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GENERAL GUIDELINES FOR HVDC ELECTRODE DESIGN

WORKING GROUP
B4.61

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WG B4.61

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M. Reynolds	US	H. Thunehed	SE
K. Zha	CN		

Observers

K. Hubbard	ZA	N. Molosiwa	ZA
N. Parus	ZA	J. Rasmussen	SE

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EXECUTIVE SUMMARY

HVDC electrodes have traditionally been installed on HVDC transmission systems to provide a low resistance current return path during both monopolar and bipolar operation, using the earth and/or sea as the conductive medium. HVDC electrodes are in general less costly and have lower losses than dedicated metallic return conductors. Although environmental concerns were less rigorously considered and applied in the past, a number of electrodes have been in use more than forty years without safety issues and very little actual measurable environmental impact.

Environmental concerns related to electrode operation have become more prominent in recent years due to greater public awareness of potential impacts, tighter environmental approval processes and increasing numbers of HVDC projects. While the environmental approval process can be challenging, the long-time successful operation of older electrodes indicates many of the potential environmental impacts from electrodes can be minimized or eliminated either by suitable selection of the electrode site for impacts remote from the electrode or by application of good design techniques if the impacts are near the electrode or on the electrode site.

Assuming that electrode use is not specifically prohibited by the regulatory framework, obtaining environmental approval requires careful consideration of both local and remote aspects of potential impacts. Local aspects at or near the electrode site generally involve electrical safety or environmental release of chlorine gas or metals from the electrodes and thermal/heating considerations. Remote impacts may include corrosion or electrical interference with existing or new infrastructure (pipelines, railways, power lines, transformers and telecommunication) or impacts on electro-sensitive species. Defining the geographical extent of such remote impacts requires good knowledge and detailed modelling of the earth and water bodies within the zone of influence to the electrode.

The available documents on HVDC electrode analysis and design are EPRI report EL2020 – "HVDC Ground Electrode Design" (1981) [1], Kimbark Chapter 9 – "Ground Return" (1970)[2], CIGRE WG 14.21 TF1 – "Summary of Existing Ground Electrode Designs" (1998)[3], CIGRE WG 14.21 TF2 – "General Guidelines for the Design of Ground Electrodes for HVDC Links" (1998) [4], and IEC pre-standard PAS 62344 – "General Guidelines for the Design of Ground Electrodes for HVDC Links" (2007) [5]

Much of the available literature on HVDC electrode design use regular geometrical shapes, rule of thumb site selection methodologies, generalized discussion of impacts of electrodes on infrastructure, and provides limited information on existing electrode installations. Topics such as electrical ground potential rise and surface gradient studies to define step voltages and transferred potentials, electrode element material selection, instrumentation and auxiliaries required for an electrode station, electrode testing and commissioning, and pond electrode analysis and design are not covered in detail.

With the development of new geophysical and geological investigation techniques, and more powerful computer simulation tools for electrical field studies and infrastructure modelling, potentially more economical designs of ground electrodes can be achieved, and the impacts of the electrode operation on existing or potential future infrastructure can be more accurately quantified. CIGRE WG B4.61 was initiated to highlight updated techniques and to formalize methodology and guidelines for the analysis, design and construction and testing of new electrodes and refurbishment or extension of existing electrodes.

The purpose of this document is to provide the general guidelines for the design of ground return electrode stations for HVDC transmission systems. The document is organised in eight chapters which are briefly described as follows:

Chapter 1 describes HVDC configurations that have electrodes as the ground return path.

Chapter 2 describes various types of electrodes. HVDC electrodes can be of three fundamental types or categories, i.e. land, shore (pond or beach) and sea. This chapter introduces the different types of electrodes and typical configurations, their advantages and drawbacks, and summarizes high level considerations for the selection of type of electrode and configuration.

Chapter 3 focuses on the electrode site selection process. The current site selection practice includes geophysical, geological, social and environmental condition investigations. Physical constructability aspects and general requirements such as availability of fresh water, rainfall analysis, wave action study, accessibility, social considerations, and distance to population centres are also relevant aspects to site selection.

