.

In figure F.6, the neutral of the MV a.c. power line is connected to the HV a.c. power line earthing system. The MV a.c. power line contributes to reduce the EPR by 50% (from 1.8 V/A to 0.9 V/A). The EPR on the neutral almost doubles (from 0.4 V/A to 0.75 V/A) but the voltage drop on electrodes 100 m from the HV a.c. power line is reduced from 0.3 to 0.1 V/A. However, the earth electrodes dissipate significant current up to a few kilometres from the HV a.c. power line. The potential at the surface of the soil 1 km from the faulted tower is still 30% of the EPR and 10% at 5 km (not shown in figure F.6).

The system of figure F.6 could be seen as a substation feeding four lines. Measurement of the EPR of the substation during a fault would require that the reference voltage electrode be located at least 5 km from the substation.

F.4. Conclusion

A.C. power lines carrying a shield wire or a neutral conductor constitute extended earthing systems. Current injected at one point is distributed between earth electrodes along the line. In low soil resistivity areas, the zone of influence of the a.c. power line is limited to short distances around individual earth electrodes. The situation is quite different for high resistivities; in the particular case of a two-layer soil structure with a lower resistivity on top, the zone of influence of the a.c. power line can reach kilometres. In such cases, the a.c. power line can cause interference (due to conductive coupling through earth) on pipelines, telephone lines or other a.c. power lines over large distances.

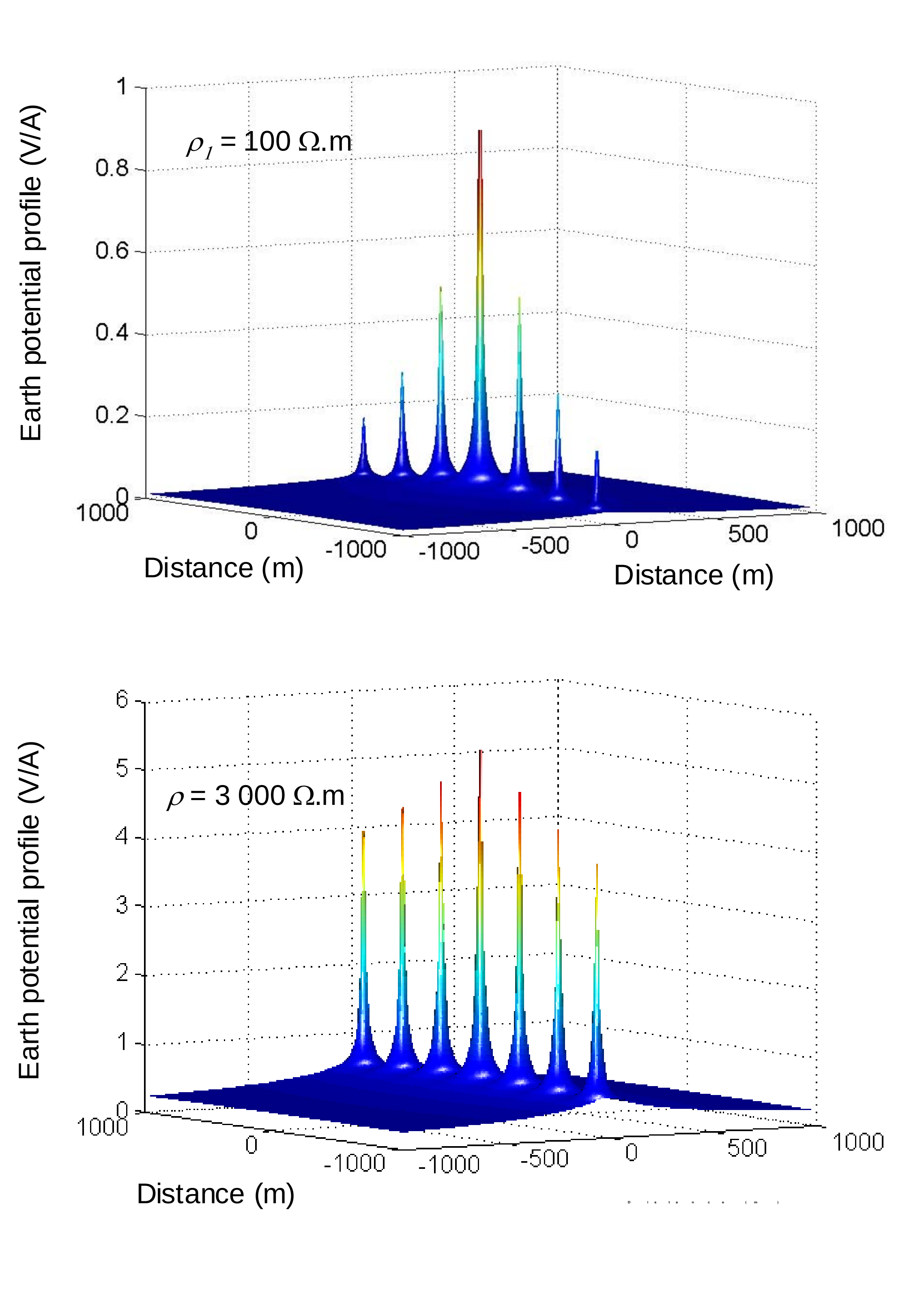


Figure F.3: **Earth potential profile due to a current injected in the middle of an HV a.c. power line (MV a.c. power line not considered and soil is homogeneous)**

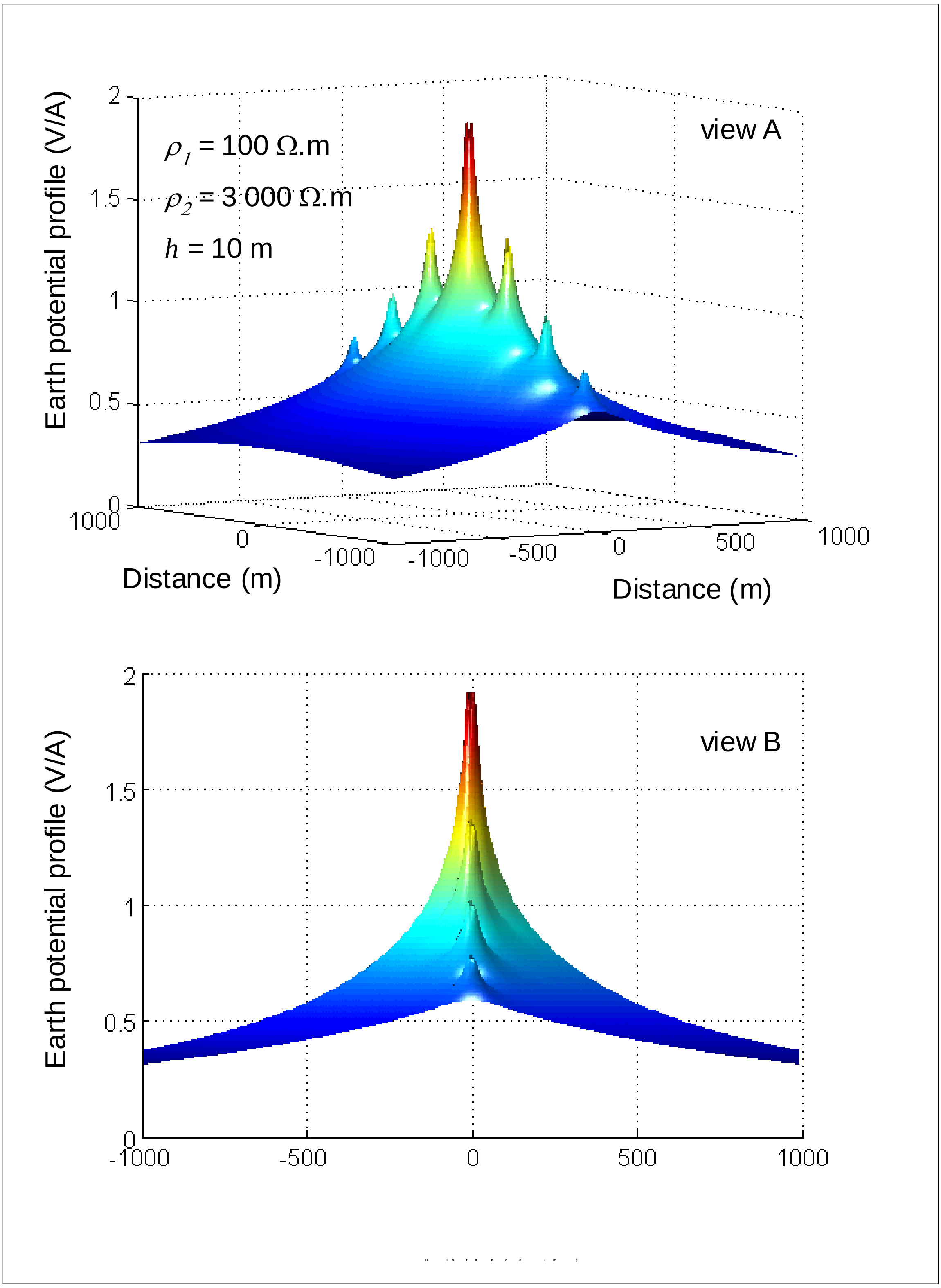


Figure F.4: **Earth potential profile due to a current injected in the middle of an HV a.c. power line in a two-layer soil structure (MV a.c. power line not considered)**

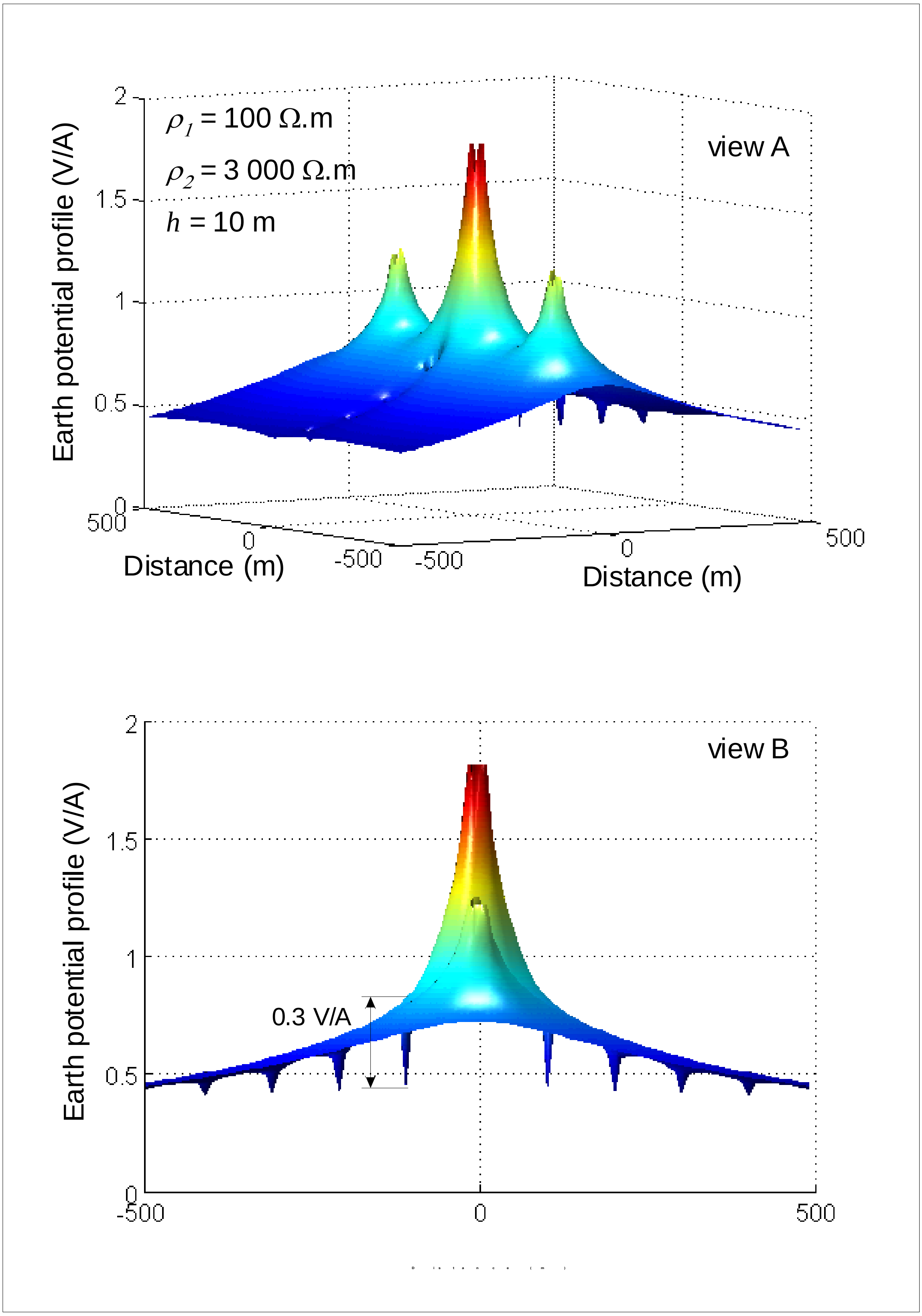


Figure F.5: **Earth potential profile due to a current injected in the middle of an HV a.c. power line in a two-layer soil structure (MV a.c. power line considered but not connected to the HV a.c. power line.)**

