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)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

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 It also gives information on projects, withdrawn and replaced publications.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.

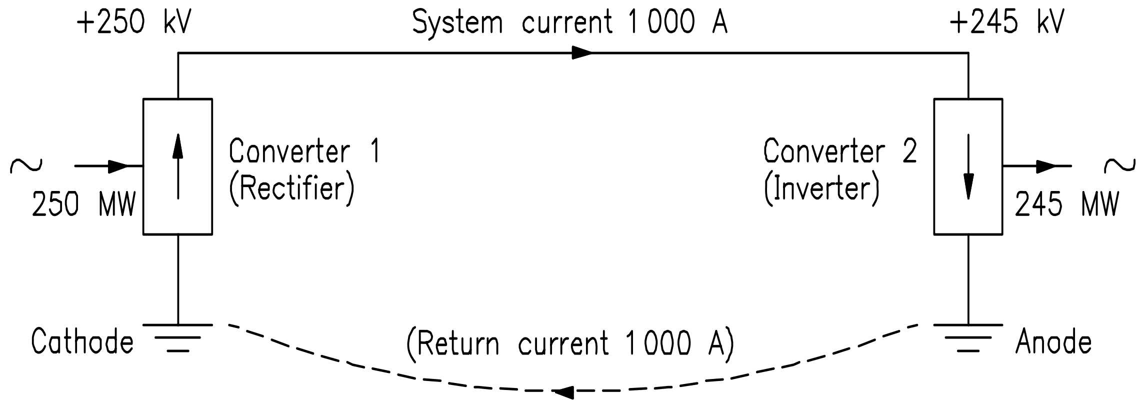


Figure 2.1.1 – A 250 MW, 250 kV, 1 000 A monopolar HVDC scheme transmitting power from converter 1 to converter 2

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.

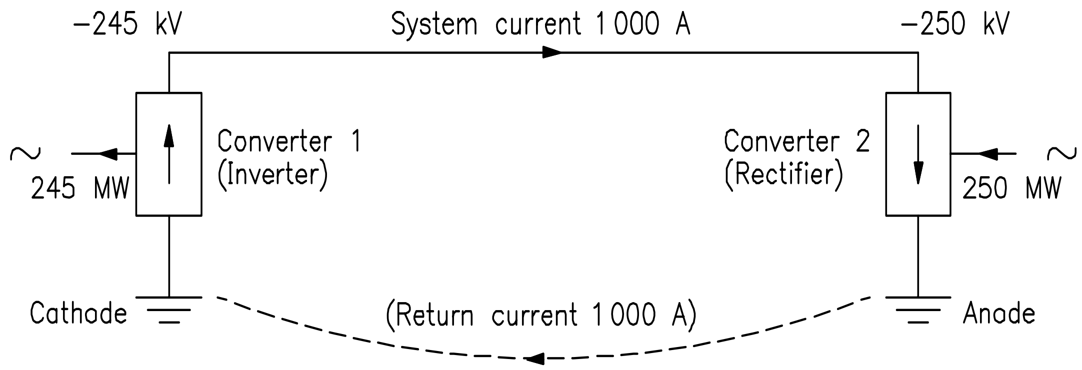


Figure 2.1.2 – A 250 MW, 250 kV, 1 000 A monopolar HVDC scheme transmitting power from converter 2 to converter 1

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.

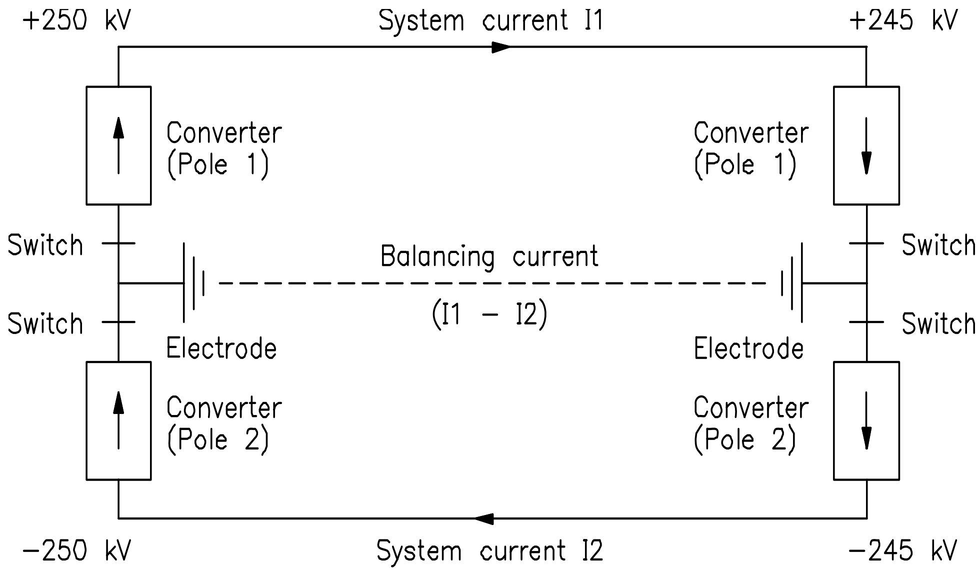


Figure 2.2.1 – A 500 MW, ±250 kV, 1 000 A bipolar HVDC scheme transmitting power from left to right

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.

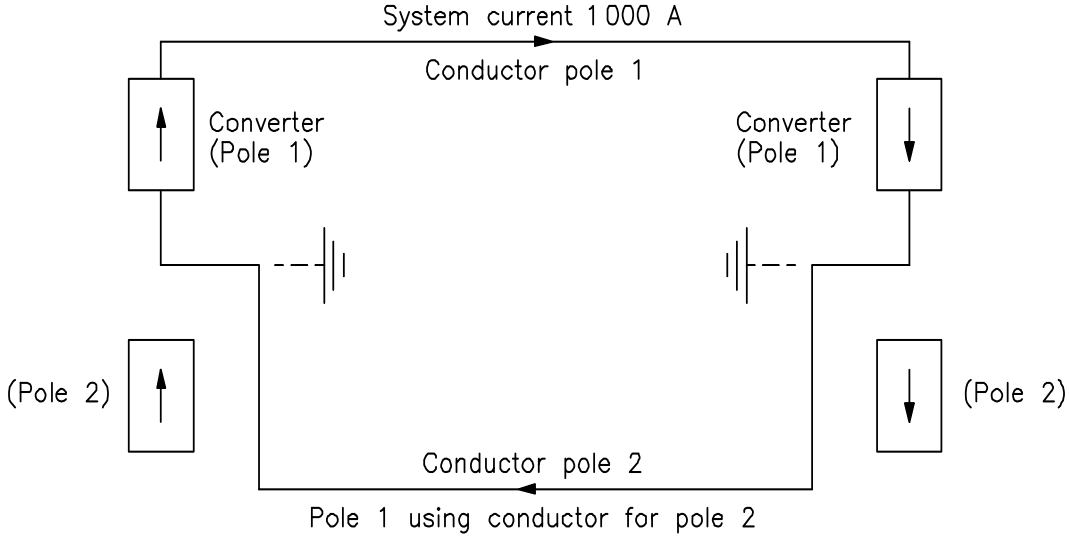


Figure 2.2.2 – A bipolar scheme using metallic return – Pole 1 is operating and pole 2 is out of service

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.

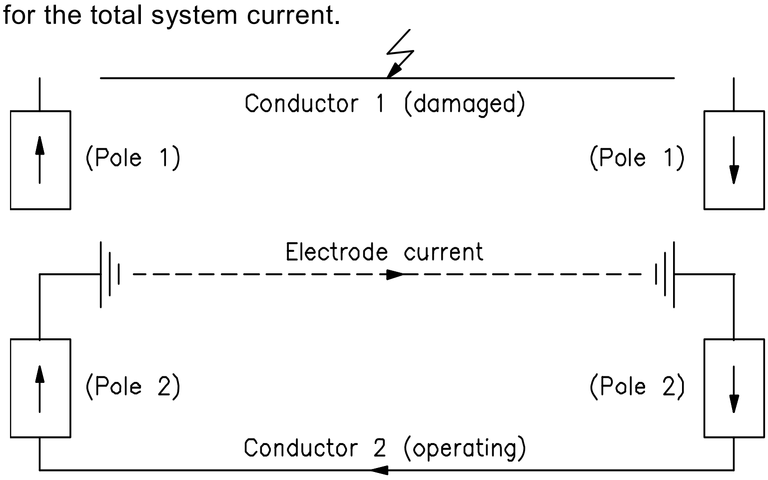


Figure 2.2.3 – Operational mode for a bipolar system where main conductor 1 is out of service – Pole 1 is out of service, even if not damaged

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 $\pm$ 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 current emanating from the anode partly enters the earthing grid of substation A, flows further in the phases and in the shielding wire(s) to substation B, where the current is discharged via the earthing grid, and flows further to the cathode.

On condition that the shielding wire(s) is/are continuous from A to B, part of the picked-up current follows these wires. Intermediate pylons closest to the anode pick up further fractions of current, while pylons closest to the cathode discharge corresponding fractions. The situation is similar to the continuous metallic pipe or cable, which over the total length is divided into a cathodic zone (left) and an anodic zone (right on the drawing). The principal risk is corrosion of the anodic part, and may be judged, for instance, by the viewpoint of S. Rusck (max. 1 μA/cm current density).

There is another principal path for the current. It enters the grounded starpoint of transformer A, follows the high-voltage phases to transformer B and leaves via the starpoint connection and earth grid for substation B. The d.c. component in the overhead line, which might be 0.1-1 A per phase, runs independently of the a.c. phase current, which might be of a magnitude of 1 000 A per phase.

The d.c. component through the transformer windings provokes a constant magnetizing of the core, which, superpositioned on the symmetrical a.c. magnetizing, lets the flux vary in an unbalanced way, which in one flux direction may lead to saturation of the core. The wave form of the current is destroyed mainly due to a rise in the content of 2nd harmonics.

This vulnerability to d.c. magnetizing is different for different core types. Monophase transformers with magnetic return equal in area to the wound leg are strongly affected. Three-phase, five-legged transformers also react to some degree, because the d.c. flux, which is unidirectional in the three-phase legs, finds a low-reluctance path in the outer two legs. Three-phase, three-legged transformers will withstand a high level of d.c. current excitation, because the d.c. flux is developed only to a small degree due to the high magnetic reluctance from the top yoke to the bottom yoke.

Returning to the five-legged, three-phase transformers, the return legs with an area of, say, 58 % of each of the main legs, each have to carry the d.c. flux from 1½ main legs. This indicates that the return legs saturate by a flux which is about $\frac{0,58}{1,5} \approx 0,39$ times the flux that would saturate a phase leg. Once the outer legs are saturated, the transformer for further excitation acts almost like a three-legged transformer.

It is only transformers having a direct grounded starpoint of the winding system that pass d.c. current through the windings. Delta-connected windings, for instance, the converter side windings of converter transformers, cannot be hit by through-passing d.c. current. As was the case for bare metallic objects, the necessary and effective protection for ground d.c. excitation of transformers is to locate the electrode station at a certain distance from any vulnerable substation, including the converter station.

Unfortunately, converter transformers are often of the monophase type, depending on price, transportation problems, and the desire to have a spare unit. For instance, the transportation infrastructure in Western Europe will normally permit transportation of units up to 250-300 tonnes to be handled. For a rating per pole of 600 MW or greater, monophase transformers are the solution, while two three-phase transformers per pole are manageable for ratings up to about 500 MW. Three-phase, five-legged transformers have lower transportation height than three-legged ones.

Three-phase converter transformers need by no means, except transportation, be five-legged, because three-legged, three-phase transformers, less vulnerable to d.c. excitation, are quite possible. For instance, pole 2 of the Konti-Skan scheme, in operation since 1989, has three-phase, three-legged converter transformers.

Kimbark [2] (p. 438) indicates that a first indication of core saturation is the audible noise, starting when the d.c. current reaches 1,2 to 1,5 times the normal a.c. exciting current per phase. Kimbark's text must be interpreted as valid for mono-phase transformers, because it refers to transformer banks, understood as three monophase units per bank. E. Reiplinger [14] confirms that monophase units increase their sound pressure level by about 10 dB when the d.c. exciting component per phase equals the normal a.c. exciting current. A d.c. current of four times the a.c.

exciting current raises the sound pressure level by 20 dB. It is not stated by Kimbark or Reiplinger which level of d.c. excitation is dangerous for the transformers.

The magnitude of a.c. exciting current for modern transformers may easily be as low as 1‰ of the rated current, which for a 600 MVA unit or bank connected to a 400 kV grid is slightly below 1 A.

Reactors with magnetic cores, for compensation purposes, are not at all exposed to d.c. saturation, because the gaps in the magnetic circuit prevent the reactor from achieving any significant constant flux. This statement is valid whether the reactors are monophase or three-phase, with three- or five-legged cores.

When analysing the possibility of saturation, the grid composition is usually much more complicated than shown in Appendix 3. A detailed resistance network containing the different stations, the mutual interconnection between stations and the resistance in transformers must be set up, and the flow in the different branches calculated. Generally speaking, the problem of saturation is not very serious for the huge number of small grid transformers (<200 MVA), because they are normally three-phase, three-legged. Attention will be drawn to large monophase units and to large three-phase units, which are often five-legged to reduce height in order to facilitate transportation.

New Zealand has published information on a serious case of saturation due to ground current from the southern electrode station Bog Roy. The converter station Benmore is situated only 8 km from the electrode station. Combined with the fact that Bog Roy has unfavourable underground resistance conditions, a current of the new 2 000 A rating will produce a voltage in Benmore of 84,4 V and less, but still considerable, voltage on other substations on southern New Zealand. The problem has been solved by introducing resistances in the transformer neutrals, not only in the Benmore converter station, but in eight South Island substations and two North Island substations.

Although the problems were serious and the solution extensive, it was found less attractive to solve the problems by moving the electrode to the coast of the ocean, being about 100 km from the present electrode station Bog Roy.

In conclusion, it is not the distance between the substation and the electrode station, but the voltage difference between the respective earthing grids of the substations that counts. If this voltage is quite low, say, <1 V (which is the case for Danish electrode stations), there is no danger, while voltages >10 V are doubtful. Voltages in the range 30-100 V must be expected to necessitate the installation of current-reducing equipment in the transformer neutrals, if these transformers are monophase or three-phase, five-legged.

DC excitation of power transformers caused by geomagnetically induced currents is a well-known phenomenon. In [18] more information is given about the consequences for transformers when affected by d.c. currents.

4.4 Reduction of impact due to polarization

4.4.1 Polarization on non-insulated metallic objects

The viewpoints and methods to calculate the impact of an HVDC ground current field are discussed in 4.1. When a metallic object picks up/discharges current, cathodic and anodic zones arise. Under the influence of the current polarization (a counter-electromotive force) is formed on the surface against the surrounding soil. The following example is a test which has been performed in Finland.