Chapter 4 describes the potential impact of electrodes on infrastructure and the environment as well as mitigation of adverse effects caused by operation of the electrodes.

Chapter 5 covers electrode design aspects. Electrode design includes the following aspects which are described in the body of chapter: design criteria, interference, operating duties, electrode life cycle, reliability, temperature rise, and chemical emissions. The design criteria include safety requirement for humans and animals and discriminate between steady state and short-time operating conditions.

Chapter 6 addresses the neutral line (or electrode line) between the converter stations and the electrode stations. Neutral lines can be built as overhead lines or using insulated cables for undersea or underground lines. Both electrode line technologies are described.

Chapter 7 describes auxiliary systems for electrode stations including the station service supply and monitoring of electrode stations.

Chapter 8 covers the testing and commissioning of electrodes.

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TERMS AND DEFINITIONS

For the purposes of this document, the following terms and definitions apply.

Earth electrode / Ground electrode (in USA and Canada) /Electrode

Structure with a conductor or a group of conductors embedded in the soil or immersed in seawater, directly or surrounded with a specific conductive medium, providing an electric connection to the earth, for transmission of dc current from a dc system. [SOURCE: IEC 60050-195:1998, 195-02-01]

Land electrode

Earth electrode buried in the ground above the high tide water level and located away from the shore and not influenced by water bodies.

Shore electrode

Electrode located on the sea shore below the high tide water level and the active part of the electrode makes contact with the soil or with underground water, but not directly with seawater.

Pond electrode

Electrode located on the sea shore below the low tide water level and the active part directly in contact with seawater, within a small area which is protected by a breakwater against waves and possible ice damage or damage from other floating debris.

Sea electrode

Electrode located away from the shoreline in a body of seawater.

Special case electrode

It is possible that an electrode is located in a particular environment where it does not fit any of the above definitions.

Electrode station

Whole facility which transfers current from/to electrode line to/from the earth or seawater, usually including the feeding cables, towers, switchgear, fencing and any necessary auxiliary equipment in addition to the electrode itself.

Shared earth electrode

Earth electrode system, which is composed of a single earth electrode or multiple earth electrodes in parallel, shared by multiple converter stations. It primarily consists of earth electrodes and intertie lines between electrodes/sub-electrodes at different electrode sites.

Electrode site

Location where the land, shore, pond or sea electrode is constructed.

Electrode line or Neutral Line

Overhead line or underground cable that is used to connect the neutral bus in a converter station to the electrode station.

Current guiding system

Collective name for the components of a system used to guide the current from electrode line to feeding electrode elements which normally consists of current-guiding wire(s), disconnect switches, feeder cables and connections (Example as shown in Figure 0.1).