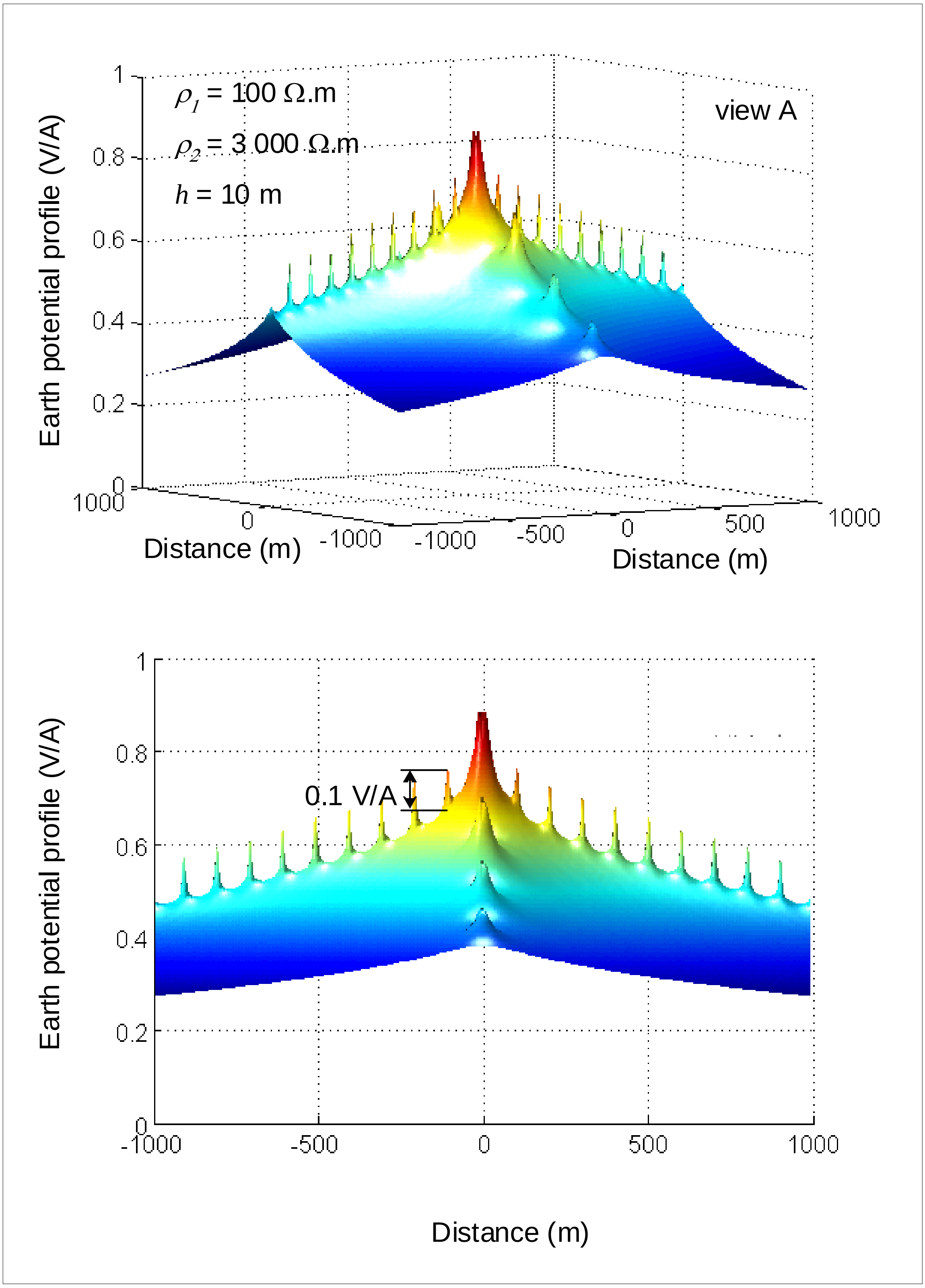


Figure F.6: **Earth potential profile due to a current injected in the middle of an HV a.c. power line in a two-layer soil structure (MV a.c. power line considered and connected to the HV a.c. power line)**

EPR and current dissipation of tower footings along a transposed transmission line

Table of content

G.1. Introduction (Description of the phenomenon)

Due to asymmetrical arrangement of the phase conductors (not an equilateral triangle), the series impedance of a HV transmission line is not the same for each of the three phases. Under balanced load conditions, this impedance asymmetry causes voltage unbalance to appear on the receiving end of the line. For long lines (more than 50 km typically), the voltage unbalance can exceed permissible limits. To solve this problem, phase conductors are transposed at regular intervals, i.e. a main transposition section is equally subdivided into three transposition sub-sections, which are separated by a transposition tower.

The load current in each phase conductor induces a longitudinal emf on the shield wire(s). The phasor sum of the emfs induced by each phase of a balanced current system tends to cancel out, but the cancellation is never perfect due to differences in the coupling (mutual impedance) between the shield wire and the conductors of the three phases. Consequently a residual emf occurs on the shield wire. If the line is perfectly transposed, the residual emf induced in the subsequent transposition sub-sections is identical in magnitude but differs by 120 degrees in phase. Therefore the net residual emf on a main transposition section is nil. The current caused by the residual induced emf on the shield wire loop, closed through the tower earthing, tends to approach a value equal to the ratio of the residual emf and the self impedance of the shield wire with earth return, both per unit length. Thus, the discontinuity at the transposition points in the phase angle of emf induced on the shield wire causes currents to be dissipated via the tower footings. As a final consequence, the current dissipation though the tower footings causes earth potential rise (T-EPR) on the tower footing of the transposition tower itself and – with decreasing magnitude – on the neighbouring tower footings as well.

In the following, calculation methods and numerical results for typical practical conditions are given for EPR and current dissipation of tower footings along a transposed transmission line.

G.2. Calculation options

Basically there are two options for the calculation of the current dissipation and EPR of tower footings along a transposed transmission line.

One option is the solution for the transmission line conductors as a whole including the phase conductors and shield wire(s). This requires such multi-conductor line solution technique, which can manage any actual conductor arrangements, the earthing of the tower footings together with the discontinuities caused by the transposition. Such methods are numerical multi-conductor line solutions (e.g. EMTP/ATP programs) [21], [22]. By the use of these techniques the complete solution will be providing in one procedure, however the calculation must be performed for the whole system even if only one parameter, e.g. the size of the shield wire, has a new value. The advantage of these sophisticated methods is their capability to consider any real conditions e.g. variation of the current along the length of the line caused by the shunt capacitive current (reactive power of the transmission line). Due to the complexity of these methods, they do not provide an easy way to interpret the relative importance of the different parameters.

The other option is to split the calculation procedure into the following two parts:

a) Calculate the residual emf induced on the shield wire per unit load current. This is affected only by the mutual distances between the shield wire and the phase conductors, including the transposition scheme and phase configuration. Its value can be recalculated from actual load current proportionally.

b) Solve the shield wire-to-earth loop with the above emf and the actual parameters characterising the loop circuit (conductor data, specific conductivity of the earth, earthing resistances of the tower footings (individual or average), average span).

This method has the advantages that it can provide a better insight to the physical phenomenon and makes possible an easier study of the relative importance of the different parameters. For example, to study the effect of the shield wire parameters, only the shield wire circuit needs to be solved repeatedly with the new parameter(s).

The split calculation procedure is applicable to power line with two shield wires as well. In this case the emf, per unit length value vs. length, has to be calculated for each shield wire individually (see e.g. the "Shield wire to earth loop emf" for vv1 and vv2. in Table G.3.3). The possibility of changes to the specific induced emf along the length of the line allows any combination of line configurations, with differing mutual relations between the shield wires and phase conductors, to be considered.

In step b) the two shield wires are represented as a two-wire line multiconductor system. Due to the fact that the MULTS method allows the changing of any line parameters – including the emf – step b) can be used for each configuration.

Considering the advantages of the split calculation method this is described and applied in the following examples.

G.3. EMF calculation

G.3.1. Conductor arrangements studied

The conductor data and arrangements of an HV (400 kV level) transmission line are given in the following figures:

(1). Figure G.3.1 shows a single circuit compact line arrangement with one shield wire.

(2). Figure G.3.2 shows a single circuit horizontally arranged line with one shield wire.

(3). Figure G.3.3 shows a single circuit horizontally arranged line with two shield wires.

(4). Figure G.3.4 shows a double circuit line with one shield wire.

(5). Figure G.3.5 shows alternative phase configurations for the double circuit line, relevant to the first transposition sub-section of the investigated double circuit line. The “identical phase order configuration” is also known as “super bundle” phasing. The “circular phase order configuration” is also known as “low reactance phasing”.

The expressions for calculating the residual emf induced on the shield wire can be found in Appendix H.

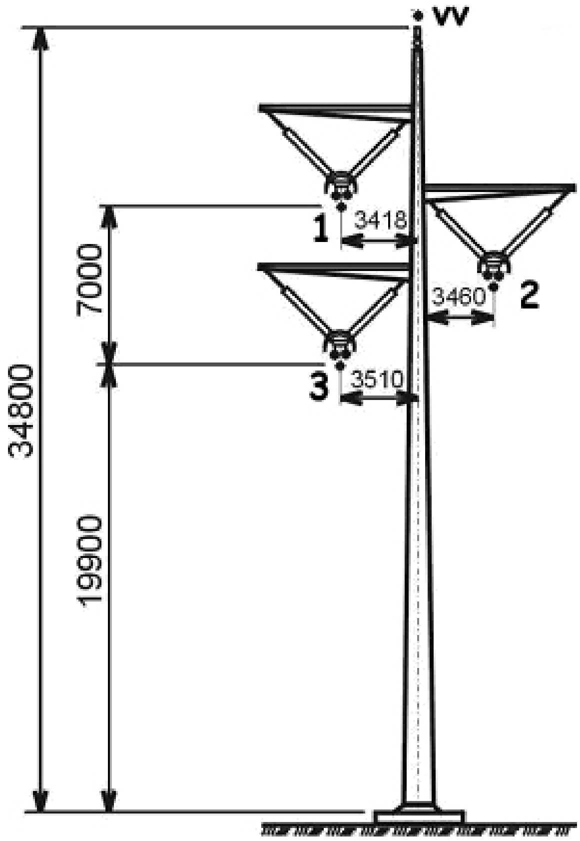


Figure G.3.1. – Data of conductor geometry for single circuit compact line arrangement with one shield wire (in mm)

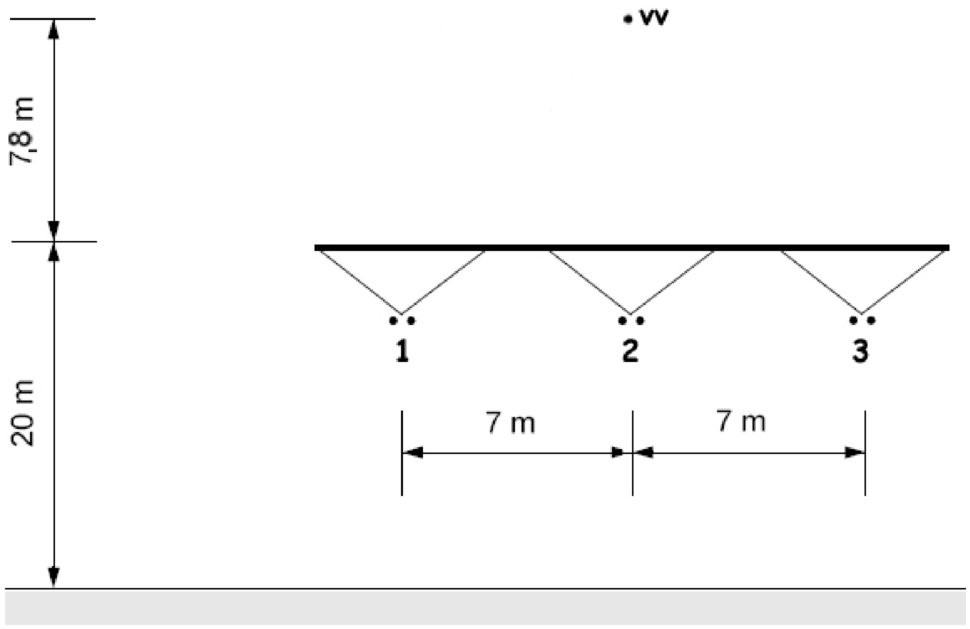


Figure G.3.2. – Data of conductor geometry for a single circuit horizontally arranged line with one shield wire (in m)

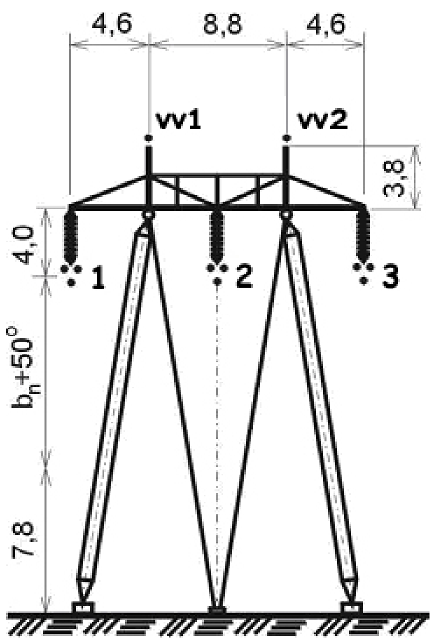


Figure G.3.3. – Data of conductor geometry for a single circuit horizontally arranged line with two shield wires (in m)