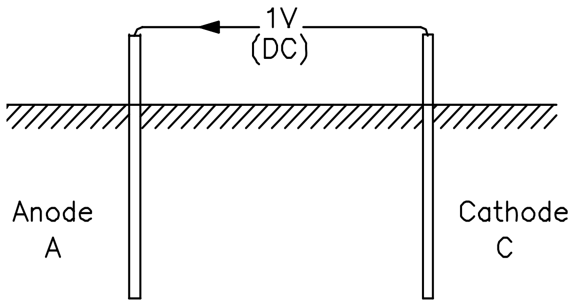


Figure 4.4.1a

Two copper rods are placed in a clayey soil and a voltage of 1 V impressed. The current is 1,75 mA. Measurement by means of a Cu-$CuSO_4$ half-cell indicates the following voltage drops:

– 0,17 V between the anode and the soil close to the rod;
– 0,68 V between the cathode and the soil close to the rod;
– 0,15 V voltage drop in the soil from A to C.

The counter electromotive force is 85 % of the totally impressed voltage, and it consists of two unequally sized polarizations, 17 % on the anode and 68 % on the cathode.

If polarization did not arise, the earth resistance from A to C $\left(\frac{0{,}15\text{ V}}{0{,}0017\text{ A}} = 85{,}7\,\Omega\right)$ would result in a current of $\frac{1\text{ V}}{85{,}7\,\Omega} = 11{,}7\text{ mA}$.

In this test, polarization has reduced the current by a factor of 6,7.

In the test, the metallic object was divided into two rods, but polarization also comes up when the metallic objects consist of only one piece located in a field.

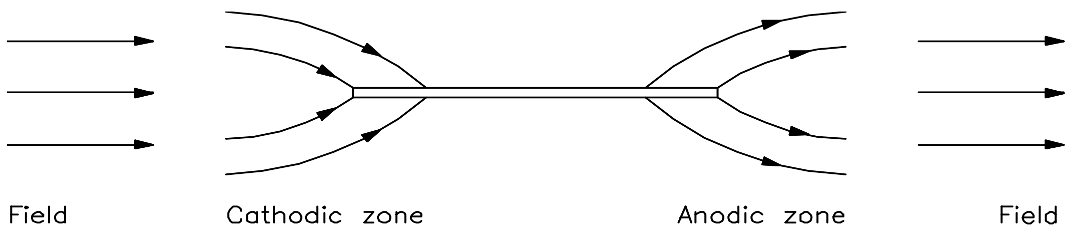


Figure 4.4.1b

The polarization will arise in this example, too, resulting in a reduction factor of the picked up/discharged current which will depend on the circumstances.

Because polarization is the sum of two electromotive forces (cathodic and anodic) arising in one galvanic cell, the sum of the polarization voltages can hardly be much greater than a saturated value of about 2 V. This means that polarization has a great influence if the external field voltage across the metallic object is smaller than the possible saturated polarization, but has less importance if the external voltage across the object is much greater than 2 V.

A research project carried out in 1996 by two students at the technical college of Aarhus, Denmark, as part of their graduate thesis included some research on polarization.

Measurements were taken on two interconnected rods of the same metal (Cu) located in a field created by two major electrodes. The curve on Figure 4.4.1c gives the effect of the polarization, expressed as a reduction factor of the current, as explained for Figure 4.4.1a.

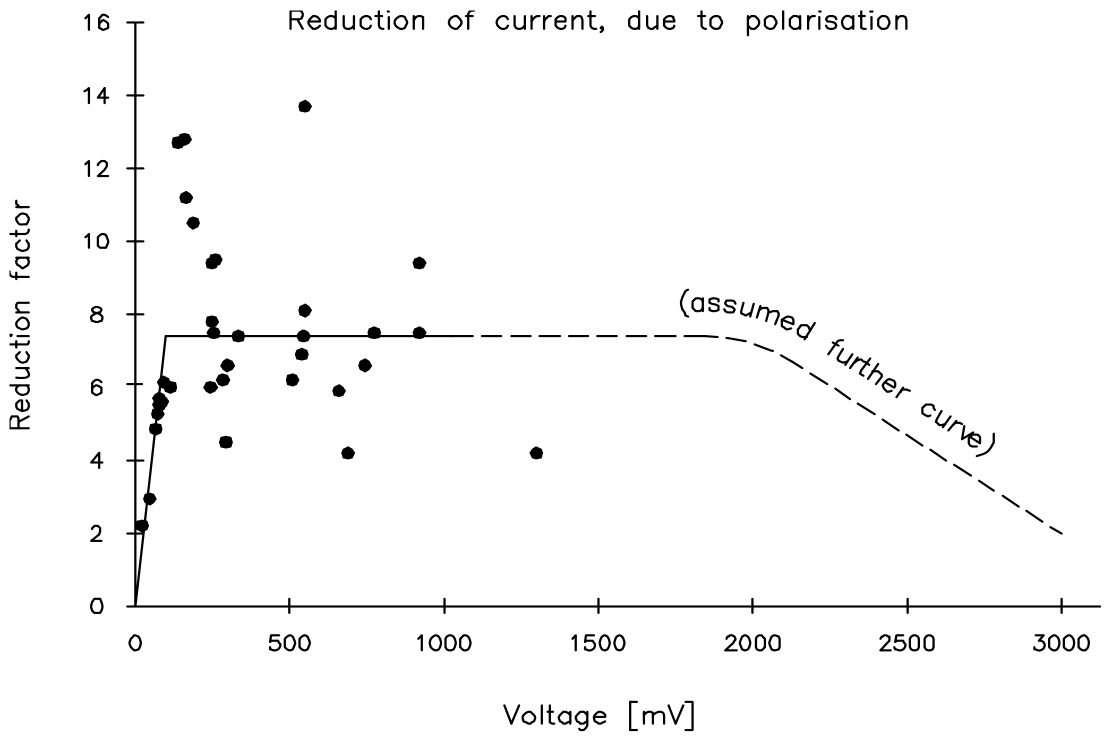


Figure 4.4.1c

For external voltages of 0-100 mV, the reduction factor due to polarization increases from 0 to about 7,4. This value, as an average of several tests, is kept constant up to external voltages of 1 V.

Although more research might be appropriate, it is suggested that the polarization reduction factor for corrosion currents on bare metallic objects has a general value of 5.

This reduction factor should not be used when judging corrosion danger on submarine cables and possible other metallic objects where the stray current is picked up/discharged in water. The formation of a thin "polarized" layer, which means a layer changed towards an acid or basic state, seems possible if the chemical-infected layer is not washed away by streaming water. This is the case for polarization in soil, especially clay, because the ground water moves very slowly. In open sea water the polarized layer cannot remain stable on the surface of the submarine object. For that reason no correction for polarization of corrosion should be made for submarine items.

4.4.2 Polarization on insulated metallic objects

The viewpoints and methods for insulated objects are given in 4.2. The objects are normally equipped with devices for cathodic protection, giving an intended polarization voltage. Because the external field does not cause a pick-up or a discharge of currents, the discussion of polarization caused by the external field is not relevant to insulated, cathodic protected objects, except if the cathodic protection setup is out of order.

4.4.3 Reduction of star-point currents due to polarization

As appears from Appendix 3, the ground mats of substations A and B pick up/discharge current. The contact area of the metallic ground mat (copper or steel) against the soil can have an area of 20-200 m^2 or even more for very extended substations. Polarization comes up on all substations to a mutually balanced degree that in a steady state reduces the currents flowing between all interconnected stations. It must be expected that the reduction factor may reach a level of 5 or more, as described above.

There remains the question of how much time is needed to build up polarization. It is a well-known fact that it takes hours to charge a battery. If the driving electro-motoric force is much greater than

1-2 V, as in the case of New Zealand, the polarization will reach a saturated value of, say, 2 V, which, by the way, does not reduce the expected currents considerably, because the impressed potentials were much greater than 2 V.

If the voltage difference between the ground mats of two substations is considerably lower than 2 V, the created polarization seems to come up about simultaneously with the variation of external potentials. This means that by rapid changes of current in the HVDC main circuit, for instance, reversal of the current, the polarization, if considerably smaller than 2 V, will change direction equally rapidly. In a research project with the purpose of measuring the field, the current in the electrode station for the Skagerrak scheme was changed repeatedly from +1 000 A to -1 000 A and vice versa within about 100 s (~20 A/s). The external voltage on the ground grid of the converter station Tjele being about 0,105 V per 1 000 A thus changed from +0,105 V to -0,105 V (2,1 mV/s). The main 400/170 kV transformer of the substation was expected to react slightly, by noise variations, but absolutely no interference was detectable. Although not proved by direct measurements, the explanation is believed to be that the counteracting polarization achieves to come up in time. As a final conclusion, it seems that polarization, which represents only a fraction (say 10 %) of a saturated value (= about 2 V), comes up with a speed of 2 mV/s or faster.

5 Compass errors

Compass errors come up due to the magnetic field from the direct current in the main cable **and** in the electrode cable. The magnitude of the magnetic field from a current of 1 000 A corresponds to the natural magnetic field of the Earth for a distance of 12 m. It is not the intention to include formulas and methods for calculation of magnetic deflections; it should be fairly easy for a skilled engineer to demonstrate the action of the magnetic field for a specific case of data. In [19] compass errors are further described.

The magnetic field is not related to the electrode itself, but consideration to compass errors may exert great influence on the possibility of using ground return. The classical example is the cross-channel HVDC scheme, where the solution to satisfy the demand of very little compass errors in the Channel has excluded the use of electrode stations. In the Baltic Cable and the Kontek scheme the German naval authorities demanded that the entrance to harbours (Travemünde and Warnemünde) should have limited compass errors. For both schemes this has necessitated that the electrode cable be laid parallel close to the main cable (~2.5 m) for a considerable distance (22 km for the Baltic Cable). When the electrode cable is finally deviated from the route of the main cable, it follows a route about perpendicular to the main cable, in order to achieve, with the shortest cable length, a sufficient distance from the main cable to the electrode station (see 4.1).

This arrangement, which clearly implies a monopolar stage, is not easy to develop to a future bipolar stage. Complete compliance with the original conditions would require the second main cable should be laid equally close to the existing cables, which is only possible if it is located between the two cables. This is, of course, a very unpleasant solution taking possible repairs into consideration. Furthermore, there is the problem of changing an electrode for cathodic operation only to a reversible electrode.

Although compass errors seem only slightly connected with electrode stations, the compliance with certain conditions may have a great impact on possible solutions. If discussions with naval authorities are likely to arise, it seems worth while to take action on this problem as early as possible in the planning process.

6 Types of electrode stations

The summary of existing electrode stations, covering 48 installations, includes the following types.

Land electrodes, reversible	28	stations
Shore electrodes, reversible	9	stations
Shore electrodes, anodic	1	station
Sea electrodes, reversible	3	stations
Sea electrodes, anodic	3	stations
Sea electrodes, cathodic	4	stations
	48	stations

The dominant number of land electrodes indicates that a majority of converter stations are located far from a salt-water coast. The investigated land electrodes are all connected to bipolar schemes, which makes it necessary to have reversible electrodes, but the use of the electrodes is mainly limited to small balancing currents.

Shore electrodes are defined as installations located on the shore to salt water. They may be divided into two subtypes: beach electrodes located 10-50 m inside the waterline, and pond electrodes, located in a sea-water-filled pond, protected by a breakwater against the sea.

Sea electrodes are located more than 100 m outside the coast line, at water depths which may range from about 5 m to more than 30 m.

Shore and sea electrodes are generally advantageous compared to land electrodes for the following reasons.

a) The field can be calculated in the design phase at more reliable values, because main parameters such as water resistivity and bathymetric conditions are known with great accuracy.

b) The risk of excessive temperature rise and of drying of soil due to heating or osmosis is practically eliminated.

Considering the possible site of the electrode station for a new HVDC scheme, there will be a genuine choice between a land electrode and a shore/sea electrode, if the converter station is about 100 km from the coast. At considerably greater distance, say, 200 km or more, the solution will turn in favour of the land electrode solution. Distances below 50 km to the sea favour shore or sea electrodes. These distances depend on the cost and loss evaluation of the electrode line.

The choice between shore and sea location depends on local circumstances.

For the case of a pure cathode produced by means of bare copper conductors, a sea electrode will be inexpensive and uncomplicated; but this type of electrode cannot be used for reversible operation at a later stage.

In the case of an anodic or reversible electrode, it has been shown in 3.3 that a sea electrode does not have lower voltages or gradients than a shore electrode when it comes to distances 10-20 km from the electrode. If it is possible to find a sufficiently "deserted" stretch of coast, then the shore possibility should be considered carefully. However, if the coast is "rocky" with cambrian and precambrian strata right up to the surface (resistivity about 5 000 Ωm or greater), then a shore station, even built as a pond type, will be difficult due to high gradients. If, on the other hand, the underground at the intended electrode site consists of quaternary, tertiary, cretaceous or jurassic strata, with expected resistivities of about 100 Ωm or less, to great depths, then a shore electrode built on the beach is likely to be quite feasible, at a lower price than a reversible or anodic sea electrode.

7 Design aspects for land electrodes

7.1 General

As already described previously, it is only justified to investigate the feasibility of a chosen site if the distant field has been, or is expected to be, accepted by environmental authorities, owners of metallic infrastructure, etc. Once a possible site has been selected, the station should be constructed in such a way that its current-carrying capacity matches the chosen rated currents of the HVDC scheme, taking into account possible operation with elevated currents or reductions of accumulated A · h due to agreed limitation of duty.

From the investigation of the expected distant field, the overall resistivities of the subsoil, as seen from the site, should be known. A further, more detailed, measurement on the site of resistivities as seen from the surface must be performed, using for instance an instrument according to the established Wenner method. The resistivity for different depths shows the stratification of the subsoil. The value of resistivities for different depths gives an indication of whether the electrode might be buried close to the surface, or made as a deep-hole, vertical electrode, possibly as a parallel connection of a number of subelectrodes.

7.2 Heating of soil

Following the viewpoints of Rusck and of Kimbark, heating of the soil close to the electrode surface is the first quantity to take into consideration.

The common assumption is that the soil temperature must be limited to the boiling point of water. A remark connected to the intermountain HVDC scheme draws attention to the fact that the boiling temperature decreases with altitude and that a corresponding correction of the limit for temperature must be made. On the other hand, if the electrode is deep below the surface and there is a water column above the active part, then the boiling point increases, for instance, to 121 °C, if a water column of 10 m exists between the active part of the electrode and the surface.

Rusck and Kimbark both deduced the formula which connects the potential field created by the current with the temperature field created by the flow of heat. According to Rusck, the formula was derived by Ollendorf.

The formula says

where

V_0 is the potential of the electrode, in V;

λ is the heat conductivity of the soil, in W/m · °C or W/m · K;

ρ is the resistivity of the soil, in $\Omega \cdot$ m;

θ_{max} is the temperature rise of the electrode surface, in °C.

The validity of this formula rests on the assumption that the soil is uniform in all directions (semisphere field!) both for electric resistivity and heat conductivity to remote earth. This is certainly never correct, but the adopted practice is to use values for the soil parameters close to the surface of the electrode. The relation expressed in the formula is independent of the geometric shape of the electrode. Further it is assumed theoretically that in the same way as current is not exchanged with the semisphere above the surface of the earth (the atmosphere), then also the heat is not dissipated through the boundary soil/atmosphere. On these assumptions the electric field and the temperature field have the same geometric structure, but the electric potential decreases faster than the temperature. At a point where the voltage is 50 % of V_o, the temperature (rise) is 75 % of θ_{max}.

In order to have the best possible foundation for the calculations, it is recommended that important parameters (electric resistivity, heat conductivity, moisture content, natural soil temperature, precipitation, etc.) be monitored throughout a complete year to get information on seasonal variations. Of course, it must also be considered, if the period for the measurements has a normal or an abnormal character of, for instance, meteorological circumstances.

