PUBLICLY AVAILABLE SPECIFICATION

Pre-Standard

IEC PAS 62344

First edition
2007-05

General guidelines for the design of ground electrodes for high-voltage direct current (HVDC) links

Reference number
IEC/PAS 62344:2007(E)

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

- Catalogue of IEC publications: www.iec.ch/searchpub

The IEC on-line Catalogue enables you to search by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: www.iec.ch/online_news/justpub

Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Customer Service Centre: www.iec.ch/webstore/custserv

If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: csc@iec.ch
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00

PUBLICLY AVAILABLE SPECIFICATION

IEC PAS 62344

Pre-Standard

First edition
2007-05

General guidelines for the design of ground electrodes for high-voltage direct current (HVDC) links

Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

PRICE CODE X

For price, see current catalogue

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

GENERAL GUIDELINES FOR THE DESIGN OF GROUND ELECTRODES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) LINKS

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with an IEC Publication.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

A PAS is a technical specification not fulfilling the requirements for a standard but made available to the public.

IEC-PAS 62344 was submitted by the CIGRÉ (International Council on Large Electric Systems) and has been processed by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

The text of this PAS is based on the following document: This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:

Draft PAS	Report on voting
22F/116/NP	22F/128/RVN

Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned will investigate the possibility of transforming it into an International Standard.

This PAS shall remain valid for an initial maximum period of three years starting from 2007-05. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.

INTRODUCTION

Most of the world's HVDC links have been (or still are) in a first monopolar stage, because this solution gives the lowest costs. If the connection between a monopolar pair of converter terminals consists of an overhead line construction, the extra costs of a return conductor on the pylons are moderate. This is certainly not the matter if the connection mainly consists of a long submarine cable, because the return cable, which must have about the same cross-section as the main cable, but much lower design voltage, may easily cost 30-50 % of the main cable.

The evaluation of the additional losses in the return path must be included when costs of different possible solutions are compared. A return path via ground electrodes will normally have a considerably smaller resistance than any reasonable metallic conductor return.

When a monopolar link becomes bipolar, the use of the return path and the number of hours of operation with nominal current decrease. At this stage the evaluation of losses in the return path loses importance; but the return path will be important for raising the overall reliability/availability of the link.

The sites chosen for converter stations belonging to a specific HVDC scheme under design/construction are generally finalized at an early stage of the time schedule of the project, while a choice of electrode station sites, or even a general analysis, whether ground return is feasible (or possible), is often postponed to a later stage in the time schedule.

The summary of existing electrode stations [0][1] shows distances from converter stations to electrode stations ranging from 8 km to 85 km. The need for a minimum distance will be explained in 4.3. The need for a maximum distance is a matter of economy. The selection of a site for an electrode station should generally involve the following considerations:

a) The possibility of obtaining permission to establish and operate the station at the intended site, and to obtain the ownership of the area, if appropriate.

b) The distance to metallic objects such as pipelines, cables, grounding networks at a.c. stations (including the converter station itself), and other infrastructure.

c) The geology of the site must fulfil certain limits for resistivity, moisture content, thermal conductivity, water exchange, water depth, etc.

The technical circumstances which could be problematic when establishing a ground return may roughly be divided into two groups.

d) Problems at some distance or far from the station: The field, produced by the current in the earth, might have an unacceptable influence on other infrastructure.

e) “Local” constructional difficulties, such as high resistivity and too dry soil. Furthermore, chemical aspects such as chlorine production may cause local difficulties. This is further described in Clause 10.

There is good reason to mention the “distance” field problem as the most important, because the remote field produced by an electrode is independent of the construction of the station, and only depends on the geology of the subsoil. This will be explained further in Clause 3.

As a general rule, local constructional difficulties may be handled to a great extent by making the size of the station greater, the number of subelectrodes larger, etc.

Following the definition in [3], the electrode stations are divided into three groups:

- land electrodes, located far away from the sea;
- shore electrodes, located on a shore against (salt) seawater. Shore electrodes can be located either on the beach at a short distance (<50 m) from the waterline or in the water, but protected by a breakwater;
- sea electrodes, located in the water at some distance (>100 m) from the coastline.