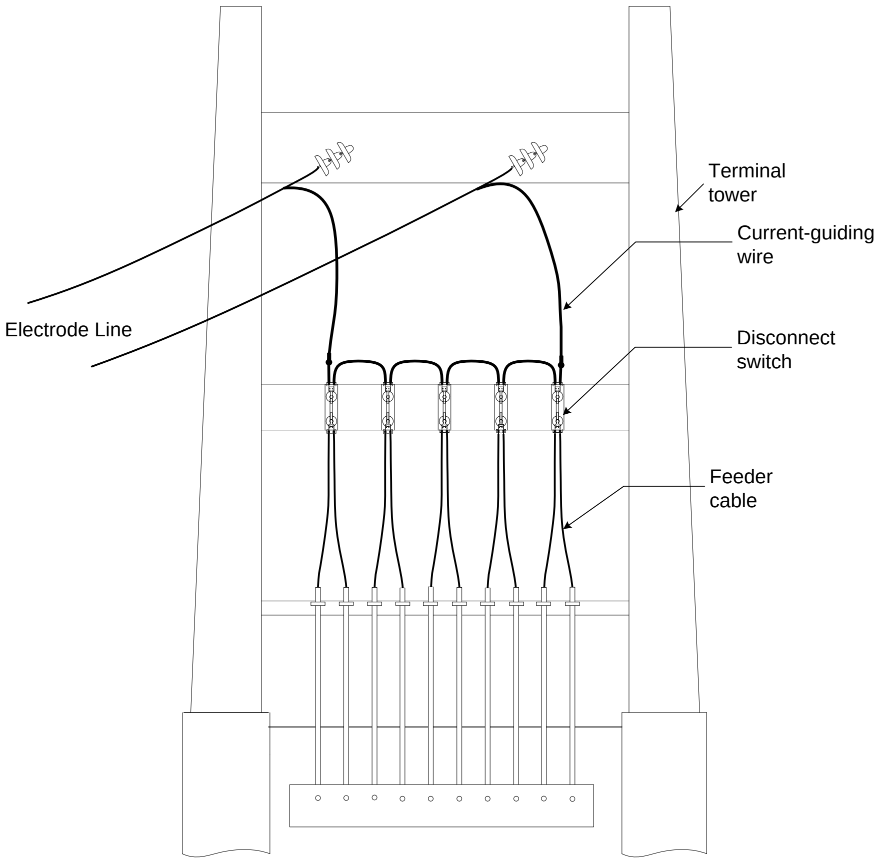


Figure 0.1 - Conceptual diagram showing the electrode current guiding system

Current-guiding wire (or Line dropper)

Main branch used to conduct current from the terminal of electrode line (or bus) to feeder cables.

Feeder cable

Cable used to guide current from current-guiding wire to electrode elements.

Distribution cable

A length of cable connected at the end of the feeder cable that is used to distribute the current to the individual electrode elements.

Electrode element

Conductive (usually metallic) portion of the active part of earth electrode that guides current into the surrounding conductive medium such as coke or directly into the soil or seawater (Refer to Figure 0.2).

Jumper cable

Cable used to connect between the distribution cable and the electrode elements (Refer to Figure 0.2).

Earth return operation mode

Operation mode of an HVDC power transmission system, using earth (or seawater) as the return path.

Cathodic operation

Electrode operation in which electrode emits negative charge carriers to and/or receives positive charge carriers from the earth.