As said above, the formula for temperature rise is independent of the geometric shape of the electrode. In the following we adopt a sphere (not a semisphere) totally buried in the ground as a mathematical model of an electrode.

The formula for θ_{max} can be changed to the following, valid for a sphere of radius r, buried at great depth:

$$\theta_{max} = I^2 \cdot \left(\frac{\rho}{4\pi \cdot r}\right)^2 \cdot \frac{1}{2 \cdot \lambda \cdot \rho} = 0{,}00317 \cdot \frac{I^2}{r^2} \cdot \frac{\rho}{\lambda}$$

If the sphere is only buried at a depth $h = 2r$ to the centre of the sphere, the result is

$$\theta_{max} = I^2 \cdot \left(\frac{\rho}{4\pi \cdot r}\left(\frac{1}{r} + \frac{1}{2 \cdot h}\right)\right)^2 \cdot \frac{1}{2\lambda \cdot \rho} = 0{,}00495 \; \frac{I^2}{r^2} \cdot \frac{\rho}{\lambda} \qquad h = 2r$$

Thus, the temperature rise is proportional to I^2, the square of current, and inversely proportional to r^2.

Further, the temperature rise is proportional to electric resistivity (Ω · m) and inversely proportional to heat conductivity (W/m · °C) (or proportional to heat resistivity (°C · m/W).

Theoretically, the sphere buried only 2 · r below the surface will have a temperature rise which is 1,56 times greater than the deeply buried sphere. It can be calculated that the potential on the soil surface above the sphere buried 2 · r from the surface is 80 % of the potential on the sphere. The temperature just above the sphere has dropped, theoretically, to 96 % of θ_{max}. However, the assumption of no heat exchange through the boundary soil/atmosphere is much too theoretical for electrodes buried some few metres below surface, since a heated soil surface must exchange heat by convection and by radiation with the atmosphere. See Appendix 4 for a numerical example.

If the information collected for different land electrodes is used for a "schematic" calculation of temperature rise, rather astonishing results are achieved (see Appendix 5). Very few electrodes seem to "respect" for instance 75 °C of a final temperature rise. Results of several hundred °C or even 2 000-3 000 °C temperature rise are calculated. No doubt, some of the odd results come out due to misunderstandings. The results of 1 000-3 000 °C indicate that these electrodes are not able to carry the rating continuously but function quite well when used for short-time duty. Results of several hundred °C indicate that the theoretical formulas exaggerate realities.

It is suggested that the formulas and viewpoints for designing temperature rise are used with a substantial correction factor. The value 5 is suggested for continuous duty, understood as follows: if the aim is to arrive at 75 °C as the final temperature rise, use 375 °C to calculate the allowable potential to remote earth. Especially for extended land electrodes of small burial depth (<3 m), the dissipation of heat to the atmosphere indicates a high correction factor. For deeply buried electrodes (50-500 m), a smaller factor than 5, but still greater than 1, could be considered. If no correction is made to the theoretical formula, then the electrode station will be more extensive and at unnecessarily high costs.

7.3 Moisture content of soil/electric osmosis

The summary of existing electrodes [0] shows a moisture content ranging from 2,1 % to 37,7 % of dry weight and, for some electrodes, "saturated" is indicated. The Indian stations Chapki and Dankaur have arrangements for adding water to the electrodes in case of very dry soil, which is possible due to a very high air temperature (50 °C). An electrode cannot be located in very dry environments, such as hard rock or dry sand. On the other hand, it is hardly possible to locate an electrode in a fresh-water lake, like a sea electrode, because gradients against the surface at an electrode in fresh water easily reach values of 100-200 V/m, which is widely above any tolerance for fish. If we aim for a current density of 1 A/m^2 in a buried land electrode, this corresponds to a gradient of 100 V/m for a soil resistivity of 100 Ω · m.

According to [3], the current density on the surface of the electrode must be limited to 1 A/m^2 in order to avoid electro-osmosis (moving of water by the electric current). By the Rice Flats electrode (Pacific Intertie) 0,5 A/m^2 has been used as a design value. In the CU-project 2 A/m^2 is found suitable if water is present.

Extended land electrodes buried close to the surface should preferably be placed in a flat terrain, with about equal height down to ground water level. The active part of the electrode must be buried at a depth below the ground water level. If possible, the configuration of the electrode should be selected and located in such a way that natural precipitation is utilized to increase the humidity around the electrode.

In the Danish shore electrodes, which are related to land electrodes in their construction, about 5-8 A/m^2 is used, the preserve of water being secured by the location close to the sea, below the water level of the sea.

7.4 Material for land electrodes

7.4.1 Inner conductor

All land electrodes investigated in the summary use an inner conductor, surrounded by coke or graphite powder, to give the contact to the soil.

Three materials which are all suitable for reversible operation dominate as far as the inner conductor is concerned.

a) Steel or "mild" steel rods or tubes, 30-40 mm in diameter. There is some evidence that rather dry conditions must be preferred, because water saturation in the coke surrounding the conductor may involve increasing the risk of metal corrosion. The steel conductor is mostly covering the length of the electrode continuously.
b) SiCrFe rods, commonly 45 mm in diameter, 1,25-1,75 m in length. These electrode bars are normally only partly covering the total length of the coke filling, 30-50 %, which means that the coke column is used also for longitudinal flow of current. There is a certain risk of an unequal current density on the outside of the coke filling.
c) Graphite rods, commonly 100 mm in diameter, 1,2-2,4 in length. With regard to the SiCrFe rods, the graphite rods only cover part of the length or depth covered by the coke.

7.4.2 Coke or graphite powder filling

All known land electrodes use a carbon-containing material as conducting backfill.

Three types of carbon material are mentioned as follows.

a) Coke breeze which EPRI describes as a small particle solid residue left by the cracking process of petroleum refining.
b) Coke which is the result of distillation of bituminous "raw" coal.
c) In one electrode station, the carbon material is described as graphite powder emulsion.

Based on information from the Indian HVDC scheme Rihand-Delhi and from Scandinavian HVDC schemes, it seems likely that there is a large difference between

– coke breeze; and
– coke.

Coke breeze has a density of about 1,6 and a bulk weight of about 950 kg/m^3, while coke has a density of about 1,0 and a bulk weight of about 460-500 kg/m^3. Coke looks shiny and has a high degree of porosity. Coke breeze is assumed to be a much tighter (less porous) substance, because the higher density of coke breeze indicates less porosity. For the purposes of comparison, the density of graphite is 2,1 according to the "Handbuch des Kathodischen Korrosionsschutzes".

The above-mentioned porosity refers to internal cavities in each piece of coke. However, the term porosity could mean also the cavities between the pieces of coke.

The preferred grain size of coke varies from 5 mm to 22,5 mm, dominated by coke breeze originating from petroleum cracking, and from 20 mm to 60 mm, dominated by coke originating from distillation of bituminous coal.

The resistivity of coke is very much dependent on compression. Because it is strongly recommended to compress the coke column to at least 1 000 kg/m^2 (10 kN/m^2) in the electrode construction, the requested resistivity should be specified for a pressure of for instance 10 kN/m^2 . If the supplier of the coke is unable to give this information, the consumer should ask for samples of 0,05-0,1 m^3 and have the samples measured.

An acceptance limit of 0,05 $\Omega \cdot$ m at 10 kN/m^2 is suggested. Some qualities of coke, especially coke breeze, may have a resistivity of 0,02 $\Omega \cdot$ m or lower.

Raising the compression to 20 kN/m^2 lowers the resistivity by about 30 %. It is assumed that coke can be used at considerably greater compressions, 200-400 kN/m^2, which must be the case for about 100 m deep electrodes due to natural pressure increasing with depth.

For chemical composition EPRI has the following specification:

Carbon	≥	92 %
Sulphur	≤	1 %
Volatile	≤	0.2 %
Ash	≤	1 %
Other minerals		0,5 %

For the New Zealand scheme a less severe specification was given:

Carbon	>	75 %
Sulphur	<	0,4 %
Volatile	<	3 %
Ash	<	20 %

It is recommended that the customer adjust his specification according to local market possibilities, but it must be preferred to have final acceptance values closer to the EPRI than to the NZ specification. Further, the customer has to consider if his local market conditions favour coke breeze or coke.

The EPRI report strongly recommends that the purchased coke be packed, transported and landed on site in such a way that no dirt (soil) can mix with the coke. The recommendation is easily understood, because the conduction of current through the coke pile is due to the numerous contact points between the individual pieces of coke. This function might be disturbed if particles of (insulating) sand mix with the coke. However, it must be remembered that the outside of the coke pile is deliberately given a contact with the surrounding soil. A certain "contamination" of the coke against soil is thus inevitable. If something should be done, it might be upward against the soil backfill. A vertical flow of water from precipitation will draw soil particles down in the coke, which acts like a drain. A cover of semisoft fibre glass or for instance PVC-plate will protect the coke, and this construction also eases a clean-up of backfill soil, if the coke trench is opened for inspection at some later occasion. The dissipation of current upwards will be blocked, too, but this might be an advantage in order to reduce step voltages above the electrode. Of course the efficiency of the electrode is slightly decreased, if the upper side of the coke pile cannot conduct current. If dirt protection of the coke is still wanted, but blocking of the current is unwanted, then the covering can be made of a woven material ("geotextile"). "Carpet" materials of this kind are well known in drainage systems, for road building, pavements, etc. Geotextiles could be used also against the side walls and the bottom of a prepared trench, but it might be worth while to investigate that the blocking of the current passage is of no importance. When coke (not coke breeze) is poured into a prepared (horizontal) trench, it must be remembered that this material, with a density close to 1,0, floats partly in water. For that reason the trench, or a suitable piece of the total length, must be drained of water, also because after having reached half of the total thickness of coke, the inner conductor must be installed.

When a vertical subelectrode is prepared, it will certainly be necessary to have a provisional tube of, for instance, steel in the drilled borehole, to prevent collapse of the hole. In a coordinated procedure the inner conductor(s) must be installed, securing their correct positioning, the coke must be filled in and the tube drawn up successively.

7.5 Geometric layout of the electrode

7.5.1 Horizontal arrangements

A horizontal electrode may be shaped in many different configurations (see Appendix 6 for examples).

The lines in the configurations are trenches in which coke beds of a certain cross-section, for instance 0,6 × 0,6 m, are buried at a certain depth, for instance, 2 m.

The choice of the geometric layout must depend on the limitations of the site area. An area equally wide in all directions calls for ring- or star-configurations, while a long-shaped area calls for a linear solution, maybe with more parallel lines in the configuration.

The layout consisting of one ring has the advantage of being symmetric, which makes it easy to obtain equal current density, all along the electrode circumference, if the resistance condition does not vary in the area covered by the ring. Other configurations, linear, stars double rings, do not have the advantage of equal current density. Generally, the current density is greater on parts of the electrode which are outstanding or exposed against the surrounding landscape. Ends of lines in a linear electrode or ends of arms in stars thus have a higher current density.

Continuous electrode trenches may be configured in the following two ways.

a) The coke string and the inner conductor cover the total length of the trench without interruption.
b) The coke string is uninterrupted, but the inner conductor consists of shorter individual pieces, for instance graphite rods covering, say, 40 % of the length of the coke string.

Coke trenches can be made deliberately non-continuous, that is, both the inner conductor and the coke string are interrupted at certain points. The purpose of these interruptions is to arrange a clear subdivision of the total electrode. See Appendix 6 for examples. The interruptions of the trench can be made, of course, as non-excavated interstices, but there is also the possibility of placing a transverse insulating plate somewhat larger than the coke section in a continuously excavated trench.

The inner conductor must be connected to a common feed point, which might be a busbar terminating the electrode line. In a ring configuration, the inner conductor, even if continuous, must be connected to the "busbar" at more points (2-8) equally spaced around the circumference. Equal lengths of the connection cables and equal angles between them make the best possible equilibrium of current sharing. However, this point is not very important, since the resistance of the feeding cable and inner conductors is of the magnitude of 0,1-1 mΩ/m while the resistance of a coke string to surrounding soil is of the magnitude of 100 Ω/m of trench. For that reason, voltage drops along a continuous inner conductor are normally not taken into account in calculations.

While ring electrodes in homogeneous earth have equal current density, this is certainly not the case for electrodes with extremities, such as linear or star types. The linear electrode consisting of one line has, on the assumption of equal voltage along the inner conductor, the following current sharing per unit length (the length given in %):

Average 0-100 % length	$n \cdot$ 1,00 A/m (average)
50 % point (midpoint)	$n \cdot$ 0,92 A/m (minimum)
25 % and 75 % points	$n \cdot$ 0,95 A/m
13 % and 87 % points	$n \cdot$ 1,00 A/m
5 % and 95 % points	$n \cdot$ 1,12 A/m
0-1 % and 99-100 % of length	$n \cdot$ 1,81 A/m (maximum)

(Reference: The computer program "CYMGRD", version 2.33 for Windows).

STRI gives 1,6 as the quotient between average and maximum current density and also has further examples.

A method to reduce this imbalance might be to divide the linear electrode into, for instance, ten parts, each fed by separate cables, and then insert resistors to the extreme parts at both ends. Resistors may also be used generally, if certain subelectrodes take too much current due to low local resistivities.

The step voltage, as discussed in 7.6, will not be raised by the increased current, caused by local low resistivity of the soil. But this is not the normal case at the end of the linear electrode, which means that step voltages are increased relative to average values at extreme points. Subclause 7.6 gives an example from New Zealand of what can be done.

Having selected a configuration, it should also be considered what to do if a future demand for an extension should arise. Any extension might be caused by later uprating, or simply if commissioning tests on a finished electrode show unfavourable results.

As a general rule, it will be difficult to arrive at the same current density in the new parts. If the new parts are located closed in or completely surrounded by the existing part, the current density of the new parts are lower (by the same cross-section of trench). If, however, the new parts are extremities to the existing configuration, then the new parts get an increased, and the existing parts a decreased, current density. Example: if a single ring electrode is extended with a new inner ring, then a diameter of about 80 % is preferable to obtain the lowest possible combined resistance to remote earth, but the inner ring will have less current density than the outer. Making the optimal electrode configuration is often a question of priority. What should the designer aim for with a given consumption of materials and labour:

a) the lowest possible losses (lowest possible resistance)?

b) the best possible current sharing among elements?

c) the lowest possible step voltages?

Of course, the shape of the intended site plays a dominant role in the final solution.

Taking the recent ease of carrying out computer calculations into account, several contradicting ideas should be tested against each other. Very often the solution giving the lowest resistance at the same time represents a not optimal current sharing, etc. Both in calculations, but also in the actual solution, a division into elements, subelectrodes, must be made. Elements taking a small share should be given more free space by adjusting the internal distances between elements. In a star configuration, the elements close to the centre tend to screen each other and the proper solution might be to remove a certain central part of each star arm and bridge the empty holes with the connection cables, which must be there in any case.

If an electrode is subdivided into elements (subelectrodes), it is a good idea to connect each element with its separate cable to the feeding point, the busbar. The current to each element may then be controlled, continuously or at certain intervals. By deviation from a normal distribution, normally in such a way that an element is carrying less or no current, the element can be disconnected for inspection/repair. It is advisable to subdivide the total electrode to the extent that the remaining elements are able to carry the total current, at least for some time, when one or more elements are disconnected.