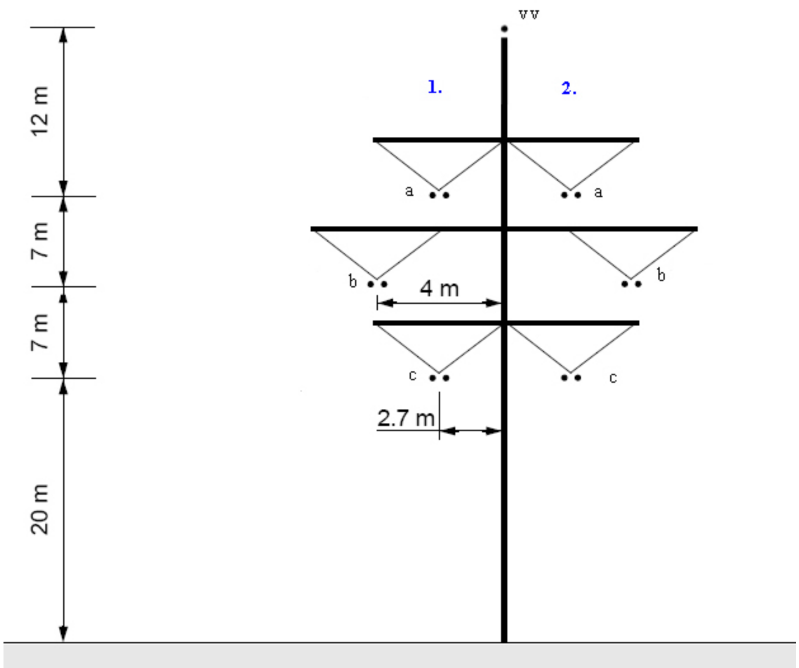
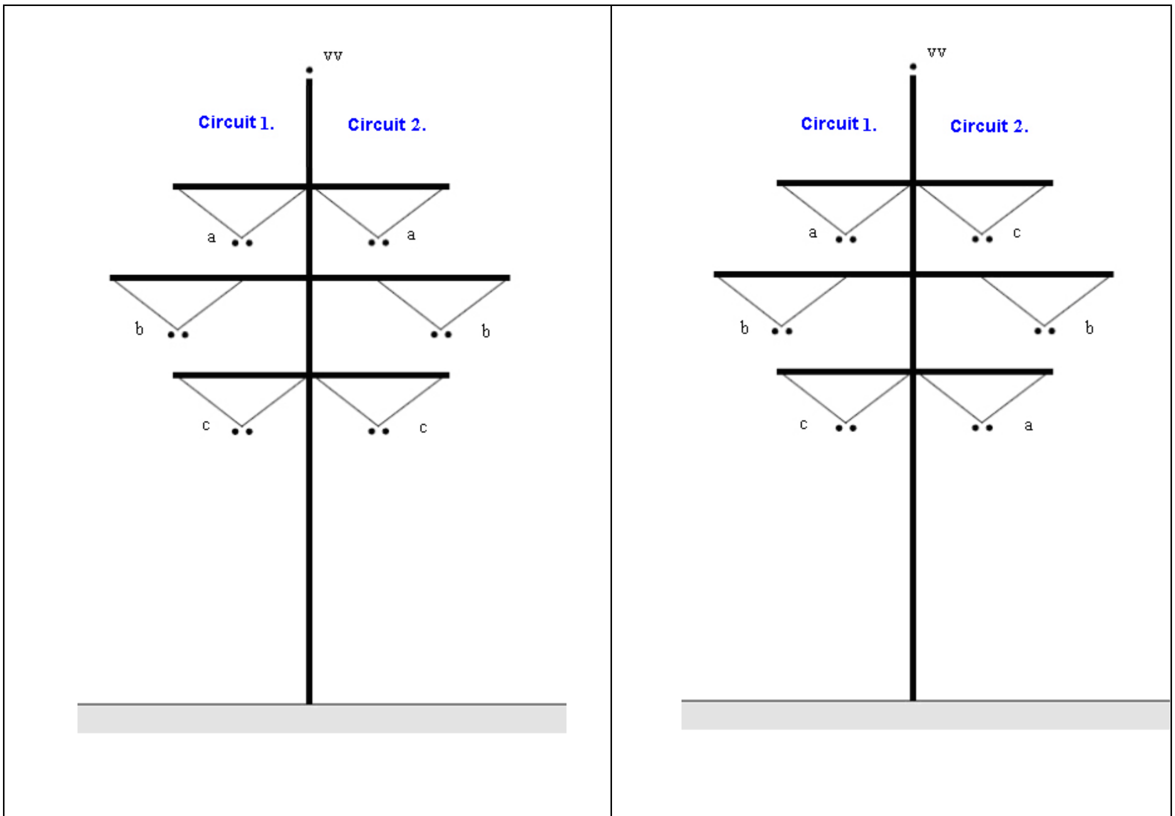


Figure G.3.4. – Data of conductor geometry for a double circuit line with one shield wire (in m)



b) Identical phase order configuration	c) Circular phase order configuration

Figure G.3.5. – Conductor configuration versions of the double circuit line along the first (I.) sub-transposition section

G.3.2. Calculated emf values

The emf values, per unit length, induced in each transposition subsection have been calculated for the following circumstances:

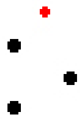
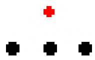
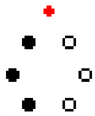
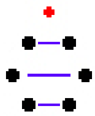
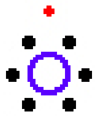
- The magnitude of the balanced current: 1 kA per circuit.
- The conductor arrangements correspond to the cases given in section G.3.1 and demonstrated in Figure G.3.1 to Figure G.3.3.
- For double circuit line the phase configuration versions – relevant to the first transposition sub-section of the investigated double circuit line – those demonstrated in Figure G.3.5.

The calculated phasor values of the emf induced in each transposition subsection are given in Table G.3.1. for line arrangements with single shield wire. The main conclusions drawn from the calculated emf values are:

- a horizontally arranged circuit induces the lowest emf;
- a vertically arranged circuit induces much higher (more than double) emf than a horizontal one;
- a compact line induces an emf laying between the values relevant to the horizontally and vertically arranged circuits;
- a double circuit line induces double emf in case of identical phase configuration (horizontally identical phases on the two circuits);

a double circuit line induces significantly lower emf than a horizontal single circuit (about half) in the case of circular phase configuration.

Table G.3.1. – EMF induced into a single shield wire-to-earth loop, per unit length, along the subsequent transposition sub-sections, due to 1 kA balanced load current

Version no.	Number of the circuits	Conductor arrangement	Phase configuration		Transp. sub-section no.	Induced emf	
			Circuit 1	Circuit 2		Modulus V/km.kA	Phase angle Degrees
1	Single	Compact			I.	31.4	*-175.9*
					II.		*-55.9*
					III.		*64.1*
2		Horizontal			I.	18.5	*90*
					II.		*-150*
					III.		*-30*
3	Double	Only one circuit loaded			I.	41.7	*-173,4*
					II.		*-53,4*
					III.		*66,6*
4		Identical phase configuration			I.	83.3	*-173,4*
					II.		*-53,4*
					III.		*66,6*
5		Circular phase configuration			I.	9.6	*-90*
					II.		*30*
					III.		*150*

The emf values induced into the circuits of two shield wires are given in Table G.3.2. For this case not only the emfs induced in the shield wire to earth loops but also their two-phase symmetrical components are given. The zero sequence component of the emf is the relevant component for judging the possible T-EPR. Its magnitude is very much the same as the emf induced in a single shield wire loop by a horizontal circuit.

Table G.3.2. – EMF induced into the circuits of two shield wires, per unit length, along the subsequent transposition subsections, due to 1 kA balanced load current

Type of shield wire emf	Shield wire relations	Transp. sub-section no.	Induced emf	
			Modulus V/km.kA	Phase angle Degrees
Shield wire to earth loop emf	vv 1	I.	34.05	*149*
		II.		*-91*
		III.		*29*
	vv 2	I.	34.05	*31*
		II.		*151*
		III.		*-89*
Two phase symmetrical components of the shield wire emf	Zero sequence[1)]	I.	17.6	*90*
		II.		*-150*
		III.		*-30*
	Positive sequence[2)]	I.	29.2	*180*
		II.		*-60*
		III.		*60*

Notes: 1) EMF acting in each shield wire-to-earth loop
2) EMF the double value of which is acting in the shield wire-to-shield wire loop.

G.4. Calculation for the shield wire circuit

G.4.1. Circuit representation and circuit data

The circuit representation of the shield wire to earth loop is shown in the Figure G.4.1.

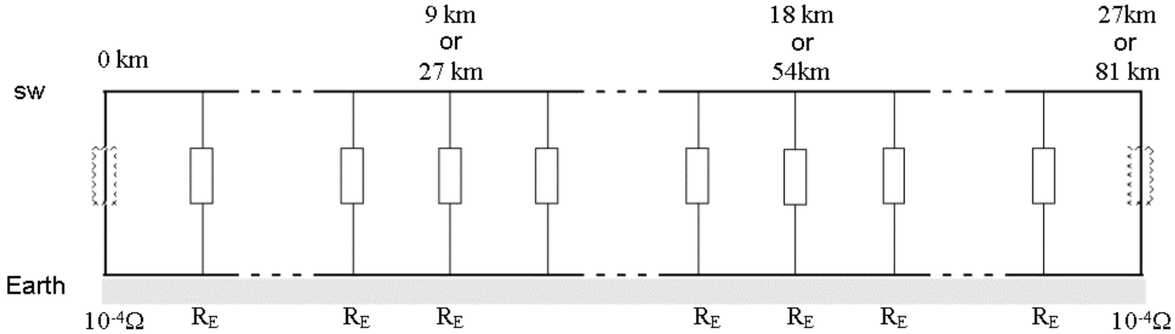


Figure G.4.1. Circuit representation of the shield wire to earth loop

The circuit parameters of the shield wire loop have been specified for the following conditions:

- line lengths: l = 27 or 81 km;
- tower footing resistances: R_e = 8, 25 or 50 Ω;
  (these values correspond to increasing earth resistivity of the surface layer)
- earth resistivity of the deeper layers: 100 Ω.m,
  (this value affects the self and mutual impedances of the conductors with earth return)
- number of the shield wire: one or two;
- tower span: 200, 300 or 500 m
- size (cross section) of the shielding conductor: 241 mm^2 (basic option) or 95 mm^2.

The distributed line parameters (series impedance and shunt capacitance) of the shield wire circuit have been calculated by a specialized program (PLINE).

The shield wire circuit has been excited by the induced series emf, the value of which was uniform along each transposition sub-section. (Not shown in Figure G.4.1.)

Finally, the calculations on the shield wire circuit have been performed by the multi-conductor method [21] for the above parameter and emf options. The main result of the solution is the potential of the shield wire, the value of which is equal to the T-EPR at the tower locations. The current through each tower footing can be obtained as the ratio of the T-EPR and the earthing resistance of the tower.

G.4.2. T-EPR (shield wire) length profiles

For comparison purposes, the T-EPR profiles along the line are shown for the three tower footing resistances and for the two line lengths for each investigated configuration.

The grouping of the profile curves provides easy comparisons for the effect of the following conditions:

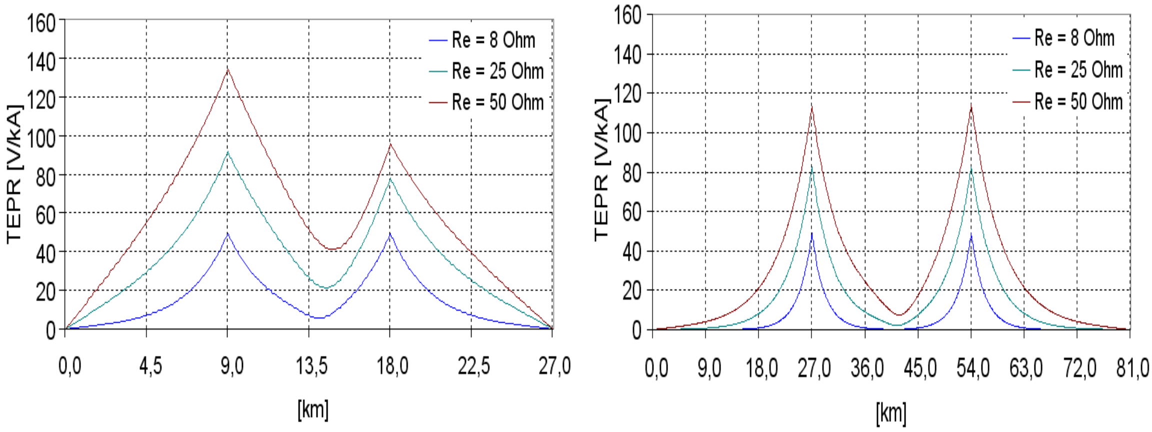
(1). Effect of the phase conductor arrangement in case of a single circuit line (Figure G.4.2.).

(2). Effect of the phase configuration in case of a double circuit line (Figure G.4.3.).