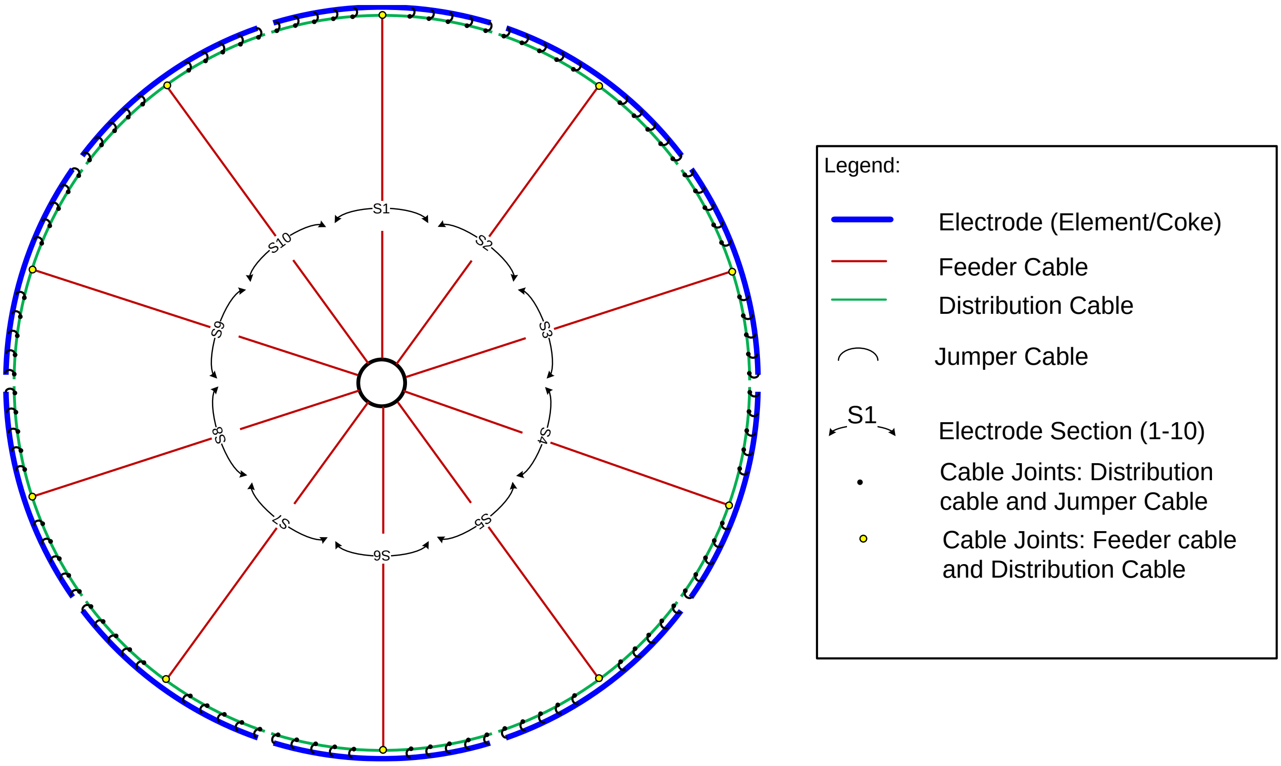


Figure 0.2 - Conceptual diagram showing a ring electrode connection

Anodic operation

Electrode operation in which electrode emits positive charge carriers to and/or receives negative charge carriers from the earth.

Current density

The total current passing through a conductor divided by the cross-sectional area of the conductor (A/m^2).

Current density at electrode element and coke boundary

Current released to coke from a unit area of an electrode element (in A/m^2).

Current density coke to soil boundary

Current released to soil from a unit area of coke surface (in A/m^2).

Design lifespan

Design operational lifespan of the earth electrode, usually not less than the operational lifespan of the converter station (excluding replacement of electrode elements).

Thermal time constant

Time required for the temperature of the soil immediately adjacent to the active elements of a land electrode to reach 63.2% of the steady state temperature rise at a given current.

Earthing resistance (or Resistance to Remote Earth)

Resistance between an earth electrode and remote earth.

Remote earth

A distant point relative to a reference point of a given electrical potential beyond which earth resistance does not increase appreciably and beyond which the electrical potential gradient is essentially zero.

Step voltage

The difference in surface potential experienced by a person or animal bridging a distance between two feet without contacting any other grounded object (expressed in Volts or V).

Touch voltage

The potential difference between the surface potential at the point where a person is standing and the surface potential of the soil where a structure in contact with the ground is touched by him having a hand in contact with a grounded structure (expressed in Volts or V).

Metal-to-Metal Touch Voltage

The difference in potential between metallic objects or structures within the substation site that may be bridged by direct hand-to-hand contact or contact between two metal structures and any two point on the body. In the case of ground electrodes this definition is modified to extend the affected area to include the entire area subject to surface potential rise due to electrode operation rather than just the substation site (expressed in Volts or V).

Transferred Voltage or Transferred Potential

A special case of the touch voltage where a voltage is transferred into or out of or within the substation from or to a remote point external or internal to the substation site. In the case of ground electrodes, the transfer voltage can originate anywhere within the area of land or water subjected to surface potential rise due to electrode operation and be transferred to any other point on the surface via an insulated metallic conductor which is in contact with the earth at one end and open-circuited at the other end (expressed in Volts or V).

Potential gradient in water

The voltage gradient that is produced in a body of water due to operation of the electrode (expressed in Volts/meter, or V/m).

Insulated metallic structures

Metallic structures coated with electrically insulating material.

Bare metallic structures

Metallic structures not coated with electrically insulating material.

Resistivity

A basic property of a material which characterizes its ability to conduct or resist the flow of electrical current when exposed to a voltage potential difference or gradient (expressed in Ohm•meters or Ω•m).