7.5.2 Vertical arrangements

Some of the existing land electrodes are arranged as a number of vertical subelectrodes, with depths of more than 100 m. The vertical elements normally consist of a column of coke/coke breeze, with an inner conductor, which most often is divided into pieces.

As for the horizontal arrangement, the designer has to select a pattern in which to place the wells. If the wells are arranged along a circle, it will be easier to obtain equilibrium in current division, assuming equal resistivity conditions for all wells. If the pattern deviates from a circle, the mutual influence among the individual electrodes and thus the current division may be calculated. As for horizontal arrangements, each subelectrode should be connected separately to the busbar. If the inner conductor in each well consists of several subelements, each of these could be connected separately.

A vertical arrangement may be preferable if a better conducting stratum is present at some depth. Generally, vertical arrangements need less space on the surface. Normally, also the step voltage on the surface is decreased by vertical arrangements, compared to horizontal arrangements.

7.6 Step voltage

Step voltages are voltage differences across a short distance, a step, which depends on whether we talk of humans or animals. Kimbark deduced the conventionally used formulas for man (step distance 1 m) and for large animals, cows or horses (step distance 2 m).

Tolerable gradients in V/m:	$5 + 0{,}03 \cdot \rho_s$	(annoyance threshold for man)
	$11 + 0{,}24\ \rho_s$	(recommended limit for large animals)

where ρ_s is the resistivity of the surface stratum.

These values are recommended as a design goal. The value for humans is, as said, an annoyance threshold, the danger limit is somewhat higher.

Kimbark gives a simple formula for the expected gradient above a coke-filled trench, buried h m below the surface. The maximum gradient occurs in a horizontal distance h from the midline of the trench and is

$$\left(\frac{dE}{dx}\right)_{\max} = \frac{I}{l} \cdot \frac{\rho}{2\pi \cdot h}$$ where $\frac{I}{l}$ is the current dissipated per metre of trench.

The summary of existing electrode stations [0] gives some examples of values of step voltage. At a Chinese electrode station, as a design criterion, half the value given by Kimbark was used, because the flooded area is used by bare-feet farmers (rice farming). From the land electrode Bog Roy in New Zealand it is mentioned that the outmost tip of star arms are buried to a greater depth to counteract the increased step voltages due to increased current density towards the end of an arm in the configuration.

If the step voltages are deemed to be intolerable, admission to the area can be restricted by fencing. Such restrictions should not prevent the staff supervising or maintaining the electrode station to enter the area, because these people, of course, are instructed and specially dressed, if necessary.

7.7 Touch voltage

Touch voltage is defined as the voltage between the soil surface and any possible object (conducting, metallic) which might be touched by a person standing close to the object. The classic example is the fence which, deliberately or not, gets earth contact at one point, and carries the potential to another point of different surface potential. The recommended limit is the same as for step voltages.

Fences showing touch voltages may be divided into mutually insulated parts by means of wooden constructions, or if they have extended horizontal wires, by inserting small insulators ("antenna eggs"). A special problem may arise if the neighbouring areas to the electrode station are fenced with "electric wire", which carries a warning shock voltage over several kilometres of fence.

The busbar equipment is often placed within the area of the electrode, as described in a previous section. If these installations are housed in a cabin, the dimensions of the cabin may cover (or short-circuit) a greater potential difference than tolerated as step or touch voltage. Such problems can be counteracted by a coke cushion or a circumferential coke-filled trench, reaching about 1 m to 1,5 m outside the cabin and buried to a corresponding depth, 1 m to 1,5 m. The circumferential coke string may also have an inner conductor for complete short-circuiting of potential differences. A connection to this inner conductor can be used inside the cabin and on the cabin walls, if metallic, as safeguard earth.

Equipment in the cabin showing touch voltages deemed dangerous, for instance the busbar, must be handled in accordance with rules for low-voltage/medium-voltage a.c. installations.

8 Design aspects for sea electrodes

8.1 General

The summary of existing electrode stations includes three kinds of constructional modes:

a) sea electrodes using titanium as their active part (for anodic operation only);

b) sea electrodes using coke or SiFeCr-rods as their active part (for reversible operation);

c) sea electrodes using bare copper conductors as active part (for cathodic operation only).

The definition of a sea electrode is an electrode located away from the shoreline at a certain distance (>100 m). The current is transferred from the active part directly to the sea water. An exception to this general rule is the Norwegian electrode Grosøysøyla in the Skagerrak scheme, in which the current is transferred from subelectrodes embedded vertically in the seabed to surrounding deposits of clay/mud. An electrode intended for open contact with the sea water may, however, also partly be covered with sand or mud, although not intended.

When installing sea electrodes, cable laying vessels, marine cranes, diver assistance and equipment for precise navigation are needed, which generally makes sea electrodes expensive compared to shore electrodes. The cable system for connection to the coast must be included as a necessary further expense.

An electrode system which transfers the current direct to the sea water will not possess any heating problem, since heating of the water will create a vertical flow of water. Besides, there is always natural streaming of the sea water. All problems of osmosis and drying out are likewise impossible.

8.2 Sea electrodes using titanium as an active part (anodic operation)

The summary of existing electrodes includes three anodes of this kind:

a) the Fenno-Skan anode Dannebo;

b) the Baltic cable anode Smyge;

c) the Kontek anode Bøgeskov.

8.2.1 Material

The material is described as an expanded mesh of titanium, of which the filaments are about 0,5 mm × 2 mm, all interconnected in about 20 mm × 50 mm meshes. The titanium is covered by a special thin (5-20 µm) layer of metals, resistant to anodic corrosion.

The expanded network is delivered in subelectrodes each covering 1,22 m × 16,5 m = 20 m^2. On both sides of the network there is a system of polyethylene tubes for mechanical protection. The plastic tubes are placed with interspaces, leaving 33 % open area for the current. For transportation and handling purposes, one subelectrode can be rolled into a cylindrical coil of 1,22 m in length and about 0,8 m in diameter.

Apart from the polyethylene tubes the 800 m^2 electrode area for the Baltic cable is mechanically protected by a layer of natural stones as backfill. For the Kontek anode, which is 2 000 m^2, no backfill material is described, but an underlying construction of fibre concrete against the seabed is included.

8.2.2 Current density and gradients

The generally accepted limit for the gradient on an electrode surface, accessible to marine fauna and to humans, is 1,25 V/m. Since the gradient is the product of current density and resistivity, an electrode needs to increase in size, at decreasing salinity (= increasing resistivity).

The following text describes the Baltic cable electrode Smyge, which consists of 40 subelectrodes.

The surface area of the metal mesh is about 6 m^2 for one "rolled-out" subelectrode covering 20 m^2. This gives a current emitting area of 240 m^2 for 1 364 A, which equals about 6 A/m^2 falling to about 3 A/m^2 at a distance of 2 mm from each filament. The interstices between the protecting polyethylene tubes have a total area of about 550 m^2 reducing the current density to about 2,5 A/m^2. Because the resistivity is 0,8 Ωm this corresponds to 2 V/m which within the next 5 cm from the surface falls to about 0,7 V/m.

Compared to Danish research from 1984, small creatures such as crabs and seastars are able to move in a natural way across areas covered with current emitting holes above which the gradient was about 14 V/m. Three times this value was also tested as tolerable, but not recommended.
The titanium electrode system has the aim of reducing the evolution of chlorine in saline water. This is explained further in Clause 10.

To sum up, the close-on gradients around the Baltic cable anode are fully satisfactory, but the current density should not be raised substantially. The Dannebo electrode for Fenno-Skan has the same physical size, 800 m^2, but the water resistivity is 1,13 Ω compared to 0,8 Ωm for the Baltic cable. Gradients are correspondingly higher at the Dannebo electrode. The Kontek electrode, 2 000 m^2 also in sea water of about 0,8 Ωm, has gradients well below acceptance limits.

8.2.3 Geometric layout

As for the physical layout the three anodes are of the linear type but with the ends of the line curved approximately to half circles against the coast. This is to ensure the best possible current sharing among subelectrodes, because the influence of current density on the production of Cl_2 makes it important that all subelectrodes carry an equally low part of the current. Reference [10] gives a simple method of calculating current sharing among subelectrodes.

All three electrodes are placed in sites with a possible harsh winter climate. The depth of the sea water is 8 m or more.

8.3 Sea electrodes using coke or SiFeCr rods as active parts (reversible operation)

There are only three electrodes of this constructional type in the world:

a) the Risö electrode (Swedish end of Konti-Skan);

b) the Santa Monica electrode (LA end of Pacific Intertie);

c) the Grosøysøyla (Norwegian end of Skagerrak).

The three electrodes are widely different in construction and basic idea.

Risö has horizontal graphite/coke subelectrodes laid at the seabed and covered by concrete (originally sacs filled with ready-mixture, stacked over the internal subelectrode).

The Santa Monica electrode consists of subelectrodes, each built as a concrete box which contains two SiCrFe rods transmitting current directly to the water.

The Norwegian Grosøysøyla electrode consists of subelectrodes containing graphite and coke in a wooden container. The subelectrodes are placed vertically at the seabed.

8.3.1 Overheating risk

Concerning the danger of overheating, this is impossible for the Pacific Intertie electrode because of the suspension in open water. Also the Swedish electrode lies open enough for heat exchange. This is not the case for the Norwegian electrode, where a minor risk of overheating seems possible especially if the mud contains much organic matter which could start a fermentation process. In Denmark there has been a case of cables, placed about 1 m in mud at the seabed. The normal heat loss at expected rating ignited a heat-producing fermentation process. The cables got faults caused by high ambient temperatures and increased thermal resistivity.

If an electrode is buried at the seabed in "ordinary" soil such as sand or clay the necessary size to prevent overheating can be calculated following the viewpoints in 7.2 but the correction factor is suggested raised to 10 instead of 5 as suggested for land electrodes. Dry-out of electrodes buried in the seabed is considered unlikely.

8.3.2 Material for sea electrodes

The material graphite shaped as cylindrical rods will act well when used for direct transfer of current to the water. Some electrode stations classified as shore electrodes use this solution. Graphite rods generally have diameters in the range 0,1-0,125 m and lengths of 1,2-2,4 m. When used in the open sea, it is not practical to have constructions for suspension of the electrodes, but, on the other hand the rods must not be buried in, or even covered with, sea-bed deposits without intention, because then the electrodes will be dissolved rapidly.

A company producing graphite electrodes has suggested to construct large flat graphite electrodes, for instance, $1{,}2 \times 2{,}4$ m, to be placed on the sea-bed in direct contact with the water.

The recommended current density for free graphite electrodes is about 6-10 A/m^2 in order to ensure a suitable gradient of 1,25-2 V/m close to the electrode (at a sea-water resistivity of 0,2 Ωm).

If the graphite electrodes are functioning in an environment open to free water but closed to marine fauna, the current density can be raised to values of about 40-50 A/m^2.

Graphite performs excellently, both as anode and as cathode, and withstands reversals between these two conditions.

The Santa Monica station has rods of SiCrFe which presumably are working well. This is also the case for some shore electrodes of the pond type.

According to one source of information, the normal current density of SiCrFe rods is 25 A/m^2 and it is indicated that this material cannot withstand current reversals. This statement is, however, contradicted by facts: the Santa Monica electrode operates with a rated current density of 106 A/m^2 for the rated current 1 800 A and the electrode is reversible! The Santa Monica electrode has a strict limit of 14 h for the rated current 1 800 A, but 1 410 A (83 A/m^2) is indicated as a continuous current rating.

For current densities of 83-106 A/m^2 producing gradients of 16-21 V/m, it is absolutely mandatory to prevent fish, marine mammals and divers from getting into direct contact with the electrodes.

The combination graphite/coke is also a good choice for reversible sea electrodes. The relations between these two active materials are described earlier in this PAS under land electrodes. The recommended current density is 5-8 A/m^2 at the outer surface of the electrode in order to achieve gradients of 1,25-2 V/m close to the electrode in 0,25 Ωm sea water.

Appendix 7 presents a proposal for a sea electrode unit according to these principles.

8.3.3 Geometric layout of reversible sea electrodes

Geometric layout of reversible sea electrodes has the same possibilities as described in 7.5. The use of subelectrodes, separately connected to a cabin on the coast is a normal procedure. Efforts should be made to ensure an equal current division by a careful matrix calculation taking mutual influence between subelectrodes into account. At a fairly large distance from the coast the circular arrangement should be preferable.

8.4 Sea electrodes using bare copper conductors as active parts (cathodic operation only)

There are four electrodes of this kind:

– the Baltic Kathode1 electrode, German end of Baltic cable;

– the Pampriniemi electrode, Finnish end of Fenno-Skan;

– the Graal-Müritz electrode, German end of Kontek;

– the La Torraccia electrode, Italian mainland end of Sacoi.

Although less precious metals than copper also could be able to act as cathodes, copper **is** apparently **the** choice. A reason for this choice is the possibility of establishing reliable clamp connections by compression or by welding, which will withstand the environmental conditions of the sea water.

Table 8.4 gives a summary for these four cathodes of size, rated current, gradients and voltage drops to distances 0,01-0,1-1 and 2 m from the conductor surface.

Table 8.4

Electrode station		Baltic Kathode1	Pampriniemi	Graal-Müritz	La Torraccia
Copper cross-section	mm^2	300	300	400	300
Copper cable radius	mm	11,5	11,5	13,0	11,5
Total electrode length	M	5 620	4 500	5 100	600
Surface of copper	m^2	406	325	417	43,4
Efficiency of surface	%	50	50	50	50
Rated current	A	1 364	1 250	1 500	1 000
Current density	A/m^2	6,72	7,87	7,20	46,13
Water resistivity	$\Omega \cdot$ m	0,8	1,6	0,8	0,2
Gradient of surface	V/m	5,37	12,60	5,76	9.23
Voltage drop over 0,01 m	V	0,04	0,09	0,04	0,07
Voltage drop over 0,1 m	V	0,14	0,32	0,16	0,24
Voltage drop over 1 m	V	0,28	0,65	0,33	0,48
Voltage drop over 2 m	V	0,32	0,74	0,38	0,55

By the calculation of current density, gradients and voltage drops, it is assumed in Table 8.4 that the current is emitted equally round the upper half of the copper conductor. This is indicated as the efficiency of surface being 50 %. If the conductor is half-buried at the sea-bed, the resistivity in the downward direction may be 5-10 times the resistivity of the sea water. An efficiency of 50 % also demonstrates that only the 180° water sector carries the current, the conductivity of 180° of the sea-bed being neglected. The efficiency might be further decreased for instance due to heavy cover of sea-bed materials or chalk deposits.

The voltage drop in the first 0,01 m from the conductor describes the conditions for a very tiny organism about 1 cm in size. The voltage drops to 0.1 and 1 m distance describe the conditions for correspondingly large organisms like crabs, lobsters and fish. The voltage drop to 2 m is the model for a diver or a large marine mammal touching the conductor directly, short-circuiting 2 m of water with the body.

The Finnish electrode Pampriniemi has the largest gradients and voltage drops, because the sea water in this area is rather brackish, with about eight times less salinity than the Mediterranean Sea. The Italian electrode station La Torraccia has by far the highest current density. It is reported that diver inspection is used in Finland and Italy, and, for the Finnish station, it is stated that the diver touches the conductor without annoyance. As for the Italian station, it is reported that the layer of deposits grows fast especially on the first 60 m from the point of change from insulated to bare conductor. This fast growth must be due to the high current density. The deposit forming a very hard substance of Na_2O, CaO, MgO, Fe_2O_3 and SiO_2 plus H_2O and CO_2 is removed by a diver once a year. This is not an easy task due to the depth of 26-28 m.