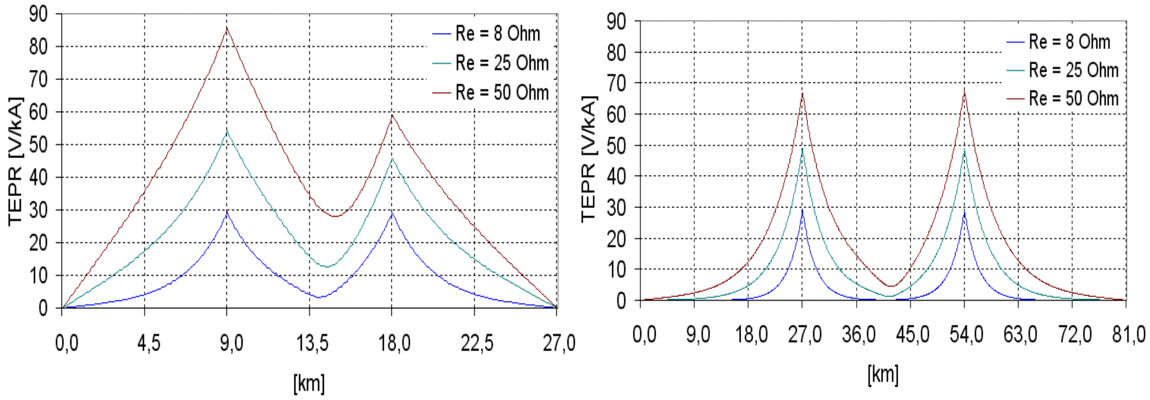
(3). Effect of the span in the case of a compact line (Figure G.4.4.).

(4). Effect of the size (cross section) of the shield wire in case of compact line (Figure G.4.5.).

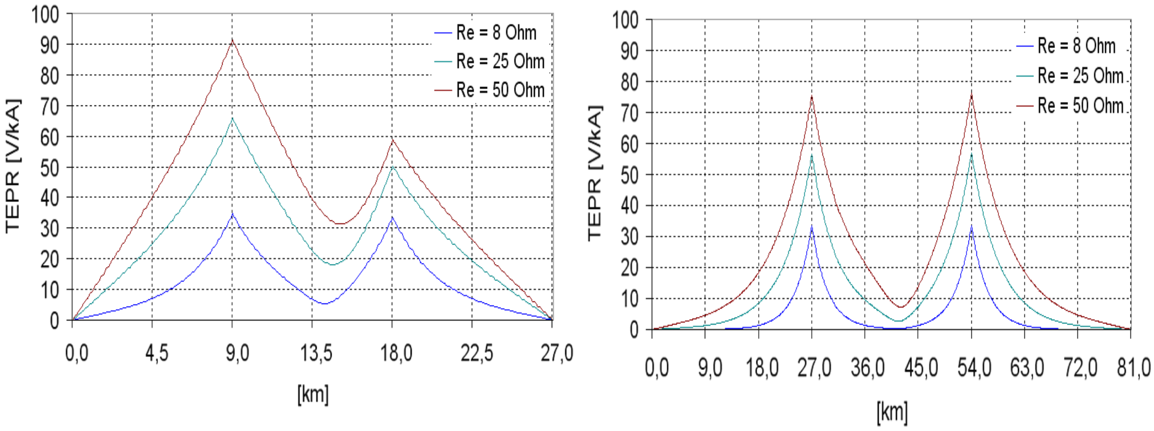
Line length: 27 km *Line length: 81 km*



a) Compact phase conductor arrangement with one shield wire



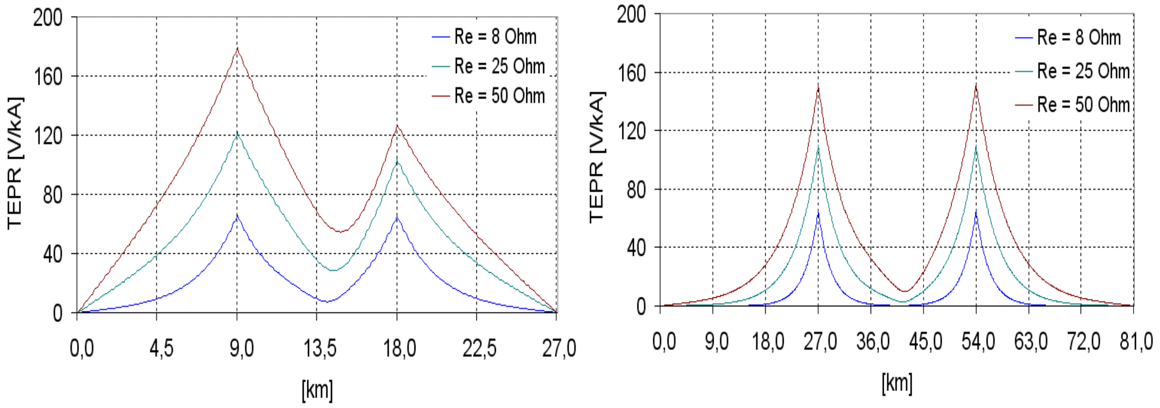
b) Horizontal phase conductor arrangement with one shielding wire



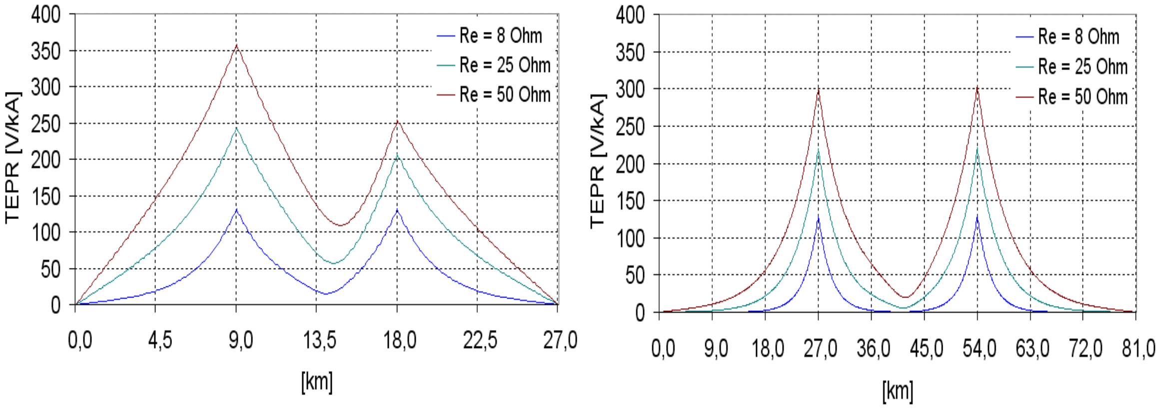
c) Horizontal phase conductor arrangement with two shield wires

Figure G.4.2 T-EPR length profiles for a single circuit line with different conductor arrangements, (span 300m, sw 241 mm^2)

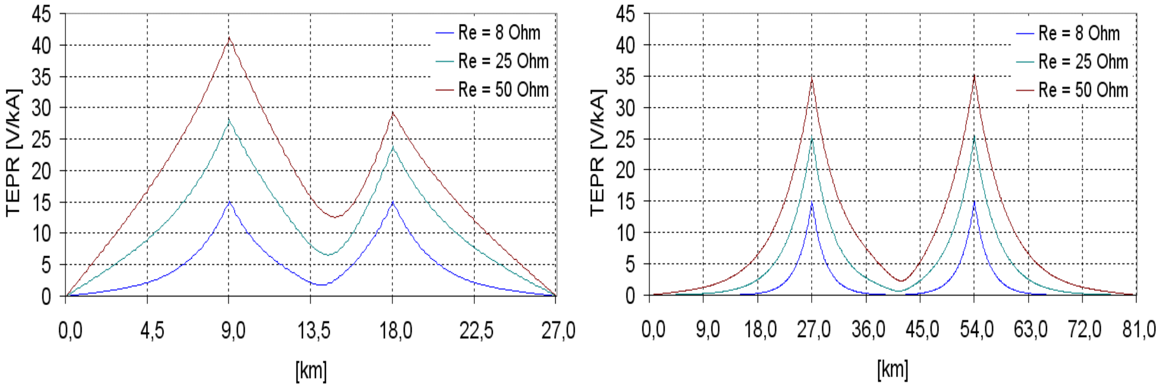
Line length: 27 km *Line length: 81 km*



a) One circuit is only loaded (by 1 kA), phase configuration: abc-000



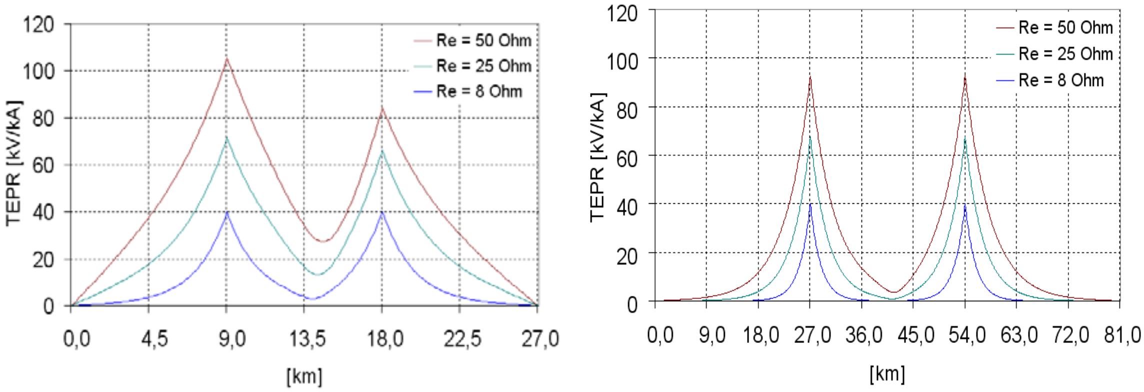
b) Both circuits are loaded (by 1 kA each), phase configuration identical: abc-abc



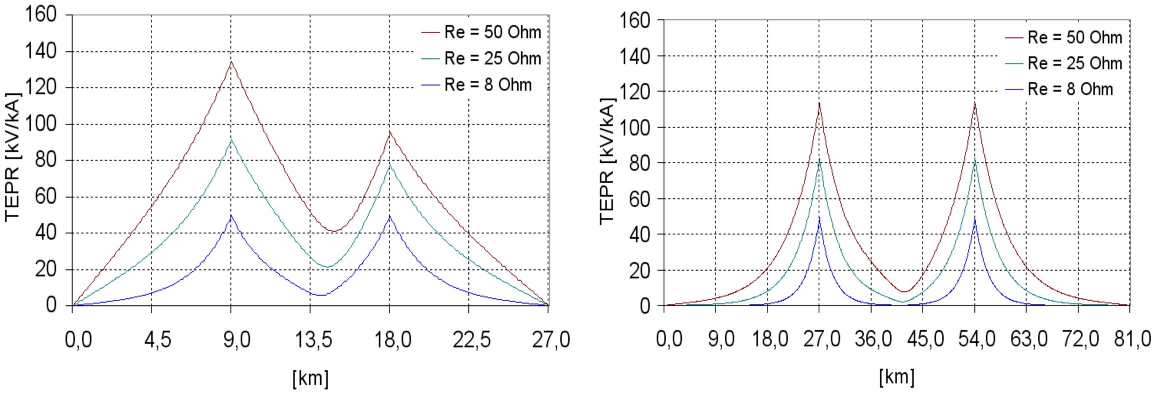
b) Both circuits are loaded (by 1 kA each), phase positioning circular: abc-cba

Figure G.4.3 T-EPR length profile for a double circuit line with different phase configurations, (span 300m, sw 241 mm^2)