---

[1] Figures in square brackets refer to Clause 14.

GENERAL GUIDELINES FOR THE DESIGN OF GROUND ELECTRODES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) LINKS

1 Scope

The purpose of this PAS is to provide a guide for the design of electrode stations for HVDC links intended for ground return. This design guide was prepared by the CIGRÉ Working Group 14.21: *HVDC Ground Electrode Design* during the period 1995-1998.

It is not the purpose of this report to provide detailed instructions on how to work out an HVDC link from the initial idea to final decisions on sites, ratings, constructional principles for converter stations and for connecting lines/cables. In the often hectic planning phase of a new link, the main emphasis will be concentrated on converter stations and the line/cable, while less attention is paid to a simultaneous evaluation of possible current return principles.

2 Basic concepts

2.1 Monopolar system

New HVDC schemes often first have a monopolar stage. The use of ground return necessitates the presence of an anodic ground electrode adjacent to one of the converter stations and a cathodic ground electrode adjacent to the other converter station.

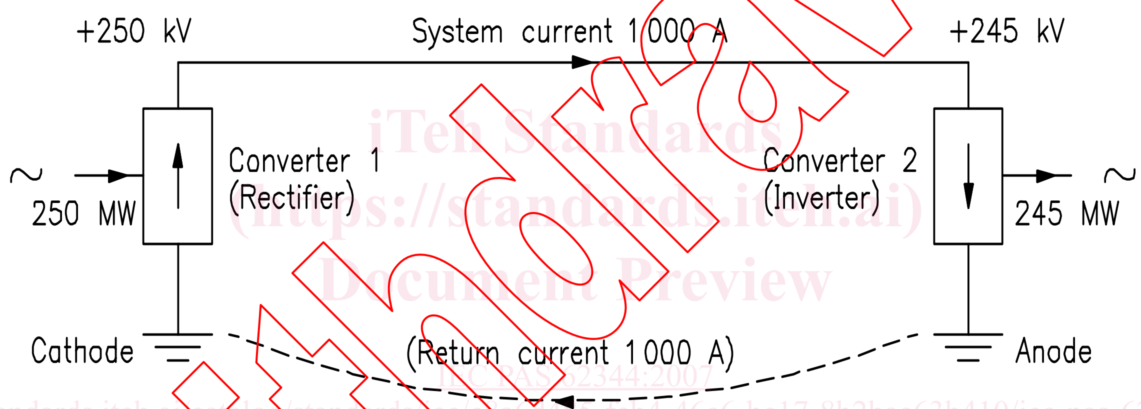

Figure 2.1.1 – A 250 MW, 250 kV, 1 000 A monopolar HVDC scheme transmitting power from converter 1 to converter 2

Normally, converter equipment is constructed for a uniform direction of current. However, the direction of power transmission can be changed by changing the polarity of voltage; see Figure 2.1.2.

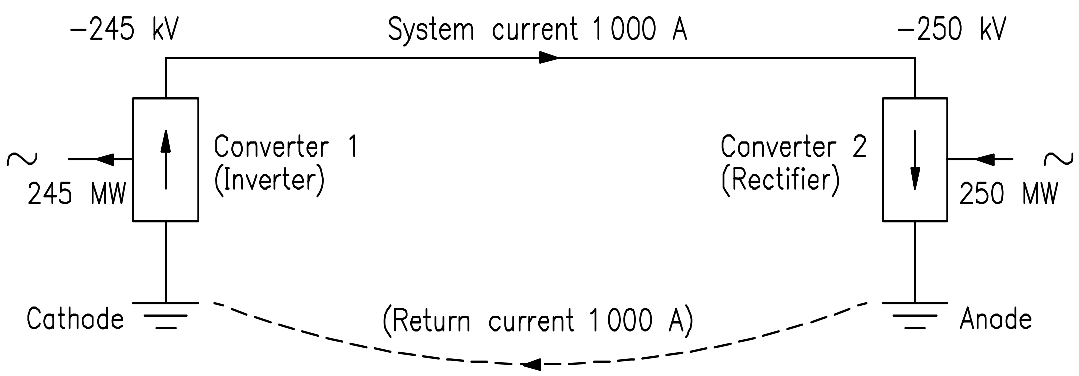

Figure 2.1.2 – A 250 MW, 250 kV, 1 000 A monopolar HVDC scheme transmitting power from converter 2 to converter 1

Thus, the basic concept of a monopolar scheme is characterized by the following.

a) Each electrode station remains in a constant mode, anodic or cathodic.

b) Each electrode station must be able to carry the rated system current continuously.