It is concluded from the Finnish and Italian experiences and for the general lack of any bad experience of influence on marine life, that these four electrodes are all within safe limits of any danger. Danish research work, including video taping of marine creatures around a test electrode, has confirmed that 6 V/m is tolerable as a general gradient from a 1 m diameter electrode. Local but short ranged gradients about 40 V/m for a few cm were also observed as tolerable for small creatures such as crabs and starfish.

For sea electrodes the symbol "step voltage" is meaningfully defined as a voltage difference between any two points at the distance of "one step", normally 1 m. The symbol "gradient" is not identical with "step voltage" even if the unit is the same, V/m. The symbol "touch voltage" is not relevant to sea electrodes, because any sense of voltage when touching the active part direct depends on the size (length) of the person/animal and their orientation in the electric field.

It is suggested that electrodes of bare copper conductors should fulfil the following conditions: it is assumed that only the upper part of the conductor emits the current and that the seabed is neglected. This expresses 50 % efficiency compared to a conductor supposed to be surrounded by sea water in all directions.

The gradient on the conductor surface: Max. 15 V/m
The voltage drop over 1 m ("step voltage"): Max. 1 V/m

Kimbark suggests a gradient of 1,25 V/m, but it is understood as a step voltage covering a distance of 1 m. Close to conductors of 300 mm^2 to 400 mm^2 cross-section higher gradients are obviously present and acceptable.

To avoid heavy depositing of chalk, it is recommended that the current density on the conductor surface be limited to max. 10 A/m^2.

As for the geometric arrangement the Baltic cable and Kontek both use rings of 1 km in diameter. Apart from this, some chords (cross-connections) are added to ensure equal potential all along the total conductor. The Finnish electrode forms an oval. The Italian one consists of two linear electrodes each 300 in length, but the mutual distance is not indicated.

9 Design aspects for shore electrodes

9.1 General

As mentioned earlier in this PAS, shore electrodes may be divided into two groups:

a) beach electrodes;

b) pond electrodes.

Beach electrodes are located on the beach inside the waterline, and the active part of the electrode makes contact with the soil or with underground water but not direct with seawater. Pond electrodes have electrodes directly in contact with sea water, within a small area which most often is protected against waves and possible ice attacks by a breakwater. Either the breakwater or the bottom of the pond or both must be able to conduct current. If the breakwater is built of rocks or boulders which are assumed to be insulating, then the flow of current through the breakwater follows the waterfilled interstices.

Shore electrodes differ from sea electrodes in a practical but important way: they are (normally) accessible by cars and persons from land, which makes maintenance easy, while access to a sea electrode demands use of boats, cranes, divers, etc.

From a theoretical point of view, shore electrodes may be calculated with sufficient accuracy on the assumption that the contact to soil/sea is the shoreline itself. The calculation method is described by various authors (for example, Kimbark [2]). This method is much too simplified for sea electrodes where a certain distance from the coast and a certain depth of the water must be taken into account.

9.2 Beach electrode stations

This type resembles land electrodes very much and may in many aspects be treated as such.

As for the possible temperature rise, the formula

$$\theta_{\max} = \frac{V_0^2}{2\lambda \cdot \rho}$$

quoted in 7.2 is very doubtful concerning shore electrodes. Firstly, the assumption that λ and ρ are both uniform to infinite distance as seen from the electrode is not fulfilled. One of the sector angles, the sea, has a low ρ about 0,2 Ω · m but an almost infinitely high λ, because the sea water is continuously exchanged with "new" unwarmed water. Because the soil in the electrode area is saturated with water close to the surface, the value of λ will be about 2,5 W/m · °C for soil and seabed.

The Danish beach electrode, Lovns, has a theoretical temperature rise according to the above formula of 209 °C, while practical measurements over half a year indicated that the steady-state temperature rise could be estimated to be 15-20 °C for continuous loading with rated current. The correction factor for land electrodes, suggested as a value of 5, should be higher for beach electrodes. The suggested value is 10 (see 7.2 for further explanation). Drying out of a beach station, including osmosis, is not likely if the electrodes are buried at a depth greater than the water level.

Coastal areas are often characterized by a layer of fresh water, rising to a higher level than the nearby sea and a deeper layer of salt water, penetrating from the sea (see Figure 9.2).

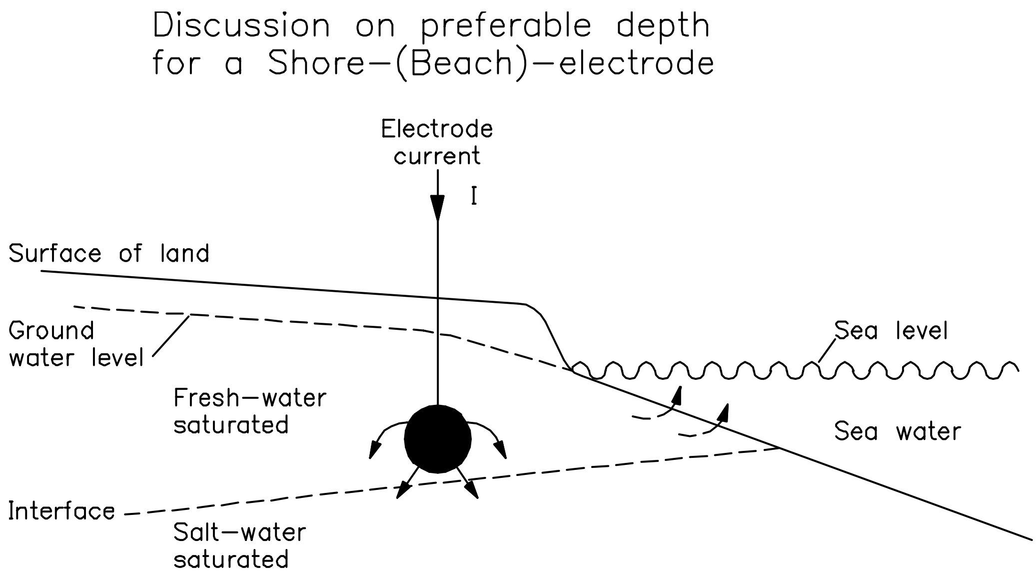


Figure 9.2

If a distinct interface between fresh water and saline water exists as shown in Figure 9.2, it might be discussed which depth is the best for the active part of an electrode station. If the current is emitted in the fresh water layer, there will be no evolution of chlorine by anodic operation but "only" evolution of oxygen. If the electrode is close to but still above the interface, the salt water layer will absorb the current almost 100 %, within a short horizontal distance. If low resistance to remote earth and decrease of loss are the goals, the electrodes should be placed in the saline strata, but some evolution of chlorine will be the result. As explained previously, it makes no difference to the field at some further distance whether the electrode is in the fresh water or in the saline water strata. For the two Danish beach stations it has been recognized that these electrodes are surrounded by fresh or very weak brackish ground water. This explains why chlorine cannot be detected by smell, even when opening a subelectrode for inspection.

If the beach electrode is located on a coast with a remarkable tide, efforts should be made to utilize low tide hours for constructional purpose, to get the station as deep down as possible.

Since the beach electrode resembles a land electrode, coke should be the natural choice of material.

As for the inner conductor, three materials are mentioned in 7.4 for land electrodes, but one of them, steel/mild steel, should be avoided by beach electrodes, because steel needs to have dry conditions in the contact zone steel/coke. In a proper beach electrode, the coke will be saturated with water. The remaining possibilities for material for the inner conductor are SiCrFe rods and graphite rods, as described in 7.4.1. At a new electrode station in the Philippines, silicon iron rods are used as the inner conductor.

The natural geometric layout of a beach electrode is the linear type, with a continuous trench, or a row of subelectrodes, parallel to the coast line. If the length of the available coast is limited, two or three parallel lines of electrodes may be needed. The problem of increased current density towards the ends of the line(s) will arise as described for land electrodes.

Beach electrodes may, like land electrodes, consist of vertical subelectrodes with a depth depending on the geological and constructional conditions.

If the total electrode is composed of a number of subelectrodes (which should be preferred), then two different "philosophies" should be considered.

a) The subelectrodes are placed with the point of view that they should be practically accessible for inspection/repair. This normally indicates a small depth of burial and generally horizontal subelectrodes.

b) The subelectrodes are placed inaccessibly with the idea that they are of a disposable (throwaway) type, which is left underground when damaged if they are too difficult to salvage. A new substitution electrode is arranged close to the damaged one. This philosophy is relevant to vertical electrodes, buried at large depths.

Whatever the electrode station is for permanent or disposable subelectrodes the total number of subelectrodes must exceed the necessary number by a certain percentage, 10 % or more depending on the number. The fault rate for individual subelectrodes is remarkably low, according to the summary [0]. As regards the previously mentioned new electrode station in the Philippines it has been decided to install two inner conductors in each vertical coke column to increase reliability.

The recommended current density on the surface of the coke is 7 A/m^2 for water-saturated beach electrodes, this value being deduced from the Danish experience.

Step voltages tend to be of a high level in beach stations, if the electrode is buried at a moderate depth. If it is preferred to avoid fencing, the total station must be made larger, or buried at a greater depth. If the station area is under risk of possible high tides, waves and/or hummoching ice, the fence will often be damaged.

Because of risk of damage to objects on the beach, a cabin (or open air installation) for the busbar and other equipment, could preferably be placed at some distance from the electrode area, on a safe level above sea surface. Distances of 600 m and 2 000 m cabin/electrode are used in Danish stations. The connecting cables between the busbar in the cabin and the subelectrodes, or subparts, should preferably be made as individual smaller cables, or mutually insulated subconductors in large cables. The extra (and equal) resistance in each subconductor will tend to equalize the current sharing among subelectrodes. Touch voltage may arise as a problem, as with land electrodes; see 7.7.

9.3 Pond electrode stations

There are six electrode stations of this type of shore electrode station:

– the Gotland scheme: Eknö and Massänge stations;
– the Haenam-Cheju scheme: Haenam and Cheju stations;
– the Sacoi scheme: Punta Tramontana (Sardinia);
– the Vancouver Island scheme: Sansum Narrows.

Pond electrodes are characterized by their location, on the shore, but with the current transmitted direct to the sea water. Normally, a closed breakwater protects the site and, at the same time, prevents the access of large marine life. The access of unauthorized persons is normally prevented by fence and signs. The following three subelectrode materials are used.

– Magnetite, Fe_3O_4 (Eknö and Massänge)
– Graphite rods (Haenam-Cheju and Sansum Narrows)
– Platinized titanium (Punta Tramontana)

Magnetite, Fe_3O_4, is commonly used for cathodic protection purposes. The substance is mined from geological ores, for instance, in Northern Sweden. The electrodes are produced in rod form, 0,06 m in diameter, 0,72 m in length, and other sizes as well. The specific resistance of magnetite is 5-10$\cdot$10^{-5} Ωm.

Platinized titanium is also well-known (as anodes) from the cathodic protection field. It is not stated whether this material can act as a cathode, but this is not relevant to the Sacoi scheme, which is monopolar, and always anodic in the Sardinian electrode.

The graphite electrodes in South Korea and in the Sansum Narrow station act as reversible electrodes.

By comparison with the Pacific Intertie sea electrode,Santa Monica, SiCrFe rods should also be a suitable material for a pond station.

The current densities used in the investigated stations are as follows, taken as average values; outer subelectrodes, located at the end of the configuration, may carry slightly more:

–	magnetite	(Sweden)	70 and 140 A/m^2
–	graphite	(South Korea, both stations)	53 A/m^2
		(Canada, Sansum Narrows)	81 A/m^2
–	platinized titanium	(Italy, Punta Tramontana)	544 A/m^2

It is an inherent trait for this type of electrode that the current density can reach very high values. The magnitudes of current densities are not greater than generally recommended for these materials, but two problems should be considered.

Firstly, the gradients and "step" voltages inside the pond may reach high values. In the two Swedish and the Italian electrodes, the gradients on the surface of the subconductors are of a magnitude of 100-150 V/m. The pond of Massänge (Sweden) seems to be the most annoying for a diver, due to the rather high water resistivity (about 1 $\Omega \cdot$ m). He will experience 15-20 V from hands to feet, if touching the electrodes. A diver in the Italian pond Punta Tramontana feels a voltage of 7-10 V, while here the water conducts much better (0,2 $\Omega \cdot$ m). The corresponding values are estimated to be 3-4 V in the Sansum Narrows station and 2-3 V in the Korean stations.

A second problem is the fairly high selectivity for evolution of Cl_2 instead of O_2 if this is considered as a problem at all. The Italian electrode with its very high current density in the electrolytic boundary (the surface of the subelectrodes) must be a pronounced example. In the former construction principle of the Danish beach station Sørå (1965-1971) graphite rods transmitted 53 A/m^2 direct to sea water in wells. A forceful evolution of Cl_2 was clearly observed, but it was not realized, or even measured, that O_2 also was part of the total gas evolution (see Clause 10 for further explanation).

In comparison, by considering Cl_2-evolution, the current density at the metallic surface of the Smyge station (Baltic cable scheme) is about 10 A/m^2, giving a selectivity for Cl_2 of 30 % and hence 70 % for O_2. The evolution of gaseous Cl_2, to which pond stations should be disposed, needs not to be traced (for instance, by smell) in the vicinity of the pond. Firstly, gaseous Cl_2 is diluted well in water up to certain concentrations, and, secondly, the water in the pond is exchanged for "new" water; it may be by tidal effects or direct by flow of water through the breakwater, even with no tidal pressure.

As regards the configuration (geometric arrangement) there will be possibilities as already described for other types, such as linear, ring, etc. As a practical consideration, a timber construction could carry the suspended electrodes, which speaks for a double linear configuration, suspended on both sides of a timber bridge.

Pond stations are advantageous for the following reasons.

a) They generally need a small area, 6 000-10 000 m^2.

b) The electrodes are very easy to supervise or to inspect direct, by lifting them out of the water. It should be considered which voltage the lifted-out subelectrode has against surrounding objects when the remaining subelectrodes are still working. If the voltage is rather harmless for skilled staff, switches to each subelectrode could be avoided.

c) Although there is only limited information on costs for different types of electrodes, it is assumed that pond stations are generally less expensive than sea electrodes.

10 Chemical aspects

In electrolytic processes there will always be a chemical action, because the materials in the soil (more precisely the substances diluted in the ground/seawater) will be decomposed and/or built up to new chemical substances [17].

In an anodic process in ground water of very low or zero salinity, O_2 (oxygen) is evolved, which is generally not seen as any problem since the atmosphere partly consists of O_2. With increasing salinity the evolution of Cl_2 (chlorine) will take over, but there will still be, also in salinities up to sea-water level, a substantial evolution of O_2. The sum of evolved gases must respect the law, which says that the mass of decomposed material is proportional to the electric charge, the number of A · h.