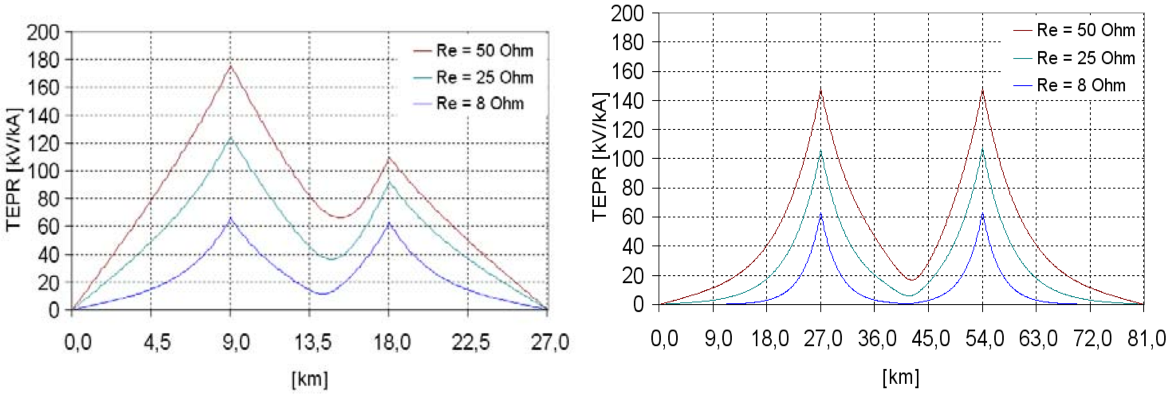
Line length: 27 km *Line length: 81 km*



a) Tower span: 200 m

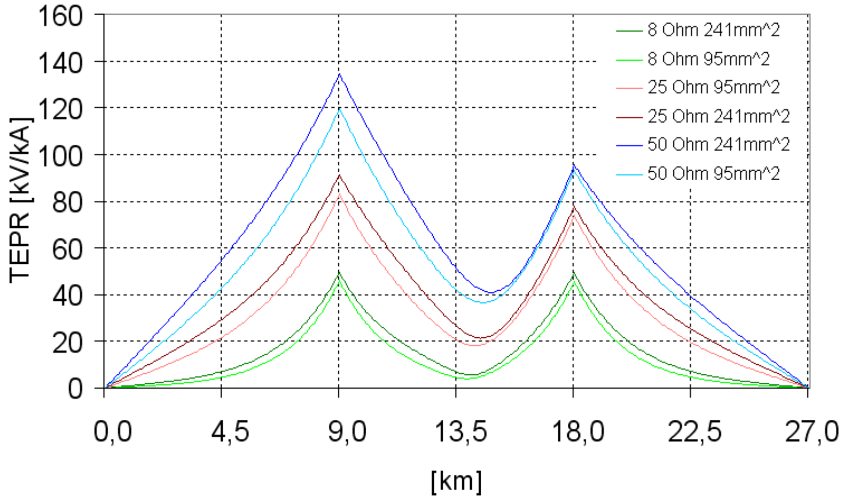


b) Tower span: 300 m

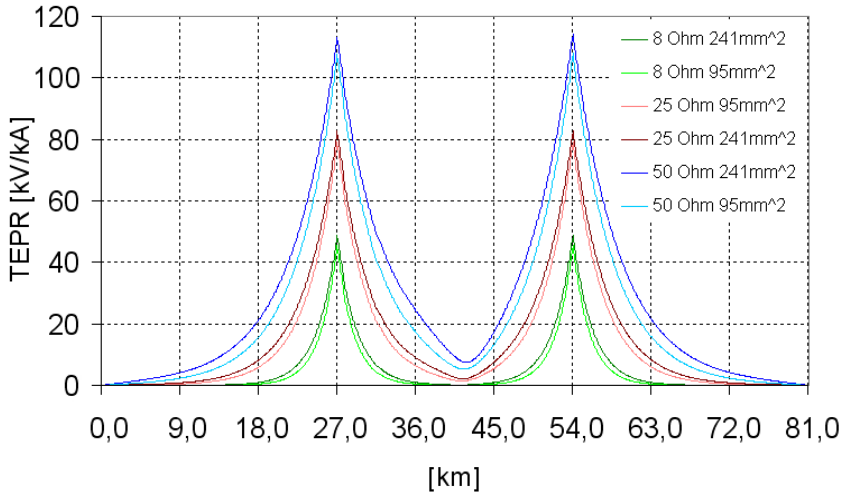


c) Tower span: 500 m

Figure G.4.4. T-EPR length profiles for compact line with different tower span, km (sw 241 mm^2)



a) Line length: 27 km



b) Line length: 81 km

Figure G.4.5. T-EPR length profiles for compact line with different shield wire sizes of 95 and 241 mm^2, tower span: 300 m)

G4.3. Tower footing voltage and current maximum values

It is clearly shown by the T-EPR profile curves that the maximum value occurs at one of the transposition towers. The maximum values of the tower footing voltage and current values are given in the form of bar plots in Figure G.4.6. These plots provide an easy comparison of the maximum values – similar to the grouping of the T-EPR profiles – for the following cases:

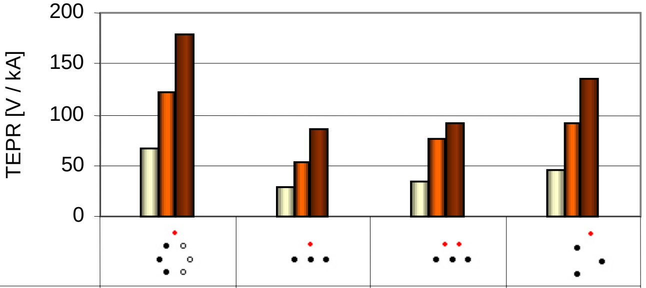
a) Maximum for different conductor arrangement in case of a single circuit line (Figure G.4.6.).

b) Maximum for different phase configuration in case of a double circuit line (Figure G.4.7.).

c) Maximum for different span in case of compact line (Figure G.4.8.).

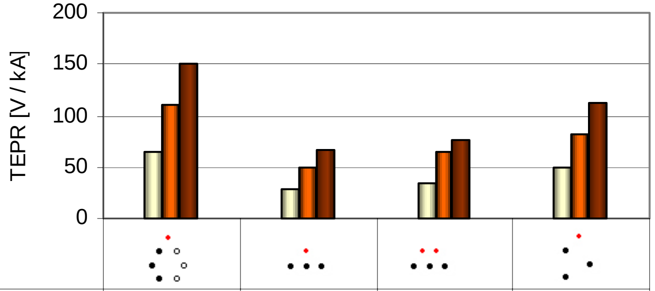
d) Maximum for different size (cross section) of the shield wire in case of compact line (Figure G.4.9.).

Line length: 27 km



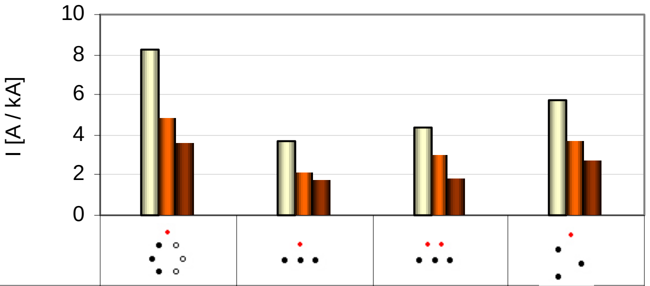
Re = 8 Ohm	65.86	29.24	34.70	46.07
Re = 25 Ohm	121.83	54.09	75.62	91.51
Re = 50 Ohm	178.94	85.64	91.42	134.41

Line length: 81 km

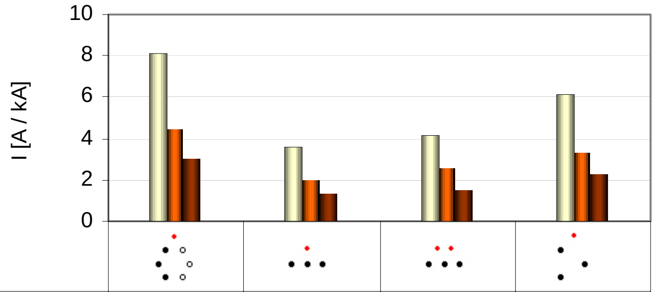


Re = 8 Ohm	65.15	28.92	33.54	48.93
Re = 25 Ohm	109.98	48.83	64.74	82.61
Re = 50 Ohm	150.78	66.94	75.55	113.25

a) T-EPR of tower footing



Re = 8 Ohm	8.23	3.66	4.34	5.76
Re = 25 Ohm	4.87	2.16	3.02	3.66
Re = 50 Ohm	3.58	1.71	1.83	2.69

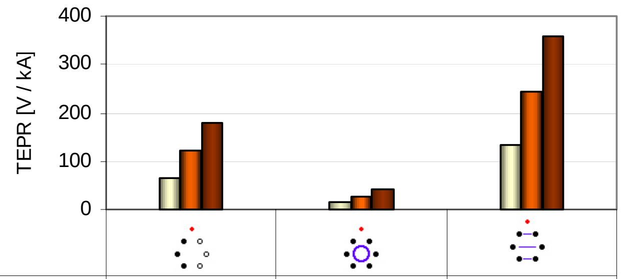


Re = 8 Ohm	8.14	3.62	4.19	6.11
Re = 25 Ohm	4.40	1.95	2.59	3.30
Re = 50 Ohm	3.02	1.34	1.51	2.27

b) Current of tower footing

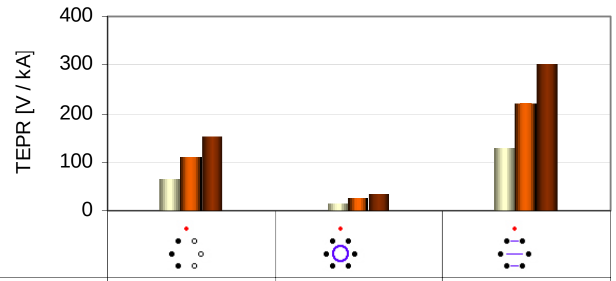
Figure G.4.6. Tower footing voltage and current for different conductor arrangements of a single circuit line, (span: 300 m, shield wire 241 mm^2)

Line length: 27 km



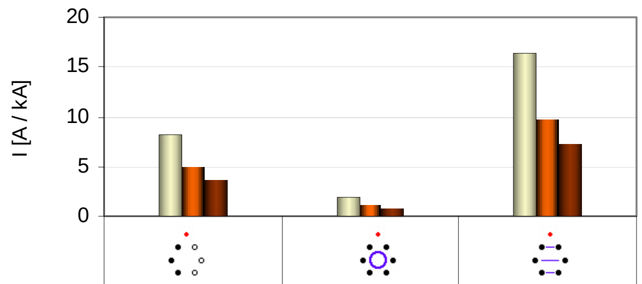
Re = 8 Ohm	65.86	15.17	131.72
Re = 25 Ohm	121.83	28.07	243.66
Re = 50 Ohm	178.94	41.22	357.88

Line length: 81 km

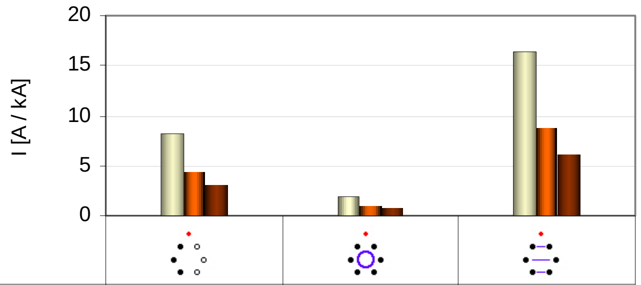


Re = 8 Ohm	65.15	15.01	130.29
Re = 25 Ohm	109.98	25.34	219.96
Re = 50 Ohm	150.78	34.74	301.56

a) T-EPR of tower footing



Re = 8 Ohm	8.23	1.90	16.47
Re = 25 Ohm	4.87	1.12	9.75
Re = 50 Ohm	3.58	0.82	7.16



Re = 8 Ohm	8.14	1.88	16.29
Re = 25 Ohm	4.40	1.01	8.80
Re = 50 Ohm	3.02	0.69	6.03

b) Current of tower footing

Figure G.4.7. Tower footing voltage and current for different phase configurations of a double circuit line, (span: 300 m, shield wire 241 mm^2)

G.5. Main effects, conclusions

On the basis of the results obtained from calculations for different conditions in practical cases, the following main conclusions can be drawn concerning the relative importance of the effects.

1) The emf induced in the shield wire loop is greatly effected by:

- the arrangement of the phase conductors in case of single circuit line. The horizontally arranged line induces the lowest emf, which is much lower than that for vertical line.

2) The magnitude of the T-EPR:

- significantly (nearly proportionally) increases with the average value of the R_e tower footing resistance;
- increases with increasing span, and
- an increase in the cross section of the shield wire causes a small increase in T-EPR.

3) The value of the current through the tower footing is larger for a lower R_e in spite of the lower T-EPR.

G.6. Zone of earth potential rise (EPR)

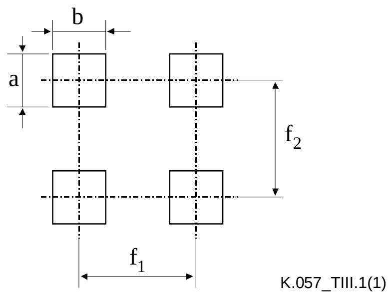
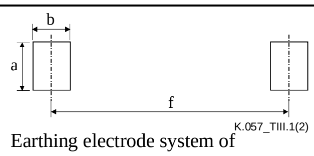
The potential rise caused at a distance x by the T-EPR voltage V_e in the vicinity of the transposition tower footing (zone of potential cone) can be calculated for practical purposes by use of the following formula for the equivalent hemisphere:

$$V_x = \frac{1}{2\pi} \frac{\rho}{R_e} V_e \frac{1}{x}$$

The formula can be useful for defining if a pipeline is in the zone of influence from the a.c. power line, see also section 3.4.2 in this guide. However, the formula is only valid well outside the tower earthing electrode arrangement.

The value of ρ/R_e has been calculated for 21 different tower footing structure in connection with the preparation of the Recommendation K.57. The results are shown in Table G.6.1.

Table G.6.1. Examples of values for the parameter ρ/R for different tower earthing arrangements

Tower earthing: Arrangement	Typical voltage level [kV]	Case code	Sizes of the frame electrode [m]: Legs spacing[a)] f_1	Legs spacing[a)] f_2	Lateral[b)] a	Lateral[b)] b	Depth	ρ/*R*
Direction of the line route  Self-supporting tower foundation	120	1	3.6		1.3		1.8	13.3
	120	2	3.7		1.3		1.8	13.5
	220	3	4.5	4.0	1.4		1.6	14.1
	120	4	4.8		1.6		1.6	15.5
	120	5	7.2	4.3	1.4		1.8	15.8
	120	6	4.5		2.0		1.9	17.1
	220	7	6.0		1.7		1.8	17.4
	400	8	6.8		1.7		1.6	17.6
	220	9	6.5		1.7		2.0	18.2
	120	10	6.0		1.9		2.4	19.3
	400	11	7.5	5.5	2.0		2.0	19.4
	750	12	9.0		2.2		1.8	21.9
	400	13	8.2		2.3		2.4	22.9
	220	14	7.0		2.8		2.0	23.1
	750	15	10.0		2.4		2.9	25.7
	220	16	9.0		3.0		2.8	27.3
	750	17	11.0		3.0		4.1	31.2
 Earthing electrode system of H-frame suspension tower	400[c)]	18	19.0		1.2		1.6	9.7
	120	19	5.4		4.2	1.8	2.5	15.5
	220	20	18.0		3.2	2.5	2.9	18.1
	750[c)]	21	26.4		2.9	1.1	5.3	18.4

[a)] A single value is given when the spacings between the legs of the tower are identical, i.e., $f_1 = f_2 = f$, or the tower foundation comprises only two legs with spacing f (see the upper and lower schemes in the 1st column of the table, respectively).