2.2 Bipolar system

In principle, the bipolar scheme consists of two monopolar systems which generally have the same rating and where the converter equipment for both monopoles is located in a common converter station.

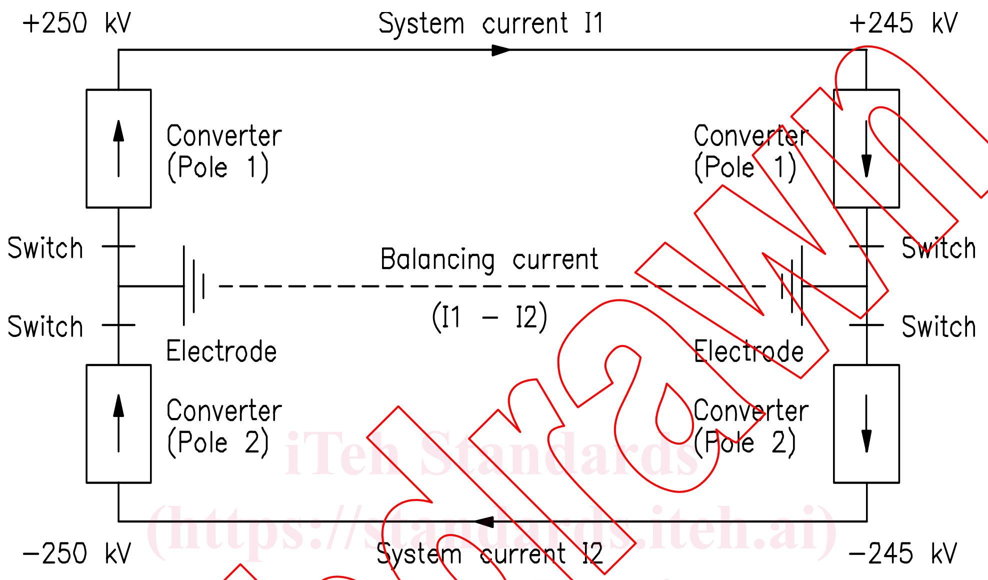

Figure 2.2.1 – A 500 MW, ±250 kV, 1 000 A bipolar HVDC scheme transmitting power from left to right

The basic concept of a bipolar scheme is characterized by the following.

a) Normally, the current in the electrode stations can be kept at a low balanced value (<3 % of system current).

b) If one of the poles is out of service due to maintenance or fault, the pole is switched off, and operation may be continued in a monopolar mode with the still operational pole.

c) The electrodes in that case must be able to carry the system current for the period foreseen or necessary for monopolar operation. Both electrode stations must be able to operate in either anodic or cathodic mode, depending on which pole is operating.

A bipolar system having one of the poles out of service can be arranged for metallic return, provided that the high-voltage conductor belonging to the pole is undamaged. To do this, a number of switches are necessary. Because the resistances of the normal conductors are usually much higher than the resistance of the electrode circuit, the use of metallic return raises the conductor losses to the same level as the total bipolar scheme, but with only one pole in operation. This means a double loss percentage for the line losses.