Electro-osmosis

The movement of water away from an anode or towards a cathode due to the electric gradient in the soil thereby affecting local soil moisture levels.

Definitions related to the capability of a person or animal to withstand electric current flowing in the body

Threshold of perception

The current magnitude at which a person is just able to detect a slight tingling sensation in his hands or fingertips or other body part caused by the passing current.

Let-go current

The current magnitude at which person loses voluntary muscular control and is not able to let go if he becomes in contact with an energized conductor.

Fibrillation current

A current flowing in the body of a human or animal which is large enough to cause ventricular fibrillation of the heart.

Body resistance

The resistance of the human or animal body that is used when calculating possible body currents when inadvertently exposed to electric potential gradients or potential differences within the zone of influence of a ground electrode (Expressed in Ohms or Ω).

Contact Resistance

The resistance at the interface where a person or animal is in contact with the earth or a metallic structure (Expressed in Ohms or Ω).

Definitions related to Electrode Impacts

Local impact

Measurable impacts such as step voltage in the geographic location near the electrode, where the electrode design has a major influence.

Remote impact

A defined impact of the electrode some distance away from the electrode site, where electrode siting and area geological conditions rather than electrode design has the major impact.

Area of influence

An area where, due to the operation of the electrode, there can be a measurable or detectable change in conditions compared to ambient conditions that may be of concern with respect to safety or other consideration such as corrosion. The boundaries of such an area would be demarcated by criteria selected so that outside the area the degree of influence would be below internationally accepted norms.

Voltage Potential Gradient or Potential Gradient

The difference in electric potential measured between two points in the earth divided by the distance between the points when a current is injected into or collected from a given point (expressed in Volts/meter or V/m).

Surface Potential Gradient (SPG)

The difference in electric potential measured between two points on the surface of the earth divided by the distance between the two points (expressed in Volts/meter or V/m).

Ground Potential Rise (GPR)

The maximum electrical potential that active elements of the ground electrode may attain relative to a distant grounding point assumed to be at the potential of remote earth (expressed in Volts or V).

Surface Potential Rise (SPR)

The electrical potential at the surface of the earth within the area affected by electrode operation with a distant grounding point assumed to be at the potential of remote earth (expressed in Volts or V).

Definitions related to the HVDC system characteristics and ratings

Transient operating condition

An operating condition or state whose maximum duration is less than 10 seconds.

Short-time operating condition

An operating condition or state that can persist for a duration between 10 seconds and 2 hours.

Nominal continuous pole current rating

The nominal rated current of one converter pole of the HVDC system (Expressed in Amperes or A).

Inherent continuous pole current rating

The continuous current of each pole of the HVDC system when all redundant cooling equipment is in service (Expressed in Amperes or A).

Maximum transient line pole fault current

The maximum line to ground fault current that can occur on the HVDC system when a ground fault occurs on the HVDC line and which would return to the station via the earth electrode (Expressed in Amperes or A).

Maximum pole short-time converter overload current

The maximum current that can be sustained in safe operation condition of the valves in each converter pole of the dc system for a defined time interval (Expressed in Amperes or A).

Maximum continuous electrode current

The maximum current at which the electrode can operate continuously without exceeding the maximum temperature rise or the limits imposed by steady state safety constraints. Generally, this is defined to be the same value as the inherent continuous converter pole current rating. However, the designer may elect to use any other current value.

Maximum electrode short-time current

For the usual case of a one bipole system this is generally the same as the maximum short time overload current rating of one pole. However, in the case where one electrode is shared by two bipoles it is equal to the sum of maximum pole short time overload current ratings of one HVDC pole from each bipole (expressed in Amperes or A).

Maximum transient electrode fault current

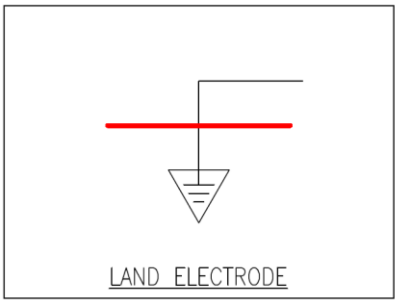
For the usual case of a one bipole system this is generally the same as the maximum transient line fault current. However, in the case where one electrode is shared by two bipoles, it is equal to the inherent continuous or the nominal continuous HVDC pole current rating plus the maximum transient line pole fault current of one pole of the other bipole (expressed in Amperes or A).