[b)] A single value is given when the lateral sizes of the frame type earthing electrode are identical, i.e., a = b.

[c)] Earthing electrode system of guyed H-frame suspension tower.

Expressions for calculating the residual emf induced on the shield wire

The emf E_{vv}, per unit length, induced on the shield wire, no 4 in Figure H.1, by the currents I_1, I_2 and I_3 flowing on the phase conductors 1, 2, and 3, respectively, can be expressed by the following formulae:

$$E_{vv} = Z_{41} I_1 + Z_{42} I_2 + Z_{43} I_3 \quad \text{V/km} \tag{H.1}$$

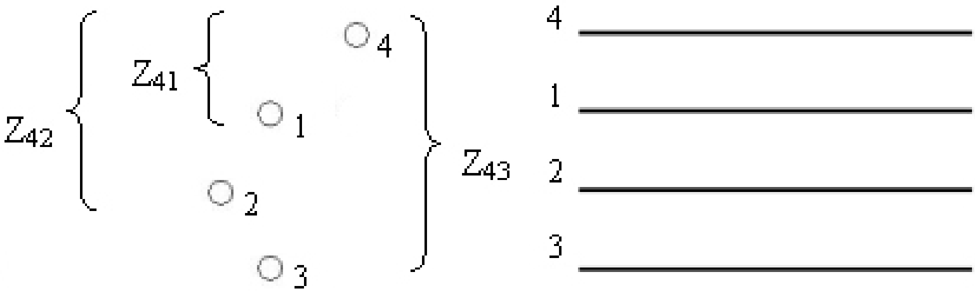


Figure H.1.
Identification of the conductors and mutual impedances between them
(No. 1, 2, and 3 phase conductors, no. 4 shield wire)

The mutual impedances can be expressed by the following expressions [7]:

$$Z_{41} = R_e + j\omega\, 0.2 \cdot 10^{-3} \ln \frac{D_e}{d_{41}} \quad \Omega/\text{km}$$

$$Z_{42} = R_e + j\omega\, 0.2 \cdot 10^{-3} \ln \frac{D_e}{d_{42}} \quad \Omega/\text{km} \tag{H.2}$$

$$Z_{43} = R_e + j\omega\, 0.2 \cdot 10^{-3} \ln \frac{D_e}{d_{43}} \quad \Omega/\text{km}$$

In the expressions H.2 R_e is the a.c. resistance of the earth return, and D_e is the equivalent current return distance which are given - on the bases of the Carson-Clem formula – by the following expressions, respectively:

$$R_e = 0.987 \cdot f \cdot 10^{-3} \quad \text{in } \Omega/\text{km} \qquad D_e = 659 \sqrt{\frac{\rho}{f}} \quad \text{in m} \tag{H.3}$$

where f is the frequency (Hz) and ρ is the specific resistivity of the earth (Ωm) in deep layers.

When – for practical calculation purposes – conductor no.2 is considered as reference conductor, the expressions (A.2) can be written in the following form:

$$
\begin{aligned}
Z_{41} &= R_e + j\left(X + \Delta X_{41}\right) \quad \Omega/\text{km} \\
Z_{42} &= R_e + jX \quad \Omega/\text{km} \\
Z_{43} &= R_e + j\left(X + \Delta X_{43}\right) \quad \Omega/\text{km}
\end{aligned}
\tag{H.4}
$$

The ΔX differences in the coupling impedances can be expressed by the use of the formulae (H.2) as:

$$
\begin{aligned}
\Delta X_{41} = X_{41} - X_{42} &= \omega\, 0.2 \cdot 10^{-3} \left(\ln \frac{D_e}{d_{41}} - \ln \frac{D_e}{d_{42}} \right) = \omega\, 0.2 \cdot 10^{-3} \ln \frac{d_{42}}{d_{41}} \quad \Omega/\text{km} \\
\Delta X_{43} = X_{43} - X_{42} &= \omega\, 0.2 \cdot 10^{-3} \left(\ln \frac{D_e}{d_{43}} - \ln \frac{D_e}{d_{42}} \right) = \omega\, 0.2 \cdot 10^{-3} \ln \frac{d_{42}}{d_{43}} \quad \Omega/\text{km}
\end{aligned}
\tag{H.5}
$$

Considering (H.5) and (H.4) the formula (H.1) can be written as:

$$
E_{vv} = \left[R_e + j\left(X + \Delta X_{41}\right)\right] I_1 + \left[R_e + j\left(X\right)\right] I_2 + \left[R_e + j\left(X + \Delta X_{43}\right)\right] I_3 \quad \text{V/km} \tag{H.6}
$$

or in a rearranged form:

$$
E_{vv} = R_e\left(I_1 + I_2 + I_3\right) + jX\left(I_1 + I_2 + I_3\right) + j\Delta X_{41} I_1 + j\Delta X_{43} I_3 \quad \text{V/km} \tag{H.7}
$$

Considering that the phase currents are assumed to reflect a balanced (positive sequence) system, and selecting again the current on conductor no.2 as reference, the following current expression applies:

$$
I_1 + I_2 + I_3 = 0 \tag{H.8}
$$

The emf induced into the shield wire-to-earth loop, per unit length, can then be expressed by the following formula, obtained from (H.7) by the substitution of (H.8):

$$
E_{vv} = j\Delta X_{41} I_1 + j\Delta X_{43} I_3 \quad \text{V/km} \tag{H.9}
$$

where

- ΔX_{41} and ΔX_{43} the coupling differences relevant to the conductors no.1 and no.3, respectively, given by the formulae (H.5) in Ω/km.
- I_1 and I_2 are the phasor values of the currents in conductors 1 and 2, respectively in Figure H.1.

Regarding their phase relations the following two options can occur in practice:

a) When the current is leading in conductor no.1 with respect to the current in the reference conductor no.2 then:

$$I_1 = I\ e^{j120} \qquad I_2 = I \qquad I_3 = I\ e^{-j120} \tag{H.10a}$$

b) When the current is lagging in conductor no.1 with respect to the current in the reference conductor no.2 then:

$$I_1 = I\ e^{-j120} \qquad I_2 = I \qquad I_3 = I\ e^{+j120} \tag{H.10b}$$

where:

$I = |I| e^{j\varphi}$ is the current phasor value with modulus $|I|$ and angle φ) flowing on the reference conductor no.2 along the transposition sub-section under consideration.

Finally, the emf induced into the shield wire-to-earth loop, per unit length, can be expressed by the following formula, obtained from (H.9) by the substitution of the appropriate version (H.10):

$$E_{vv} = j\Delta X_{41} I_1 + j\Delta X_{43} I_3 = j\Delta X_{41}\, e^{\pm j120} I + j\Delta X_{43}\, e^{\mp j120} I \quad \text{V/km} \tag{H.11a}$$

or

$$E_{vv} = \left[j\Delta X_{41}\, e^{j(\pm 120 + \varphi)} + j\Delta X_{43}\, e^{j(\mp 120 + \varphi)} \right] |I| \quad \text{V/km} \tag{H.11b}$$

where the upper signs associated with the 120 degree values apply when the current is leading in the conductor no.1 (see Table H.1.) while the lower signs apply for lagging case (see Table H.2).

The phase φ of the reference current in conductor no.2 changes at the transposition point by plus or minus 120 degrees according to the transposition direction. The induced emf is calculated for each sub-transposition section. In the case of a perfect transposition scheme the emf of each sub-section is identical in modulus, changes by 120 degrees in the subsequent sub-sections and the phasor sum for a whole transposition cycle is nil.

The expressions for the calculation of the emf induced on each transposition sub-section, per unit length, are summarized for leading and lagging phase configuration schemes in the Table H-1 and Table H-2, respectively.

Table H-1
Phase configurations along the sub-transposition sections I., II. and III., when the current on the conductor no.1 is *leading* with respect to the reference current in conductor no.2

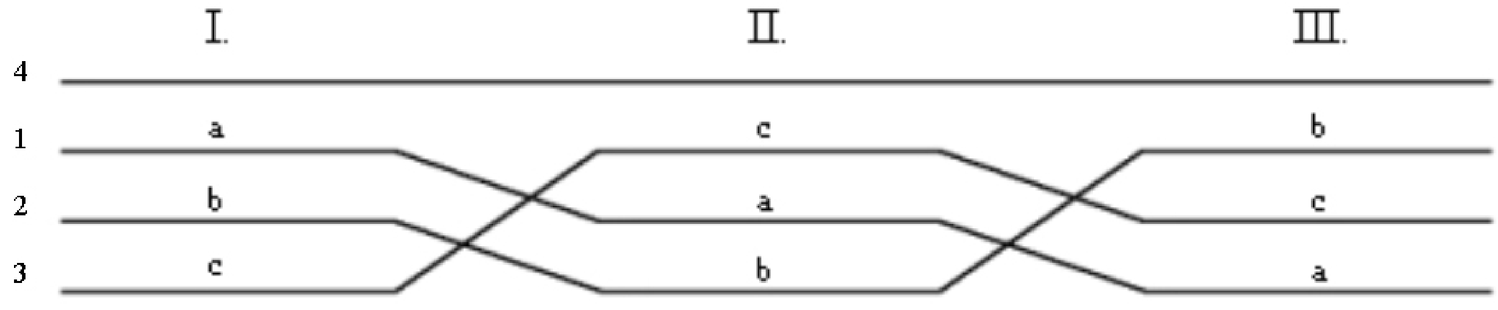
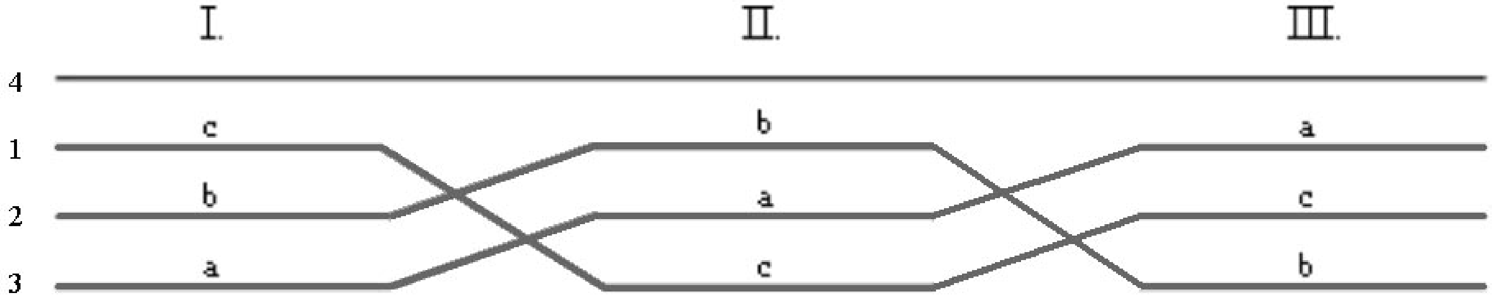
Quantity	Expressions for the transposition sub-sections		
			
$\underline{/I}_1$	+120°	-120°	0°
$\underline{/I_2} = \underline{/\varphi}$ (deg)	0°	+120°	-120°
$\underline{/I}_3$	-120°	0°	+120°
E_{vv} (V/km)	$j\left(\Delta X_{41} e^{j120^\circ} + \Delta X_{43} e^{-j120^\circ}\right) \cdot \lvert I \rvert$	$j\left(\Delta X_{41} e^{-j120^\circ} + \Delta X_{43}\right) \cdot \lvert I \rvert$	$j\left(\Delta X_{41} + \Delta X_{43} e^{j120^\circ}\right) \cdot \lvert I \rvert$

Table H-2

Phase configurations along the sub-transposition sections I., II. and III., when the current on the conductor no.1 is *lagging* with respect to the reference current in conductor no.2

Quantity	Expressions for the transposition sub-sections		
			
$\underline{/I}_{1}$	-120^{o}	0^{o}	+120^{o}
$\underline{/I_2} = \underline{/\varphi}$ (deg)	0^{o}	+120^{o}	-120^{o}
$\underline{/I}_{3}$	+120^{o}	-120^{o}	0^{o}
E_{vv} (V/km)	$j\left(\Delta X_{41}e^{-j120^\circ} + \Delta X_{43}e^{+j120^\circ}\right)\cdot\lvert I\rvert$	$j\left(\Delta X_{41}e^{j0^\circ} + \Delta X^{-j120}{}_{43}\right)\cdot\lvert I\rvert$	$j\left(\Delta X_{41}e^{j120} + \Delta X_{43}e^{j0^\circ}\right)\cdot\lvert I\rvert$

A. C. corrosion criterion based on induced voltage: introduction of some probabilistic concepts

I.1 Introduction

Among the different criteria, proposed to establish the risk of a.c. corrosion on buried pipelines the induced a.c. voltage (with respect to the remote earth) on the pipeline is the most convenient both from the measurement and from the calculation point of view.