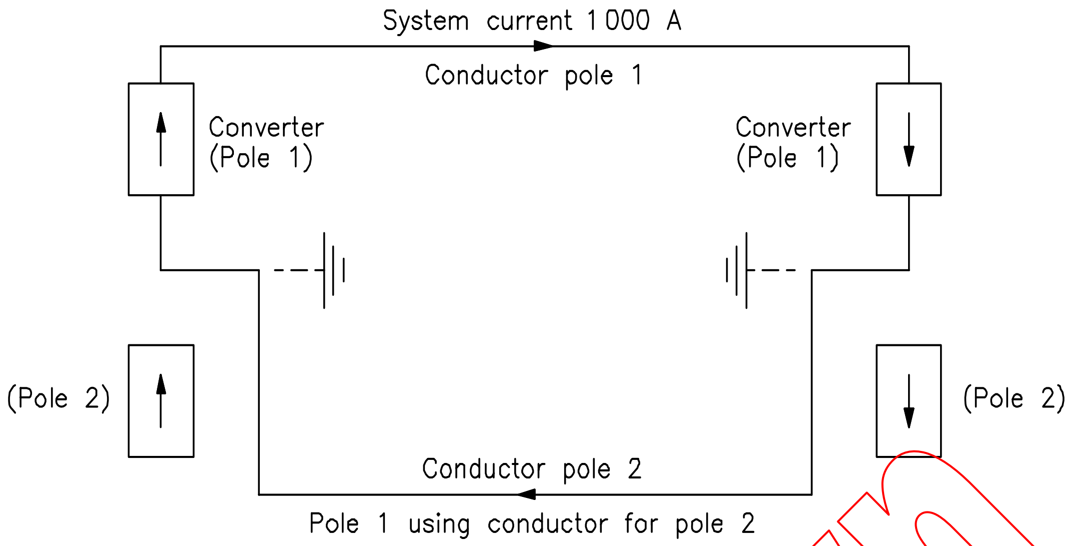

Figure 2.2.2 – A bipolar scheme using metallic return – Pole 1 is operating and pole 2 is out of service

There will be another emergency operational mode for a bipolar system if one conductor is out of service. In this case the bipolar system changes to a monopolar system, needing the electrode circuit to be used for the total system current.

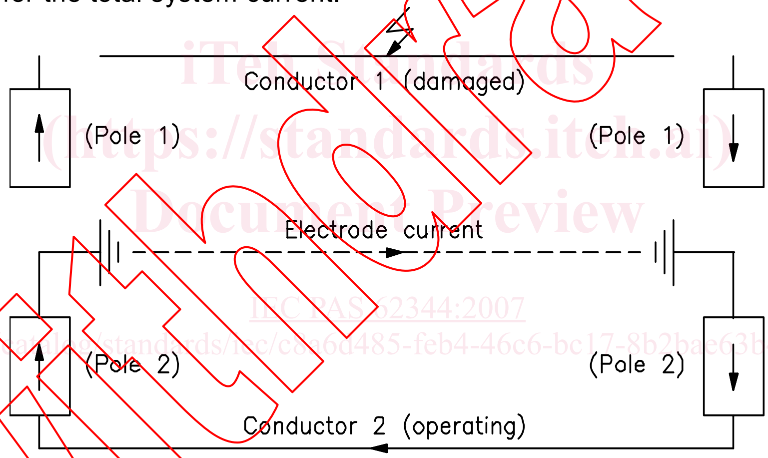

Figure 2.2.3 – Operational mode for a bipolar system where main conductor 1 is out of service – Pole 1 is out of service, even if not damaged

2.3 Mixed or combined systems

A balanced bipolar system consisting of two identical monopoles is normally specified in a single contract and is constructed and put into operation within a short period of time. If pole 2 of a bipolar system is not constructed together with the first pole but at a later stage, the technical evolution may result in differences of ratings, voltages, etc. between the old and the new pole.

This might result in unbalanced technical solutions of different kinds. For instance, the Konti-Skan scheme consists of two poles of unequal ratings, but using the same pair of reversible electrode stations. The Skagerrak scheme, originally consisting of a balanced bipole, now consists of three poles, of which the youngest, pole 3, is opposite to a parallel connection of the two old poles. For the electrode stations this has resulted in less favourable (unbalanced) operation.

3 Electric field as the decisive factor for selection of site

3.1 Why is the electric field the decisive factor?

The field (voltage and gradient) at a point with a certain distance from an electrode station is dependent only on two parameters once the possible site area has been selected:

a) the current transmitted from the station;

b) the resistivity conditions in the underground/sea as seen from the site of the electrode.

The way the electrode station is constructed has no influence on the magnitude/direction of the distant field, whether it is superficial or deep, small or large in size, linear, star- or ring-configurated, etc.