The sum of evolution of Cl_2 and O_2 amounts to about 327 mol/A · yr. A company which has delivered coated titanium mesh electrodes (see also 9.2) has given the following information concerning the anode for the Baltic cable, electrode station Smyge: at the salinity of this site (about 0,8 %) the rated current 1 364 A produces Cl_2/O_2 in relative amounts 30/70 %. The fraction of evolved Cl_2 as a ratio to the sum of Cl_2 and O_2 is called the selectivity for Cl_2, which is then, in the example, 30 %. At 50 % of the rated current the selectivities Cl_2/O_2 are about 17/83 %, and by 20 % of the rated current 9/91 %. The absolute rate of evolved mols is, as already explained, proportional to the current, which means that the absolute rate of Cl_2 evolution is decreased by a factor of 16,7 when the current density of the electrode is decreased by a factor of 5. The method to diminish evolution of chlorine is obviously to use low current densities, which means electrodes of large sizes.

It is not specifically described if all electrode materials follow the same trend. If the method to transfer the current to water is by means of rather small-sized subelectrodes, for instance, SiCrFe-rods direct in water, it is not feasible to achieve low current densities, but the use of coke could imply low current densities in a feasible way. The literature does not indicate clearly whether the selectivity function for evolution of Cl_2 is only dependent on current density or is also dependent on the actual composition of the anode materials. A point which needs discussion/research is whether the surface area of a coke pile is just the projected area against the electrolyte, or if the effective area is greater due to the irregular shape of the coke grains.

It seems further stated that if Cl is evolved in a low rate it will not form gaseous Cl_2 but will form hypochlorite ions, which are considered much less harmful, because they react with the buffer content of carbonate in normal water.

The buffer effect of carbonate is ineffective, either in the case of forceful evolution of Cl by high current density or if the electrolyte liquid is not exchanged. Lack of exchange of the liquid may be the case with deep vertical electrodes, especially if the vertical solution has been chosen because of saline strata in the underground. The need for ventilation of gases also seems mostly discussed for deep vertical electrodes.

The anodic reaction of HVDC-electrodes means that, although not generally discussed, the anode itself has to be noble, that is, it does not liberate any significant amount of itself. In this sense, graphite, coke, SiCrFe and titanium are noble chemicals. If the electrode is non-noble, as Al, Zn, Mg or Fe, it will liberate metallic ions which will participate in the anodic chemical process. If an anode was made by just ramming down a number of coarse sectional steels, to a large, but still practical depth (20 m?), then the evolved gases, oxygen and/or chlorine will react with the anode material to form substances like Fe_2O_3 (= common rust), $FeCL_2$ or related chemicals, and no gas is expected to be released.

Of course, such an electrode is eaten up but still with a rate of "only" 9 130 kg/kA · yr. If the intention or licence of operation limits the electrode to a short-time duty, an electrode of this simplified type will last for many years. Deep non-noble metallic rods electrodes will also be eaten up from the bottom, because the current density is expected to be largest at the bottom ends of the vertical electrodes.

By the cathodic process H_2 (hydrogen) is evolved in gaseous form. This hydrogen is partly dissolved in the water, finally to a saturated concentration, if there is little or no exchange of electrolyte close to the cathode. The part of hydrogen not dissolved is presumably released to the atmosphere, which has a natural content of H_2 of about 0,5 ppm (parts per million). If there is only little exchange of water by the cathode, the strong base NaOH (sodium hydroxide) will concentrate around the cathode.

It is well known from sea electrodes running only cathodic that the cathodic process involves chalk-like substances being deposited on the electrode surface. These deposits are not harmful to the electrode surface, but may involve local extra resistance and then heating. If this heating is too accentuated, the deposit may even be blasted off due to steam explosions inside the deposit.

Changes between anodic and cathodic direction of current may be a problem for certain materials. Running as an anode the surface of the electrode develops an acid environment, and is polarized according to that, while a cathode develops a chemically basic environment, also involving polarization. The sum of polarization voltages in a pair of electrodes can easily reach about 2 V, which represents a voltage drop, corresponding to a loss.

When a polarized pair of reversible electrodes is inversed, the polarisation, starting with the "wrong" direction, will diminish the total voltage drop, until opposite chemical conditions have been established by the electrodes.

Materials like coke and graphite withstand current reversals well, while high silicon iron is indicated as less suited, because a layer of SiO_2 on the surface bursts. Likewise, titanium and coated titanium, which withstand the harsh anodic condition extremely well, will not withstand cathodic conditions. A warning has even been expressed against very low current densities and the combination of ripple and low current density. A company producing titanium electrodes has announced that research is going on to develop metallic electrode materials with enhanced cathodic current capability.

In [17], the effects of sea electrodes on marine life are further described.

11 Connection converter station – Electrode station

11.1 Separation of a.c. grid from electrode station

As explained in 4.3, a certain separation is needed between the electrode station and a.c. stations, including the converter station. The separation is conveniently expressed by the distance in km. However, the separation can also be expressed as a voltage, defined as the change of potential in the underground beneath the converter station produced by the rated current in its own electrode station. For a greater precision the interaction from the counter-electrode should also be included.

Recently, it has been suggested that the necessary separation could be achieved not by horizontal distance but by vertical distance, using a deep-hole electrode. A test of this principle has been performed at the Swedish converter station for the Baltic cable scheme. The crucial point in this principle is whether the potential transferred to the ground grid of the converter station can be accepted. It is not necessary that the potential be kept below a certain limit. The experience from New Zealand using blocking devices for d.c. currents entering starpoints could also be the solution.

The following table gives examples where the available information has made it possible to indicate, or roughly calculate, the potential influence from electrode station to converter station.

Table 11.1 – Examples of separation – Electrode station/converter station

HVDC scheme	Electrode station	Separation km	Potential influence by rated current V
New Zealand	Bog Roy	7,6	84,4
Cantons-Comerford	Lisbon	9	15,5
Gotland	Massänge	12	14,6
Itaipu	Foz do Iguacu	15,5	10
Pacific Intertie	Rice Flats	11	9,7
Fenno-Skan	Pampriniemi	30	9
Itaipu	Sao Roque	67	6,3
Konti-Skan	Risö	20	Approximately 2
Baltic Cable	Smyge	23	0,45
Skagerrak	Lovns	24	0,24
Konti-Skan	Sørå	26	0,06

Although lack of information prevents indication/calculation of the potential rise for a majority of converter stations, it seems quite probable that magnitudes of 1-10 V are common. Subclause 4.3 deals further with the impact of potential rises.

If the design phase contains a value for maximum potential influence on the converter station, and the resistivity pattern of the underground is known, the minimum distances are calculated, say, at 10 km. But in most cases the circumstances will dictate solutions with greater distance, for instance to a promising sea- or shore-site.

11.2 Constructional principles of electrode connection

The electrode connection can be arranged in the following three ways:

a) as conductor(s) on a combined overhead line, together with the conductor(s) for the high voltage part of the circuit;

b) as conductor(s) on a separate overhead line for electrode purpose only;

c) as cable(s).

These three arrangements can be combined in such a way that the connection partly consists of a) and/or b) and/or c). Further to these possibilities a)/b)/c), the electrode connection can be with single, double, or even triple circuit. In the overhead line case, it is not a genuine double-circuit solution, if the conductor consists of two subconductors, suspended in the same insulators. Unfortunately, the information given very often does not indicate clearly whether "duplex" means one duplex conductor or two independent conductors. Double conductors can be suspended on common pylons, or each conductor on separate pylons.

For the cable solutions, the options are easier. The single cable solution, one (large) cable, is generally the least expensive for a given current; but, for the double or triple cable solutions, the cables should not be laid in a bundle in the same trench, but for thermal and redundancy reasons be laid in trenches separated by 3-5 m at least.

Double or triple arrangements of the connection increase the availability. Generally, the costs for a split-solution are greater than for one common conductor. The designer has to consider whether increased availability warrants extra costs. It is not absolutely obvious that a redundant solution should be preferred, because the total availability pattern of an HVDC scheme includes faults on a lot of equipment, such as high-voltage connections, valves, transformers, filters, etc., making faults on electrode connections of less importance.

11.3 Detection of faults on electrode connections

If an electrode connection consists of a single circuit (overhead line conductor and/or a cable without screen), an earth fault is almost impossible to detect, especially if the fault is located close to the electrode station. If, for instance, a suspension insulator loses its overhead line and the line touches the ground surface over, say, 100 m without being broken, the current carried to the ground can be insignificant to the total electrode current, but the electrode line will still represent an extremely dangerous object, due to its touch voltage.

Splitting of the electrode connection into two (or three) independent circuits gives the opportunity to monitor that the total current is equally shared between the subcircuits. This principle needs a certain threshold of current and will not work if the current is almost zero, as might be the case for a well-balanced bipole. On the other hand, the electrode connection is not particularly dangerous when it carries no current.

Electrode cables can have a screen, insulated against the inner conductor **and** the cable surface with a small guarding voltage, say, 24 V, 50/60 Hz, supplied to the screen; this principle works on single cables, too. If the screen of an electrode cable, either deliberately or not, is connected to earth in more than one point, the harmonics in the d.c. current induce counter-currents in the screen. In the case of too small a cross-section of the screen, this may cause overheating, and consequently insulation faults on the screen or, worse, faults on the main inner conductor.

Of course, it should be considered by the operator whether a signal received from a supervising relay equipment should result in immediate shutdown of the HVDC scheme, or if a "delayed" procedure is allowable.

11.4 Electrode connection terminations

An electrode connection arriving at the station site should conveniently be terminated in a cabin, 10-20 m^2. Equipment of different kinds is installed in the cabin such as

– a busbar for collecting the current from the main conductors and transmitting it to subelectrodes;
– main switch(es) between main conductors and the busbar;
– shunts, instruments, relays, telecommunication gear.

At the converter station end of the electrode connection the equipment can include

– switches for individual parts of connection and for poles in bipolar or multipolar arrangements;
– transducers for measurement of currents;
– possible circuit-breakers;
– surge arresters.

12 Operating experience – Reliability, availability, maintainability

The summary of existing electrode stations has not given extensive information. Most of the answers given conclude HVDC electrodes to be practically free of faults as for the total station.

When it comes to single subelectrodes, faults are reported. These faults are mainly located at the cables belonging to each subelectrode. The cables are damaged for instance when cut by sharp stones or on edges of concrete. The rate of fault may for each individual electrode be of a magnitude of one per 100 years. This means that for a total station of, say, 50 subelectrodes, subelectrode faults are experienced about every two years. The total station is not interrupted hereby, because the general state seems to be that a few missing subelectrodes will not decrease the total current carrying capacity.

There is also very little information on faults on electrode connections (overhead lines, cables). The risk for these parts must be comparable with similar medium a.c. lines and cables, of which the great number of km ought to result in useful statistics. There is no evidence that electrode cables have faults specially connected to the specific influence from the d.c. voltage, which means that faults generally come up due to mechanical damage by ploughs, digging machines and rodents, or by improper connections.

Scheduled outages of electrode stations and their connections, lines/cables of 1-7 days per year seem common, but these outages are for obvious reasons taken over the same time as general scheduled outages for the HVDC scheme as a whole.

13 Commissioning

"Commissioning covers all the measures which need to be taken in order to assure the correct functioning of both single components of the equipment and of the station as a whole" (this scope is quoted direct from another CIGRÉ report concerning a.c. substations).

Some typical relations may lead to commissioning tests.

a) The designer of the electrode station needs to confirm to himself, or to his company, or to his customer, that the specific design fulfils its purpose.

b) The contractor must prove to his customer that the installations are in accordance with specifications.

c) An authority may have, as part of an approval and/or license given to the operating company, a condition that tests must be done to prove the performance of the electrode station.

Generally, there is not a great number of functions, circuits and equipment to be checked in an electrode station, compared to, for instance, an a.c. substation. The functions, circuits and equipment that can be checked must of course be checked. To a well-managed set of commissioning tests belongs a careful check manual!

A general check of the electrode system should include measurements on each subelectrode and a comparison of possible differences. If the electrode station consists of a number of subelectrodes for reversible operation, a small-scale test of performance can be executed by testing one subelectrode as anode and another as cathode, by means of a d.c. welding generator.

Performance of genuine tests for the whole electrode station makes the following necessary.

– A counter-electrode. The best counter-electrode is the one belonging to the far end of the total HVDC scheme.
– A current source matching the rated current of the new HVDC scheme.

Measurements of the performance of the total electrode most often have to be postponed until the HVDC scheme is generally ready for operation. The first period of operation will include observations and measurements of, for instance,

a) a measurement of the field closer (say, within a few km) to the station;

b) current division among subelectrodes;

c) step and touch potentials.

The best measurements of potential influence and of gradients are made if the current can be changed/inverted rapidly. But since this may involve large, and disturbing, fluctuations of power exchanged via the HVDC scheme, the operating staff of the scheme will be very reluctant to allow tests involving rapid changes.

A method to achieve large and rapid changes of current, without having large changes of power, was performed at the Skagerrak HVDC scheme while it was still a clean bipolar scheme (see Figure 2.2.1). The bipolar scheme for 250 kV, 250 MW, 1 000 A rating per pole was adjusted for full operation of pole 1, pole 2 ready, but not loaded. A change of operation mode is commenced, reducing the current on pole 1 successively and, synchronous to this, to increase the current of pole 2. An intermediate state is reached when pole 1 is reduced to (plus) 500 A, and pole 2 increased to (minus) 500 A. At this moment the electrode station current is zero. The procedure continues until pole 2 carries its full current, and pole 1 current equals zero. During the whole procedure the power was about constant, 250 MW. The time for the total procedure was about 100 s. Because the current in the electrode stations has changed from +1 000 A to -1 000 A, there is a change of about 2 000 A, with a speed of 20 A/s.

The total procedure is then reversed and further repeated a sufficient number of times.

When measuring the voltage difference between two geographically separated points, by means of telephone circuits, it is very easy to distinguish disturbances from genuine measurements, if the current in the electrode station is changed for the double rating over 100 s. The disturbances on the telephone circuit are often caused by interaction with the HVDC scheme, since the advantage of having the telephone circuits as twisted, twin-pair conductors will not work by these measurements of potential differences.

Measurements of the field at large distances from the electrode station requires greater effort, even if the methods described above are used. A warning should be given not to include everything which seems measurable as commissioning tests. A customer must not demand tests or proof from his contractor which are likely not to be feasible. Likewise, a company having obtained a licence to build and operate the station must try to convince the authority about which tests are feasible and which are not.

14 List of references

[0] *Summary of Existing Ground Electrode Designs, 1998*
M.R. Nielsen on behalf of CIGRÉ Working Group 14.21

[1] *HVDC Ground Electrode Design* EL-2020 Research Project 1467-1
International Engineering Company Inc. for Electric Power Research Institute (EPRI), 1981

[2] *Direct Current Transmission Volume 1*
Edward Wilson Kimbark
Wiley Interscience, 1981

[3] *HVDC Ground Electrodes* Technical Report S90-003
Swedish Transmission Research Institute (STRI), 1990

[4] *High Voltage Direct Current Cost Reduction Via System Integration*
Project IIB: Monopolar Operation, Electrode Siting and Design
Richard J. Holt, John Dabkowski and Ronald L. Hauth
New England Power Service Company, NDT Engineering Inc. & Electro-Sciences Inc., 1996

[5] *Compendium of HVDC Schemes Throughout the World*
CIGRÉ Working Group 14.04, 1994

[6] *Soil Surface Potentials Induced by Itaipu HVDC Ground Return Current*
Part II - Measurements
C.E. Caroli, N. Santos, D. Kovarsky and M.A.M. Marques
IEEE 1987

[7] *Design of Ground Electrodes for the Gezhouba-Shanghai HVDC Transmission Project*
Weng Baoguang, Ministry of Water Resources & Electric Power. N.S. Crawford and D.L. Gordon, Teshmont Consultants Inc.
IEEE 1987.