Likewise, one can state that pipeline corrosion can occur only when holidays exist on the insulating covering. Therefore this Appendix proposes an approach based on some probabilistic concepts that can incorporate the purely deterministic criterion given in chapter 7.

I.2 Distribution of holidays along the pipeline route

The main parameter to be considered is the average number of holidays per unit length n_h present on the pipeline; these data should be made available by the owner or operator of the pipeline from field data. As an example, we report in Table I.1 some data collected in the field. [10].

Table I.1: number of holidays detected on pipelines having different diameters.

diameter [mm]	M: number of holidays	L: total length [km]	n_h=M/L: number of holidays per km
100	37	66	0.561
150	92	74.8	1.23
200	115	160.5	0.717
250	107	185.4	0.577
300	199	165.1	1.205
400	145	267.1	0.543
500	143	129.3	1.106
600	94	108.9	0.863
750	33	150.6	0.219
850	7	14.2	0.493
900	39	178	0.219
1000	7	47	0.149
1200	455	376.6	1.208
Total	**1473**	**1923**	**0.766**

The last row of the table contains the values referred to the whole population with no relation to the pipe diameter.

If L is the pipeline length, the total number of holidays N_h present on its insulating covering is given by:

$$N_h = round(n_h L) \tag{I1}$$

where *round* is the function approximating the numeric value $n_h L$ to its nearest integer.

In the absence of specific information, the easiest hypothesis that can be used concerning the distribution of holidays is that they are uniformly spread along the pipeline route; hence, if s' and s'' (s'' > s') are two generic progressives along the route, the probability p(s', s'') that the generic i-th holiday is present in the pipeline section between s' and s'' is:

$$p_i(s', s'') = \frac{s''-s'}{L} \qquad (i = 1,2,.., N_h) \tag{I2}$$

while the probability $q_i(s', s'')$ that the generic i-th holiday is not present in the section [s', s''] is:

$$q_i(s', s'') = 1 - \frac{s''-s'}{L} \qquad (i = 1,2,.., N_h) \tag{I3}$$

Where all the p_i are equal, it is convenient, in the following, to drop the index i; thus, we shall consider the probabilities p(s', s'') and q(s', s'') associated to each holiday.

I.3 Probability of having at least one holiday in the generic pipeline section [s', s'']

If, after a calculation or a series of measurements, the voltage profile along the pipeline route has been determined and in one or more region a certain threshold value V^* (considered meaningful for a.c. corrosion risk) is exceeded, one has to evaluate the probability that *at least* one holiday is present in that/those section(s).

By referring to the generic section [s', s''], all the possible partitioning of the total number of holidays N_h along the pipeline route is described in Table I.2 .

Table I.2: Partitioning of Nh holidays inside and outside a generic section [s', s''] along the pipeline route.

number of holidays inside section [s', s'']	number of holidays outside section [s', s'']
0	N_h
1	N_h-1
2	N_h-2
⋮	⋮
N_h-1	1
N_h	0

By applying the binomial distribution to Table I.2, the probability P(k, N_h, [s', s'']) of having k out of N_h holidays in the pipeline section [s', s''] is:

$$P(k, N_h, [s', s'']) = \binom{N_h}{k} p(s', s'')^k \, q(s', s'')^{N_h - k} \tag{I4}$$

Thus, the probability P' of having at least one holiday in the section [s', s''] is:

$$P' = \sum_{k=1}^{N_h} P(k, N_h, [s', s'']) \tag{I5}$$

Equivalently, the probability P' can be calculated in a more straightforward way by means of the relation:

$$P' = 1 - \binom{N_h}{0} q^{N_h}(s', s'') = 1 - (1 - p(s', s''))^{N_h} \tag{I6}$$

where the second addendum, on the right hand side of formula (6), is the probability of having no holiday inside section [s', s"].

Therefore, by applying the simple formula (I6) (or (I5)), one can associate to each section [s', s"], the probability that at least one holiday is actually present in the section itself. In particular, by focusing the attention to that/those section(s) where the threshold value V^* is exceeded, it is possible to better quantify the a.c. corrosion risk.

I.4 Examples

It is worthwhile to give some examples: Let S be the length of pipeline section where the voltage V^* is exceeded. Figs. I.1, I.2, I.3 show the per cent probability $P'_{\%}$ versus S for different values of the number of holidays per unit length and for different pipeline lengths.

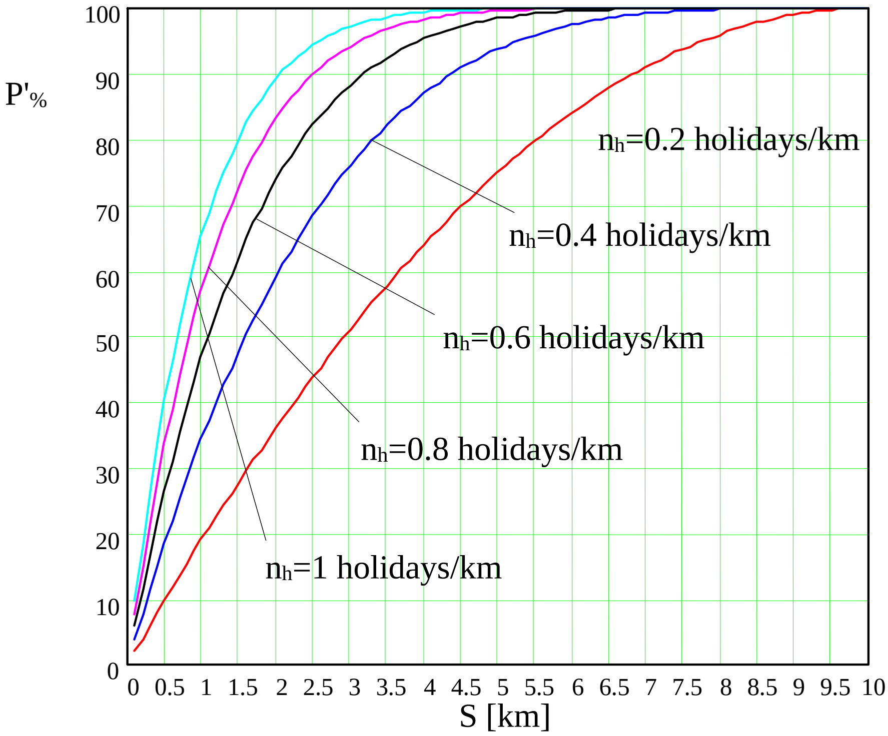


Figure I.1: Per cent probability of having at least one holiday in a pipeline section of length S: L=10km.

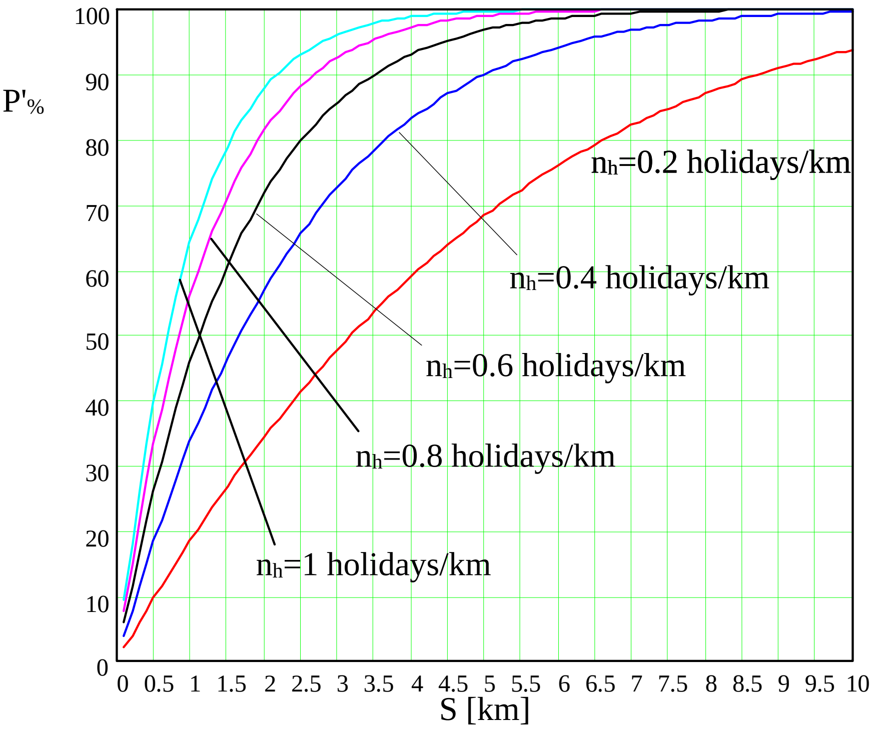


Figure I.2: Per cent probability of having at least one holiday in a pipeline section of length S: L=20km.

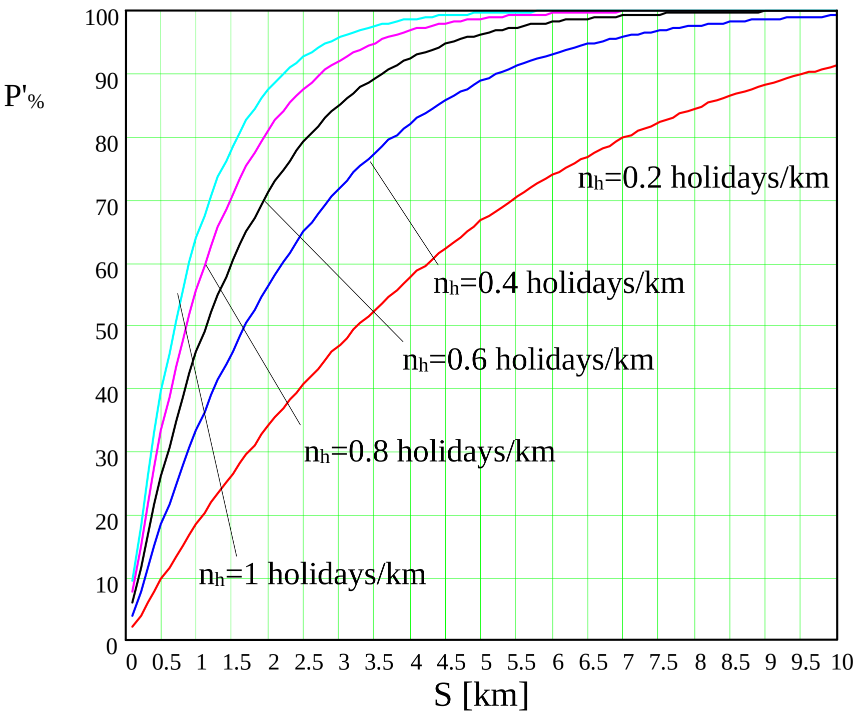


Figure I.3: Per cent probability of having at least one holiday in a pipeline section of length S: L=30km.

As one could expect, the probability $P'_{\%}$ increases by increasing the number of holidays per unit length and also by increasing the length S of interval; moreover, by comparing the corresponding curves in Figs.I.1, I.2 and I.3 (i. e. for the same n_h) one can see that an increase of the total pipeline length, results in a decrease of the probability $P'_{\%}$.

However, for small values of the section S, the values of $P'_{\%}$ are relatively small so reducing the a.c. corrosion risk, even if the threshold value V^* is exceeded in the section.

I.5 Conclusions

In this Appendix, a simple method to evaluate the probability of having at least one coating holiday in a given section of pipeline has been presented; such information should integrate the purely deterministic criterion for a.c. corrosion risk based on the induced voltage.

Voltage drop in the soil: remote earth from a practical point of view

J.1 Introduction

The aim of this Appendix is to try to clarify, by means of some numerical examples, the concept of remote earth when dealing with electromagnetic interference and corrosion problems on pipelines under the influence of a.c. power lines.

From a theoretical point of view, remote earth is a region in the soil sufficiently far away from both structures (inducing and induced) or other sources of electromagnetic interference so that any influence from them can be neglected.

From the experimental point of view, when measurements of induced voltage on pipelines are involved, it is necessary to know what lateral distance D from the pipeline can be considered large enough in order to reliably neglect any kind of conductive influence from the pipeline itself on the reference electrode. (See Figure J.1).

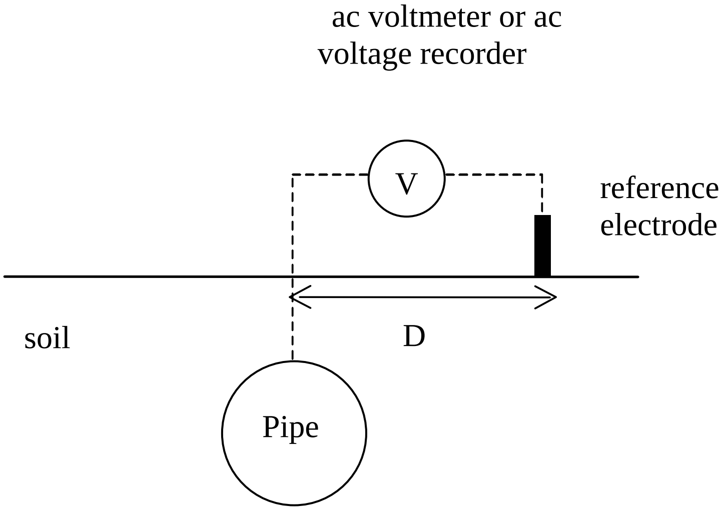


Figure J.1: Pipeline voltage measurement scheme.