It is crucial, therefore, to reach agreement, or at least have a positive discussion with environmental authorities, with other utilities having metallic infrastructure in the ground, or whoever might have an influence on the possibility of using ground return. If an agreement on acceptance of the field is not likely at any suggested site, the intended HVDC scheme must be based on return principles other than ground return. The authorities, other utilities and others being against ground return should bear in mind the following consdierations:

c) ground return, maybe with limitations, is operating successfully in about 25 HVDC schemes throughout the world;

d) the saving in investment and capitalized loss costs when using ground return is normally much greater than expenses for changes or modifications to existing infrastructure.

3.2 Data necessary to determine the field

3.2.1 Reference currents (or electrode rating)

The most important piece of data needed for designing electrode stations is the system current or the reference current (for the schemes in the summary this ranges from 880 A to 4 000 A). There is no absolutely clear understanding whether the reference current is the maximum current to be handled under any circumstances, or if we speak of a general rating which under certain circumstances may be surpassed in a limited time period. In the following, the reference current will be understood as a general rating and it is up to the designer of the electrode station to include for elevated levels of current for specified periods of time.

3.2.2 Resistivity data

The interference (magnitude of electric field around the station) must be calculated in the design phase, based on the best obtainable information on resistivities of the different strata in the underground and, if the earth is not uniform, in all directions. If the electrode is a shore or sea electrode, design values must be set up for resistivity of seawater and for the bathymetry (depth conditions) in a sufficient zone around the intended site.

3.3 Considerations on site selection

Basically, the current rating and the data for resistivities in different directions and depths are the only parameters necessary to determine the field. It makes no sense to include as a criterion that the voltage or gradient in a certain point at a considerable distance must not exceed a prescribed limit. This fact is obvious if we look at a very simple case, that of uniform earth having uniform resistivity in all directions and all depths. The voltage against remote earth is $V = \frac{\rho \cdot I}{2\pi \cdot x}$ and the gradient $\frac{dV}{dx} = \frac{\rho \cdot I}{2\pi \cdot x^2}$

where x is the distance from the midpoint of the electrode.

It is not that obvious, but still true, that the constitution of the underground/sea and the current are the only field-determining factors for distances which are at least five times the diameter, length or burial depth of the electrode.

This means that if an electrode in the design phase or during commissioning tests turns out to have an unexpectedly high field influence on a metallic structure, then this problem cannot be cured by demanding modification of the electrode station.

Let us assume, as an example, a shore electrode located on a long straight coast. The slope angle of the seabed is 0.05, the resistivity of the seawater 0,2 Ωm and the resistivity of land and seabed 100 Ωm. Reference current 1 000 A.

At a point off the coast line, 10 km from the station, the potential is calculated at 0,178 V and the gradient at 0,0178 mV/m. The potential in the sea 1 000 m from the coast as well as the potential 1 000 m deep below the shore stations are 1,78 V.

Now, if the voltage 0,178 V or the gradient at the distance 10 km are deemed to be too high, then two suggestions might be brought up as a remedy:

a) to move the electrode from the shore to a position 1 000 m outside the shore in a water depth of 1 000 × 0,05 = 50 m;

b) to transfer the shore electrode to a deep hole electrode 1 000 m below the shore line.

It is readily calculated that none of these suggestions will have any notable effect at a distance of 10 km, because the voltage is reduced by only 0,5 % from 0,178 V to 0,177 V. In both cases, the resulting voltage at a point on the coast line at a distance of 10 km is calculated by interchanging the cause and the effect. It is actually the resulting voltages at a position 1 000 m outside the shore and 1 000 m below the shore line that is calculated with the electrode positioned on the coast line 10 km away.

Of course, the local voltages and gradients will be significantly changed by moving a shore electrode to a sea position, or to drill the electrode deep down. In both of the above suggestions the voltage on the original beach position will be 1,78 V, while the electrode on the beach will produce voltages of a higher level, depending on the size and physical layout of the station.

A general piece of advice, seen in literature about electrode stations, is that at least three different sites should be investigated. If any problems are located 10 km from a site, as in the previous example, the possibilities of moving the electrode 1 km aside or 1 km vertically down do not represent genuine alternatives to the basic site. It is the horizontal distance from sites to points or zones with problematic infrastructure that should distinguish the suggested site from the choice of several sites.