[8] *The Rice Flats DC Ground Electrode for the Pacific Northwest-Southwest HVDC Intertie*
Carleton L. Waugh
Bonneville Power Administration, Portland, Oregon

[9] *Paper 2.7*
DC Ground Currents and Transformer Saturation on the New Zealand HVDC Link
J.C. Gleadow, Trans Power NZ Ltd., B.J. Bisewski, Teshmont Consultants Inc., M.C. Stewart, Design Power NZ Ltd.

[10] *Environmental and geographical aspects in HVdc electrode design*
Krister Tykeson, Anders Nyman and Hanna Carlsson
IEEE Transactions on Power Delivery, Vol. 11, No. 4, October 1996

[11] *Experiences of the Mitigation of Corrosion of Buried Metal Structures in the Surroundings of Monopolar HVDC Earth Electrodes*
U. Jonsson, A. Nyman, M. Kuussaari and S. Orivuori
Cigré, 36-201, 1992 session

[12] *Calculation and measurement of the stray current effects of monopolar HVDC systems*
A. Nyman, M. Kuussaari and M. Nielsen
Cigré, 36-03, 1988 session

[13] *A method for the indication of power transformer saturation*
D. Tousignant, L. Bolduc, A. Dutil
Electric Power Systems Research 37 (1996) pp. 115-120

[14] *Geräuscherhöhungen bei Groβtransformatoren bei gleichstromüberlagerten Netzen*
Erich Reiplinger
Elektrizitätswirtschaft, Jg. 91 (1992), Heft 6

[15] *Earth Return*
S. Rusck
H.V.D.C. Transmission Study Course, ASEA Information, 1962

[16] *VDI-Wärmeatlas Berechnungsblätter für den Wärmeübergang*
VDI-Verlag GmbH, Düsseldorf 1963

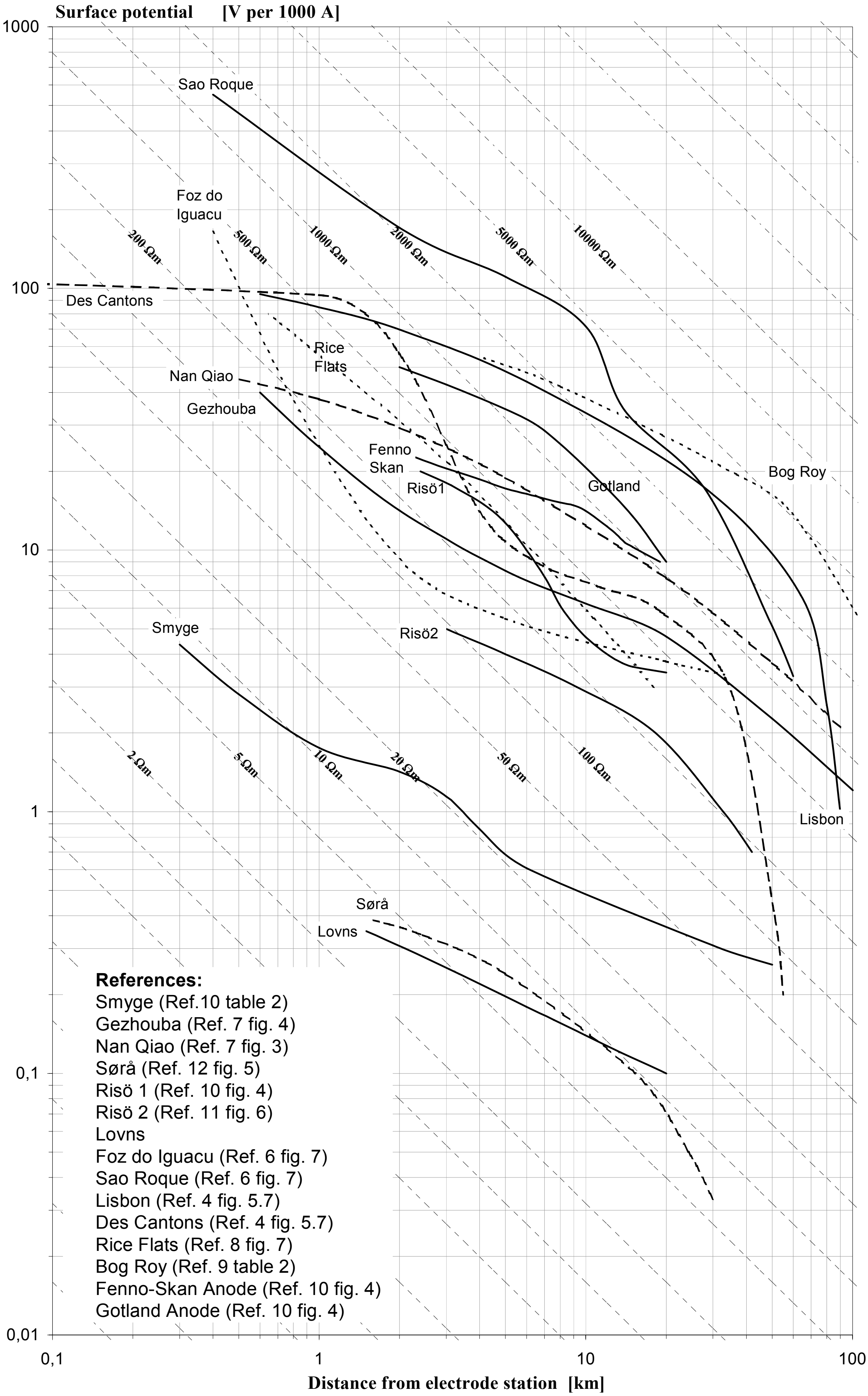
[17] *High Voltage Direct Current (HVDC) Sea Cables and Sea Electrodes: Effects on Marine Life*
Antonio B.S. Poléo & Morten Harboe jr.
Institute of Biology, University of Oslo, April 1996

[18] *Geomagnetically Induced Currents in the Nordic Power System and their Effects on Equipment Control Protection and Operation*
J. Elovaara, P. Lindblad, A. Viljanen, T. Mäkinen, P. Pirjola, S. Larsson, B. Kielen
CIGRÉ paper 36-301, CIGRÉ 1992 general meeting

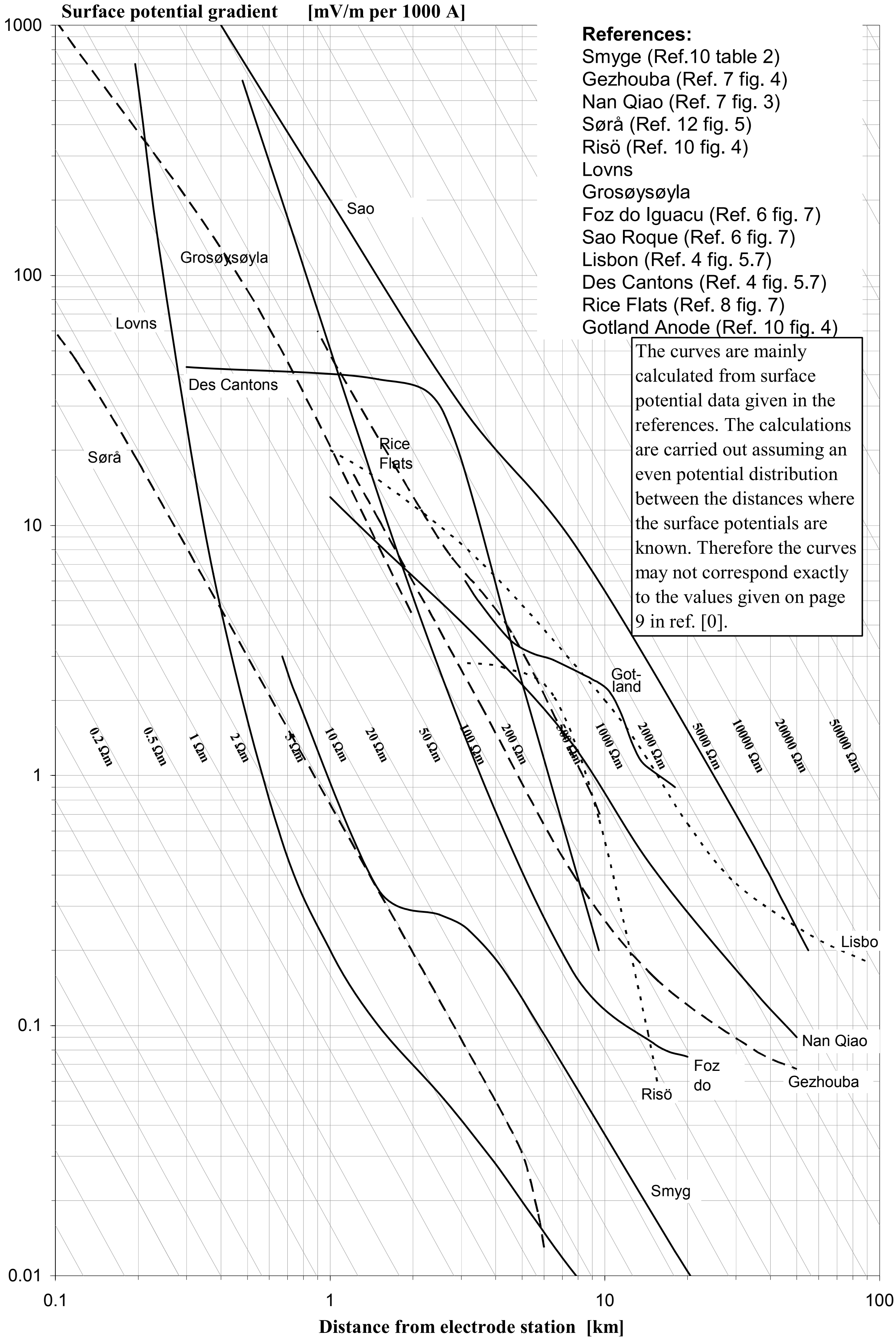
[19] *Non-linear interaction of DC cables and magnetically controlled ship-steering autopilots*
Magnus Akke, Karl Heinz Lampe
IEEE Transactions on Control Systems, Vol. 3, No. 4, December 1995

[20] *Deep Hole Ground Electrode for HVDC Transmission*
Dan Karlsson, Jan-Olov Sjödin, Sören Nyberg, Leif Eriksson

Appendix 1

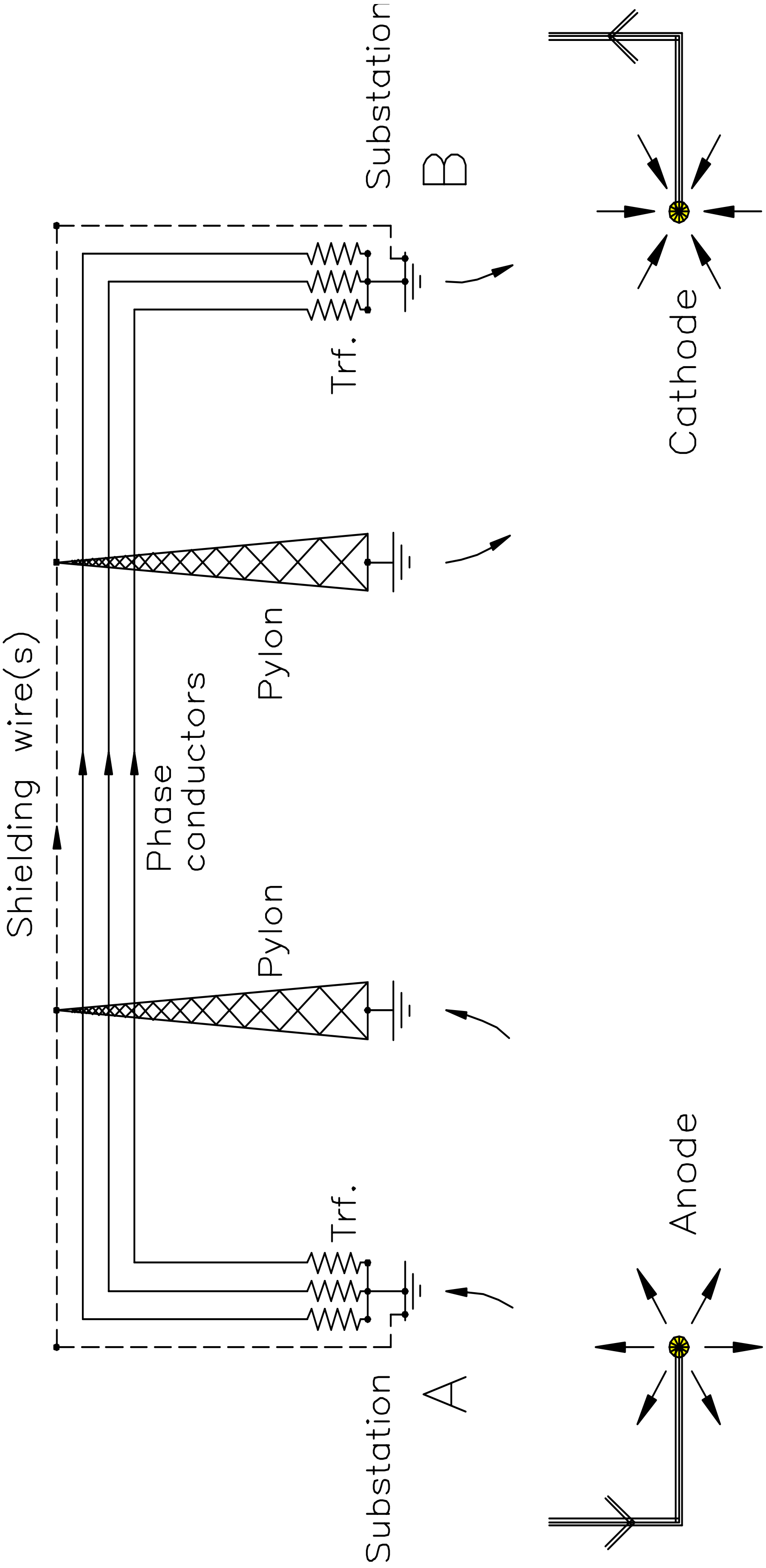

Surface potential [V per 1000 A]
1000
100
10
1
0,1
0,01
0,1
1
10
100
Distance from electrode station [km]
Sao Roque
Foz do Iguacu
Des Cantons
Nan Qiao
Gezhouba
Rice Flats
Fenno Skan
Risö1
Gotland
Bog Roy
Smyge
Risö2
Lisbon
Sørå
Lovns
200 Ωm
500 Ωm
1000 Ωm
2000 Ωm
5000 Ωm
10000 Ωm
2 Ωm
5 Ωm
10 Ωm
20 Ωm
50 Ωm
100 Ωm
References:
Smyge (Ref.10 table 2)
Gezhouba (Ref. 7 fig. 4)
Nan Qiao (Ref. 7 fig. 3)
Sørå (Ref. 12 fig. 5)
Risö 1 (Ref. 10 fig. 4)
Risö 2 (Ref. 11 fig. 6)
Lovns
Foz do Iguacu (Ref. 6 fig. 7)
Sao Roque (Ref. 6 fig. 7)
Lisbon (Ref. 4 fig. 5.7)
Des Cantons (Ref. 4 fig. 5.7)
Rice Flats (Ref. 8 fig. 7)
Bog Roy (Ref. 9 table 2)
Fenno-Skan Anode (Ref. 10 fig. 4)
Gotland Anode (Ref. 10 fig. 4)

Appendix 2


Surface potential gradient [mV/m per 1000 A]
1000
100
10
1
0.1
0.01
0.1
1
10
100
Distance from electrode station [km]
References:
Smyge (Ref.10 table 2)
Gezhouba (Ref. 7 fig. 4)
Nan Qiao (Ref. 7 fig. 3)
Sørå (Ref. 12 fig. 5)
Risö (Ref. 10 fig. 4)
Lovns
Grosøysøyla
Foz do Iguacu (Ref. 6 fig. 7)
Sao Roque (Ref. 6 fig. 7)
Lisbon (Ref. 4 fig. 5.7)
Des Cantons (Ref. 4 fig. 5.7)
Rice Flats (Ref. 8 fig. 7)
Gotland Anode (Ref. 10 fig. 4)
The curves are mainly calculated from surface potential data given in the references. The calculations are carried out assuming an even potential distribution between the distances where the surface potentials are known. Therefore the curves may not correspond exactly to the values given on page 9 in ref. [0].
Sao
Grosøysøyla
Lovns
Des Cantons
Sørå
Rice Flats
Got-land
Lisbo
Nan Qiao
Foz do
Gezhouba
Risö
Smyg
0.2 Ωm
0.5 Ωm
1 Ωm
2 Ωm
5 Ωm
10 Ωm
20 Ωm
50 Ωm
100 Ωm
200 Ωm
500 Ωm
1000 Ωm
2000 Ωm
5000 Ωm
10000 Ωm
20000 Ωm
50000 Ωm

Appendix 3

Simplified diagram of an a.c. connection exposed to a field from two conjugated electrode stations.