J.2 Earth potential produced by a current flowing into the soil through a holiday in the pipeline coating

Let us consider a pipeline buried in an homogeneous soil having resistivity ρ_s and covered by an insulating coating having thickness d; let us suppose that a holiday in the coating, characterized by area A, is placed on the top of the pipe surface at a depth H (see Figure J.2); moreover let ρ_h be the resistivity of the electrolyte filling the small cylinder (of base A and height d) modelling the vacancy in the coating.

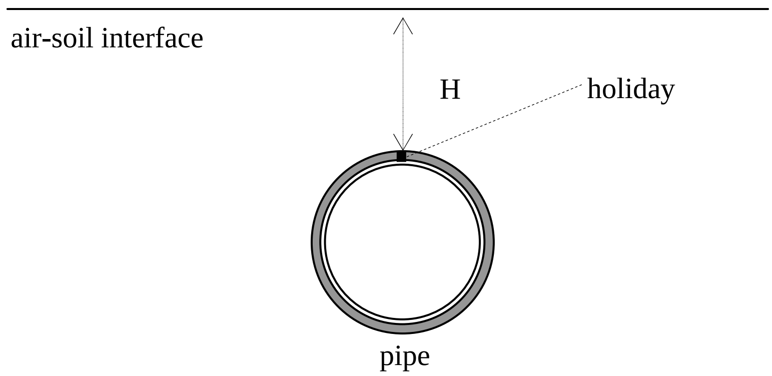


Figure J.2: Schematic representation of the pipeline with holiday in the insulating coating

In order to evaluate the potential produced in any point P in the soil due to the current flowing through the coating holiday, the holiday itself can be modelled as a point electrode buried in the earth at a depth H.

This simplified hypothesis can be applied when the distance between P and the holiday is much larger than the holiday equivalent radius; such a condition is certainly fulfilled in the case considered here (some metres against some tenths of a centimetre).

If I is the current through the holiday (located at (0, 0, -H)), the potential in the earth V_e=V_e(x, y, z) is given by:

$$V_e(x,y,z) = \frac{\rho_s I}{4\pi}\left(\frac{1}{\sqrt{x^2+y^2+(z-H)^2}} + \frac{1}{\sqrt{x^2+y^2+(z+H)^2}}\right) \qquad \text{(L1)}$$

In particular, the earth potential at the air-soil interface (z=0) is of primary interest, so that (L1) becomes:

$$V_e(x,y,0) = \frac{\rho I}{2\pi}\left(\frac{1}{\sqrt{x^2+y^2+H^2}}\right) \qquad \text{(L2)}$$

Let us suppose that V is the pipeline potential at the holiday location; by remembering that the holiday resistance R_h is given by:

$$R_h = \frac{\rho_h d}{A} + \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}} \qquad \text{(L3)}$$

where *d* is the thickness of the insulating coating and *A* the area of the holiday.

it is possible to express the current I through the holiday by means of the following relation:

$$I = \left(\frac{\rho_h d}{A} + \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}}\right)^{-1} V \qquad \text{(L4)}$$

Thus, the earth potential can be written as a function of the pipeline potential V; in particular, at the air-soil interface, from (L2) and (L4) one has:

$$V_e(x,y,0)=\frac{\rho}{2\pi}\left(\frac{1}{\sqrt{x^2+y^2+H^2}}\right)\left(\frac{\rho_h d}{A}+\frac{\rho_s}{4}\sqrt{\frac{\pi}{A}}\right)^{-1}V \qquad \text{(L5)}$$

It should be emphasized that the absence of any other source able to conductively influence the system under study has been implicitly assumed; e.g. earthing systems of power line towers, stray currents due to electrified traction lines.

J.3 Ratio of potential at soil surface with respect to pipeline voltage

In order to determine a suitable distance from the pipeline at which to locate the reference electrode shown in Figure J.1, it useful to consider the per cent ratio $p_{\%}$ between the potential V_e at the soil surface and the pipeline voltage that is:

$$p_{\%}(D)=\frac{\rho}{2\pi}\left(\frac{1}{\sqrt{D^2+H^2}}\right)\left(\frac{\rho_h d}{A}+\frac{\rho_s}{4}\sqrt{\frac{\pi}{A}}\right)^{-1}100 \qquad \text{(L6)}$$

in terms of D, the lateral distance of the reference electrode from the pipeline axis (see Figure J.1).

Thus, the range relevant to the distance of the pipeline from the reference electrode fulfilling the condition $p_{\%}<1$ identifies a space region that can be considered with good approximation to be at zero potential i.e. remote earth.

Figures J.3a to J.3f show the plot of $p_{\%}$ versus the lateral distance D for different values of resistivities ρ_h and ρ_s and of the holiday area A. In all the calculations the values d=5mm and H=0.5m have been considered.

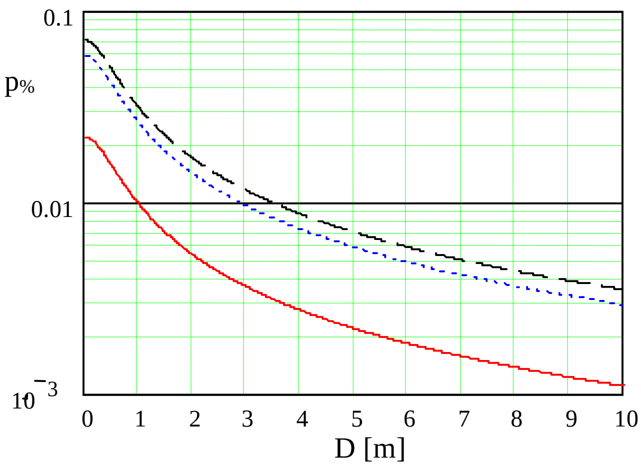


Figure J.3a: $p_{\%}$ versus D for different values of soil resistivity (from top to bottom 5000Ωm, 500Ωm, 50Ωm) ; ρ_h=10Ωm, A=0.01cm^2.

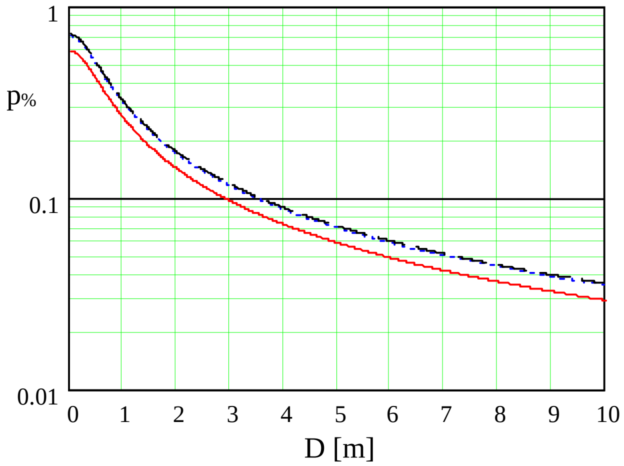


Figure J.3b: $p_{\%}$ versus D for different values of soil resistivity (from top to bottom 5000Ωm, 500Ωm, 50Ωm) ; ρ_h=10Ωm, A=1cm^2.

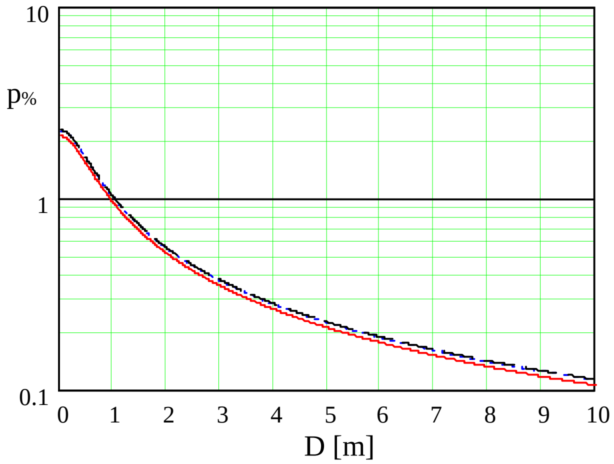


Figure J.3c: $p_{\%}$ versus D for different values of soil resistivity (from top to bottom 5000Ωm, 500Ωm, 50Ωm) ; ρ_h=10Ωm, A=10cm^2.

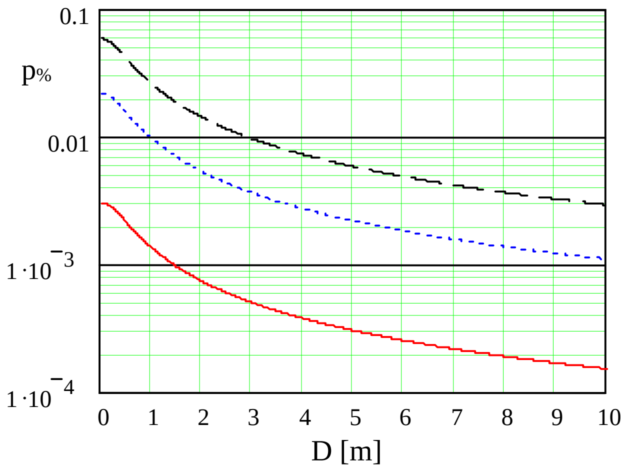


Figure J.3d: $p_{\%}$ versus D for different values of soil resistivity (from top to bottom 5000Ωm, 500Ωm, 50Ωm) ; ρ_h=100Ωm, A=0.01cm^2.

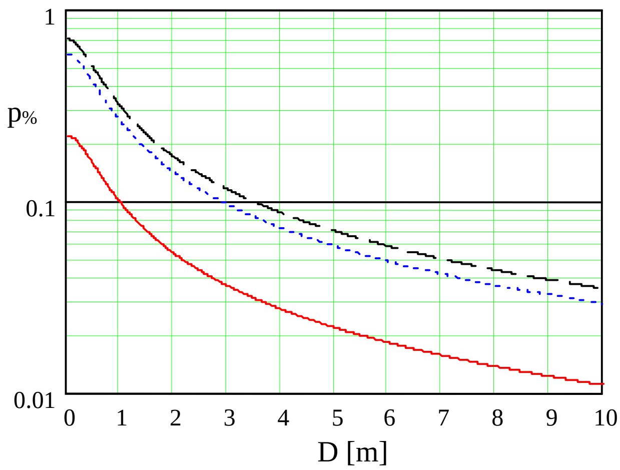


Figure J.3e: $p_{\%}$ versus D for different values of soil resistivity (from top to bottom 5000Ωm, 500Ωm, 50Ωm) ; ρ_h=100Ωm, A=1cm^2.

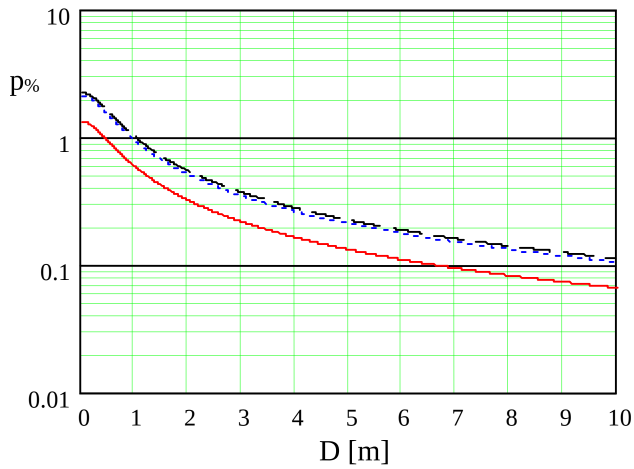


Figure J.3f: $p_{\%}$ versus D for different values of soil resistivity (from top to bottom 5000Ωm, 500Ωm, 50Ωm) ; ρ_h=100Ωm, A=10cm^2.

It can be seen from the figures that in all the cases, at a distance of a few metres, the ratio $p_{\%}$ assumes values smaller than 1%. It is therefore possible to conclude that at a distance of 3 to 5m the conductive influence of the current flowing into the soil through the holiday in the coating is completely negligible.

J.4 Conclusions

The calculations performed by varying significant parameters in their typical range show that, in all the cases, the potential produced by the current through the holiday at a distance of a few metres from the pipeline can be disregarded. This also gives a practical indication about the location of the remote earth (i.e. reference for zero potential in measurements) relevant to these kinds of problems.

This is true as far as influences from other sources of voltage gradients in the soil (e.g. power line tower earthing systems, stray currents due to electrified traction systems) can be neglected.

Measurements by use of coupons

Measurements of the a.c. current density and some other measurements related to a.c. corrosion cannot be performed on the pipeline itself. Instead auxiliary test coupons have to be used.

A test coupon is a steel coupon covered with an isolating coating. In the coating there is an open holiday with known surface area. The coupon is installed in the soil, close to the pipeline and electrically connected to the pipeline so it has the same a.c. and d.c. potentials as the pipeline. Consequently, the test coupon is cathodically protected, in the same way as the pipeline itself. The coating holiday surface is the active area where the steel is in contact with the soil. An often-used active area of the test coupon is 1 cm^2.

As the active area of the coupon is known it is possible to calculate the current density by measuring the current in the connecting electric conductor divided by the coupon area.

One important parameter, when using test coupons, is the contact between the metallic surface of the coupon holiday and the surrounding soil. This must be representative of the contact at a pipeline coating holiday.

Details regarding the design and use of test coupons can be found in the CEOCOR guide [2].