3.4 Calculation of field

It is not the intention of this PAS to include a comprehensive set of formulas or methods for calculation of the field from design data. As already said, the size and the physical layout are not important when distances from the electrode are 3-5 times the diameter, length or depth of the electrode. The electrode should be treated as a point, mathematically speaking, from which the current emanates. Dr Kimbark's book “Direct Current Transmission” [2] contains formulas and viewpoints of calculation, including more complicated conditions such as 2- and 3-layer earth. If the subsoil resistivity conditions are rather irregular, the modern FEM (finite element method) provides the possibility of extensive computer-aided calculations.

Most of the existing formulas and methods take into account only the conditions around the electrode dealt with, although no field exists without a counter-electrode. It is fairly easy to include the influence of the counter-electrode by means of superposition of the fields from each of two conjugated electrodes. The formula for the voltage in a two-dimensional room of height h

$$V = \frac{\rho \cdot I}{2\pi \cdot h} \cdot ln \frac{d_2}{d_1}$$

contains in this very simple expression the distance to the electrode (d_1) and to the counter-electrode (d_2). The expression has no mathematical solution if the counter-electrode is ignored.

When judging whether a pair of conjugated electrodes have an acceptable field, there may be cases where interference from two pairs of conjugated electrodes mixes and forms a superpositioned field. In [10], the interaction of fields from the Baltic cable scheme and the Kontek scheme is shown. The anodes of these two schemes are located about 50 km apart. It has been calculated that the potentials at certain points raise as much as 80 % when both schemes are running at rated currents, compared with the values when only one scheme is operating.

3.5 Apparent resistivity

If the calculated field (surface potential and gradient) is plotted in a double logarithmic diagram, it can be compared to the field from existing electrode stations. See Appendix 1 for plotting of surface potential, and Appendix 2 for plotting of gradients, both against distance from electrode stations. In these diagrams inclined lines for the apparent resistivity are shown. The apparent resistivity is the resistivity that fits the formula for a uniform semi-sphere field with current emanating equally in all directions (the counter-electrode not defined).

$$V = \rho \cdot \frac{I}{2\pi \cdot x}$$

$$\frac{dv}{dx} = \rho \cdot \frac{-I}{2\pi \cdot x^2}$$

The use of such diagrams is restricted to distances within about 15 % of the distance to the counter-station because of the impact of the counter-station.

It can be seen clearly on these diagrams whether the current for a given distance has a tendency to plunge to deeper good conducting strata (inclination of the gradient curve >2) or has a tendency to flatten out horizontally because of high resistivity of deeper strata (inclination of the gradient curve = 1).

4 Impact of the field on buried metallic objects

Metallic objects in the ground can be divided into three categories:

– non-insulated objects, i.e. the metal is directly and continuously in contact with the surrounding soil;
– objects coated with insulating material such as polyethylene and normally cathodic protected;
– the earthing grids of substations which are interconnected by the power lines.

4.1 Impact on non-insulated buried metallic objects

Examples of non-insulated objects are cables with a conducting layer, lead or steel armouring, against the soil or, in the case of submarine cables, against the water. Naked metallic conducts for water supply, buried tanks and sheet piling in harbours are also examples.

Depending on the orientation of the metallic object, its size (length) and the strength of the field, the object picks up current in the part closest to the anodic electrode and discharges the current from the part closest to the cathodic electrode.

To judge the impact, it is normal to calculate the distribution of current density, often expressed in μA/cm^2 (1μA/cm^2 = 0,01 A/m^2). The Swedish professor S. Rusck [15] treated these calculations as early as 1962. Dr Kimbark [2] also gives comprehensive consideration to the corrosion due to picked up/discharged d.c. ground current.

For formulas and methods for calculation of current density, reference is made to the reference list last in Clause 14, mainly [1], [2] and [3]. Rusck concludes that a current density of 1μA/cm^2 can be permitted. It corresponds to a rate of corrosion of 0,174 mm per year removed from the surface of an iron object.