Appendix 4

Heating of soil – Numerical example

In some references, for example, [2] Kimbark and [15] Rusck, a method for calculating the temperature rise of land electrodes is given. In this method the atmosphere is assumed to be a perfect heat insulator, that is, no heat is lost to the atmosphere. This assumption leads to a considerable calculation error. In the following the size of this error is illustrated with a numeric example.

Example electrode

The very simple electrode shown in Figure 1 is considered. It is shaped as a sphere with a radius *a* of 0,5 m and buried at the depth h = 1 m below the ground surface. The electrical resistivity ρ of the surrounding soil is 100 Ωm and the thermal conductivity λ is 1 W/°C · m. The electrode is loaded with 5 A d.c. The arrows in Figure 1 indicate the current.

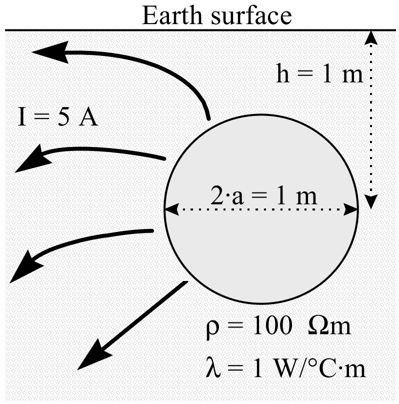


Figure 1 – Sphere-shaped electrode with given dimensions

Temperature rise

In Figure 2 the arrows illustrate the heat flow Q away from the electrode. The figure is based on the assumption that no heat is lost to the atmosphere. By comparing Figures 1 and 2, it is seen that the two flows, heat and current, are assumed to be equivalent. By using this equivalence it can be shown that θ_e (the temperature rise of electrode and contiguous soil above ambient temperature) can be calculated by

$$\theta_e = \frac{V_e^2}{2 \cdot \lambda \cdot \rho} \qquad (1)$$

where V_e is the potential of the electrode with respect to remote earth.

In [2], it is mentioned that a more accurate value can be calculated by using the equation:

$$\theta_e = \frac{V_e^2 \cdot R_\theta}{2 \cdot R_e} \qquad (2)$$

where R_e is the electrical resistance between electrode and remote ground and R_θ is the corresponding thermal resistance. In the following paragraphs these two resistances are determined in order to be able to calculate the temperature rise θ_e in two different ways.

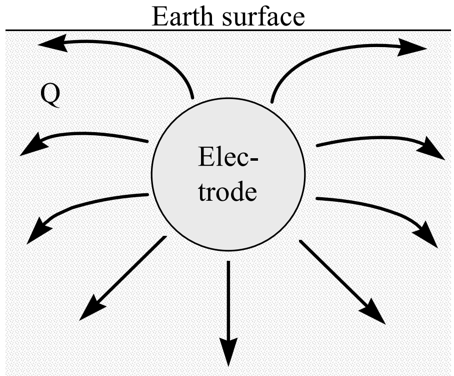


Figure 2 – Heat flow Q away from the electrode when no heat is lost to the atmosphere

Electrical resistance and potential

The electrical resistance of a spherical electrode in an infinite and homogeneous soil and the potential of the electrode with respect to remote earth can be calculated by the ordinary equations:

$$R_e = \frac{\rho}{4 \cdot \pi} \cdot \frac{1}{a} + \frac{1}{2 \cdot h} \quad (3)$$

$$V_e = R_e \cdot I \quad (4)$$

The values of the numeric example yield R_e = 19,9 Ω and V_e = 99,5 V.

Thermal resistance

If the heat flows from the electrode as illustrated in Figure 2, the thermal resistance of soil alone $R_{\theta e}$ can be calculated by an equation equivalent to equation (3). The only difference is that ρ in, for example, equation (3) is substituted with 1/λ:

$$R_{\theta e} = \frac{1}{4 \cdot \pi \cdot \lambda} \cdot \frac{1}{a} + \frac{1}{2 \cdot h} \quad (5)$$

The values of the numeric example yield $R_{\theta e} = 199 \cdot 10^{-3}$ °C/W.

If it is assumed that $R_{\theta e}$ constitutes the full thermal resistance, i.e. $R_\theta = R_{\theta e}$, then equation (2) can be derived by isolating ρ and λ in equations (3) and (4) respectively, then substituting them into equation (1); that is with a heat flow as shown in Figure 2, the two temperature-rise formulas are identical. However, $R_{\theta e}$ does not constitute the full thermal resistance, since a more realistic heat flow would be as shown in Figure 3. In this figure the influence of the convection heat loss Q_c to the atmosphere is illustrated.

It is assumed that the convection heat loss from the electrode to the atmosphere passes through a well-defined thermal resistance, R_c. This resistance can be divided into two different parts, R_{c1} and R_{c2}, connected in series. R_{c1} is the thermal resistance of the soil between the electrode and the surface. R_{c2} is the thermal resistance of the convection from soil to atmosphere.

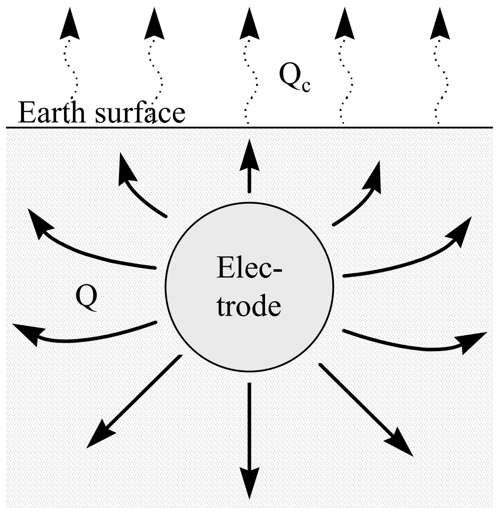


Figure 3 – Heat flow away from the electrode including convection heat-loss to the atmosphere

The soil above the electrode is assumed to be equivalent to a cylinder with the length h and the radius r = 4 times the radius of the electrode. Then R_{c1} can be calculated by

$$R_{c1} = \frac{h}{\lambda \cdot \pi \cdot r^2} \quad (6)$$

The values of the numeric example yield $R_{c1} \approx 80 \cdot 10^{-3}$ °C/W.

For calculation of the convection resistance R_{c2} the following are assumed: the wind is turbulent, speed 1 m/s, air temperature approximately 20 °C and the cooling area on the surface is a circle with a diameter of 4 m. The calculation is not easily performed and it will not be further described here. For further information, see [16] Wärmeatlas. The calculation yields $R_{c2} \approx 17 \cdot 10^{-3}$ °C/W. In order to obtain the full thermal resistance, R_θ, the two heat-flows (conduction in soil and surface convection) are assumed to be parallel. Then R_θ can be calculated by:

$$R_\theta = R_{\theta e} \| R_c = \frac{R_{\theta e} \cdot R_c}{R_{\theta e} + R_c} \quad (7)$$

where $R_c = R_{c1} + R_{c2}$. With the values of the numeric example the thermal resistance becomes $R_\theta \approx 65 \cdot 10^{-3}$ °C/W.

Evaluation of temperature-rise calculation methods

The calculated resistances are inserted into equations (1) and (2) in order to obtain the two different temperature-rise values. The results are:

temperature rise when no heat is lost to the atmosphere:	49,5 °C
temperature rise including heat-loss to the atmosphere:	16,2 °C

The importance of not neglecting the influence of heat loss to the atmosphere is clearly seen from this example. Actually, the temperature rise of 16,2 °C is also a pessimistic value because the calculation of the thermal convection resistance is based on the pessimistic assumption that all the heat is supplied by the surface of the electrode. In fact, most of the heat is generated in the surrounding soil by the loss of electrical energy in the soil's resistance. Therefore, a more accurate calculation would indicate an even smaller temperature rise than the one stated above.

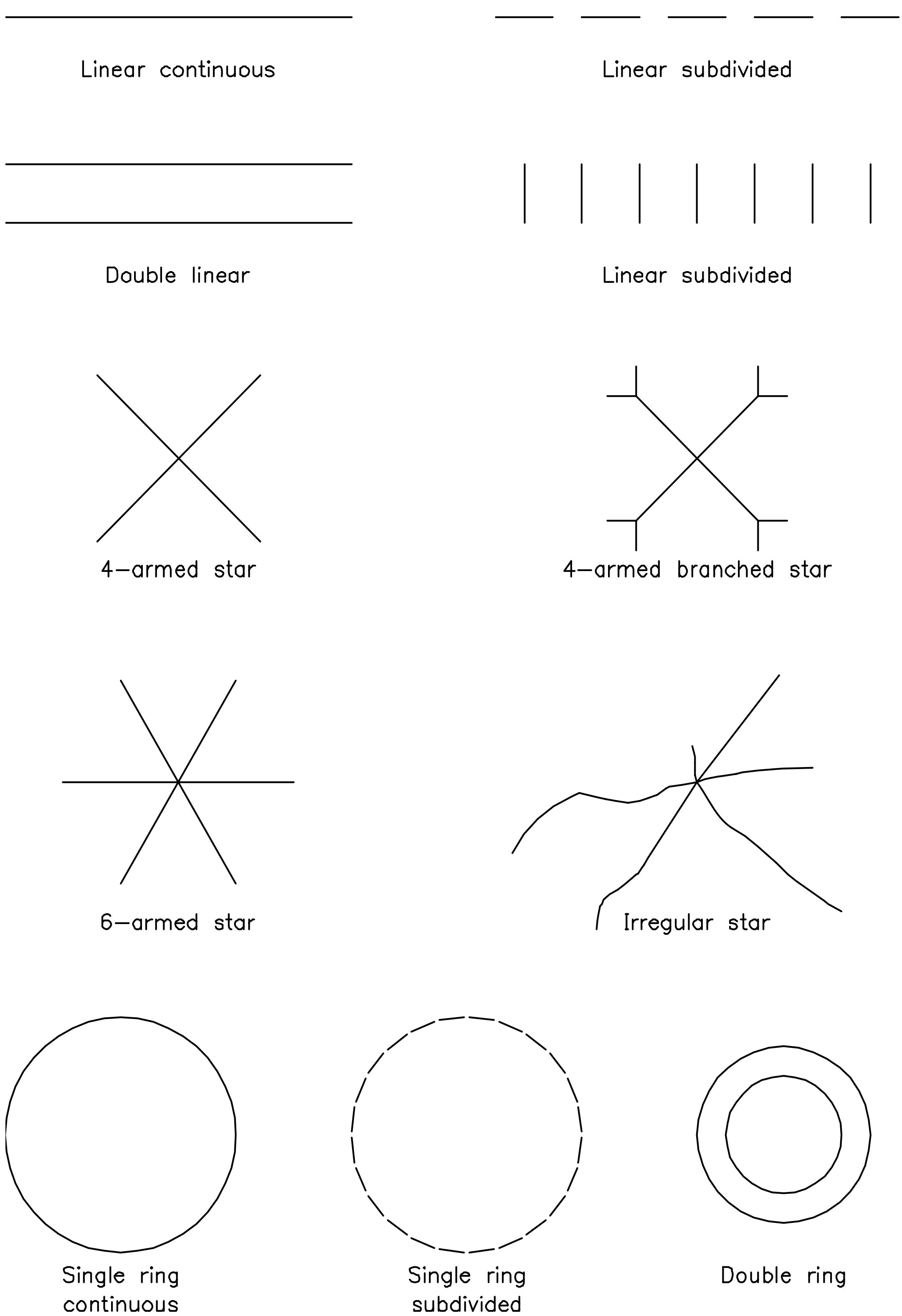
Appendix 5

Calculation of "theoretical" temperature rise to be expected from the formula $\theta_{max} = \frac{(I \cdot R)^2}{2 \cdot \lambda \cdot \rho}$

Scheme	Electrode station	I A	R Ω	λ[a] W/°C · m	ρ Ω · m	θ_{max} °C
Cahora Bassa	Songo	1 800	0,055	1	10	490°
C.U.	Coal Creek Dickinson	1 500 1 500	0,033 0,038	1 1	10 12	123° 135°
Gezhouba-Shanghai	Gezhouba Nan Quao	1 200 1 200	0,3 0,05	1 1	25 2,5	2592° 720°
Itaipu	Foz de Iguazu São Roque	2 930 2 930	0,267 0,242	1 1	400 75	765° 3 352°
Nelson River	Radisson Hendaye Dorsey	2 000 2 000 2 000	0,4 0,4 0,4	2,5 1,5 4	280 90 32,5	457° 2370° 2461°
New Zealand	Bog Roy	1 200	0,35	2	61,5	717°
Pacific Intertie	Rice Flats	1 800	0,105	1	70	255°
Cantons Comerford	Windsor	2 200	0,108	1	150	188°
Inga-Shaba	Inga Kolwezi	1 120 1 120	0,24 0,3	1 1	420 90	86° 627°
Intermountain	Sevier Coyote	1 600 1 600	0,04 0,04	1 1	60 20	34° 25°
Rihand-Delhi	Chapki Dankaur	1 568 1 568	1,00 0,034	1,2 1,2	250 40	4098° 30°
Skagerrak	Lovns (1976)	1 000	0,28	2,5	75	209°
Konti-Skan	Sørå	1 000	0,05	1	5	250°

[a] Comment for the value λ: if no information has been given in the specific case, the value λ = 1 W/°C · m is used.

Electrodes, forms and configurations



ISBN 2-8318-9094-2

9 782831 890944

ICS 29.240.99

Typeset and printed by the IEC Central Office
GENEVA, SWITZERLAND