Apart from d.c. ground currents, metallic unprotected objects in the ground corrode for “natural” reasons, which is due to local differences in soil composition along the metallic object and/or to the fact that naturally generated currents (called telluric currents) also take a path via the metallic objects. STRI in its report [3] concludes that the impact of natural telluric currents is greater than that from an electrode station for distances greater than 66 km to 110 km from the electrode station.

If an HVDC connection contains land cables or submarine cables it is important to investigate the corrosion danger of the cable armouring, which normally deliberately is not insulated electrically against the surrounding soil or seawater.

As for other metallic infrastructure, the necessary precaution consists of having sufficient distance between the main cable(s) and the electrode. A general suggestion has been 8-10 km. As an example of a closer location, the distance between the main cable of the Kontek scheme and the cathode station Graal-Müritz outside Warnemünde is 5,5 km. Curiously, the main cable for another scheme, the Baltic cable, passes the Kontek cathode at a distance of 7 km.

As shown in Kimbark's text (p. 429), the presence of a cathode at a certain distance from a submarine cable or buried pipe results in a worse condition, because the surface of the closest part of the cable/pipe will be anodic which means corrosion. If the electrode station is an anode, the current density of dangerous directions is reduced by a factor of 4,95, compared with the impact of a cathode.

Generally, it is assumed for bare metallic objects that there is continuous contact with the surrounding soil along the object, that is, all of the surface of the object participates in the formation of current paths. There are polyethylene-coated submarine pipelines for oil or gas which may have bracelets of zink or magnesium at about 100 m intervals. With this semi-continuous contact to surrounding water, the picked-up/discharged current is concentrated on a small part of the total surface. The expected corrosion of the bracelets in an HVDC field must be judged taking the greater current density into consideration.

4.2 Impact on insulated metallic objects

The insulated metallic objects are mainly coated pipelines for oil or gas, located on land. It is normal to have insulating joints, at 10-100 km spacing, which divide the metallic tube into non-interconnected sections. Each section is equipped with a device for cathodic protection, generating a voltage which measured against the surrounding soil through a Cu-$CuSO_4$ half-cell is about -1,0 V. The preferred voltage level may vary according to the soil composition in a range of, say, -0,85 V to -1,1 V; but under anaerobic conditions (lack of oxygen), the margin is limited to about ± 0,05 V. If the voltage is "too positive", there is a danger of discharge of current, which means corrosion. If the voltage is "too negative", hydrogen embrittlement of the steel may occur on a faulty spot. Faulty spots are often unavoidable pinholes in the coating, due to imperfect production, or damage during installation or later.

When a section of an insulated pipeline has to cross an HVDC ground current field, the largest difference from the varying voltage in the soil to the constant voltage impressed on the tube must be limited to the above-mentioned margin. If the field which the section of the pipeline covers has greater differences than the margin, further insulating points must be inserted. Insertion of a further insulating point necessitates the pipeline to be emptied, then refilled with an inactive gas such as CO_2 or He, then cut and the new point inserted. This procedure may take many days, costing loss of gas blown out, and cost of interruption of supply. To limit expenses, especially those connected with outage of the pipeline, the required voltage difference along the pipeline can be generated by introducing a current (2-20 A) in the metallic tube over about 1-2 km. This current causes a voltage drop in the longitudinal resistance (~ 0,01 Ω/km) of the tube. The current can be controlled, even in the reverse direction, by means of an inverter. The inverter is regulated from a signal picked up as a voltage difference from two points along the pipeline, or the inverter gets a direct signal from the converter station or the electrode station, proportional to the HVDC ground return current.

Current compensating devices of this kind are running successfully on a Swedish main gas pipeline which passes the electrode station Risø (the Konti-Skan scheme) at a distance of about 10 km. In Denmark, the uprating of the electrode current for the Skagerrak scheme, from 1 000 A to 2 300 A, demanded two insulating joints and two current compensating devices to be installed on a 508 mm (20 inches) main gas pipeline, which gave costs of a total of about USD 600,000. The gas pipeline passes the electrode station Lovns at a distance of 6 km.

4.3 Impact on an a.c. grid

The impact of the ground current is shown on the drawing in Appendix 3 in a simplified way. The