Unbalanced current

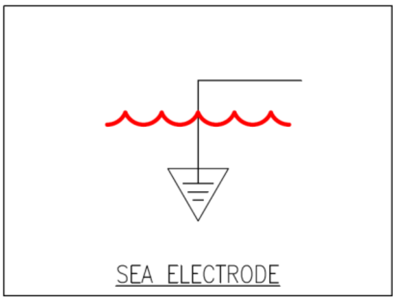
Difference of current between poles during operation of a bipolar or multipolar dc system (expressed in Amperes or A).

Electrode Symbols

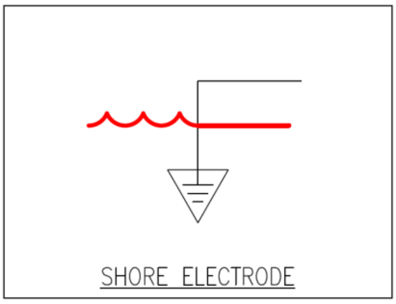
Electrode symbols for each type of electrode have been developed with reference to the IEC-60617 standard and the IEEE/ANSI 315-1993 standard.



(REF IEC S00202, S00407 & S00426)



(REF IEC S00202, S00408 & S00426)



(REF IEC S00202, S00407 & S00408)

1. HVDC CONFIGURATIONS WITH GROUND RETURN CURRENT

The basic configurations of HVDC systems include back-to-back, bipolar, monopolar and multi-terminal systems. The configuration of an HVDC scheme determines the current path under both normal operation and contingency operation, and whether ground return operation can occur. HVDC schemes using electrodes as the ground return path are described in this chapter.

Figure 1.1 shows monopole configurations with continuous earth return operation. The converter station may use either Line Commutated Converter (LCC with thyristors) or Voltage Sourced Converter (VSC using IGBTs).

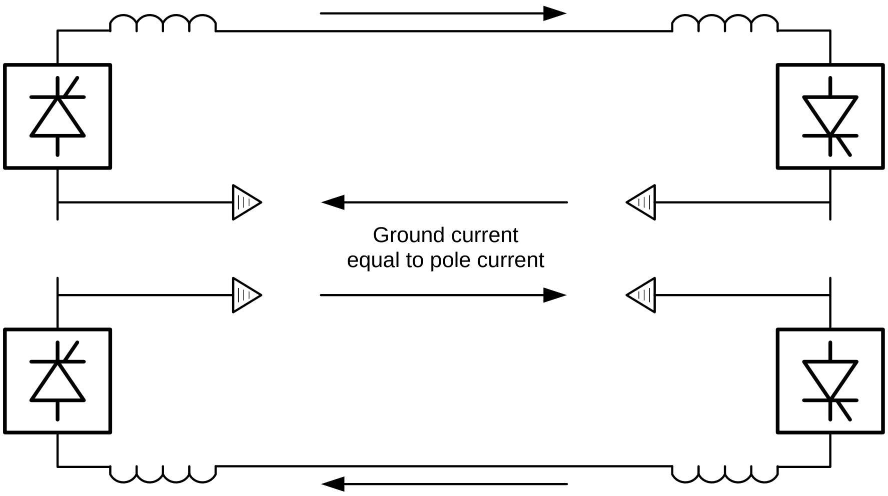


Figure 1.1 - Monopole Configurations with Electrodes

Figure 1.2 shows a bipolar configuration. Under normal operation, the earth return circuit carries only the bipolar unbalanced current and but will carry full pole current possibly including overload current under a contingency involving the loss of one pole. One of the pole conductors of the HVDC line can be used as a metallic return to limit the duration of earth return operation under a contingency of a converter pole.

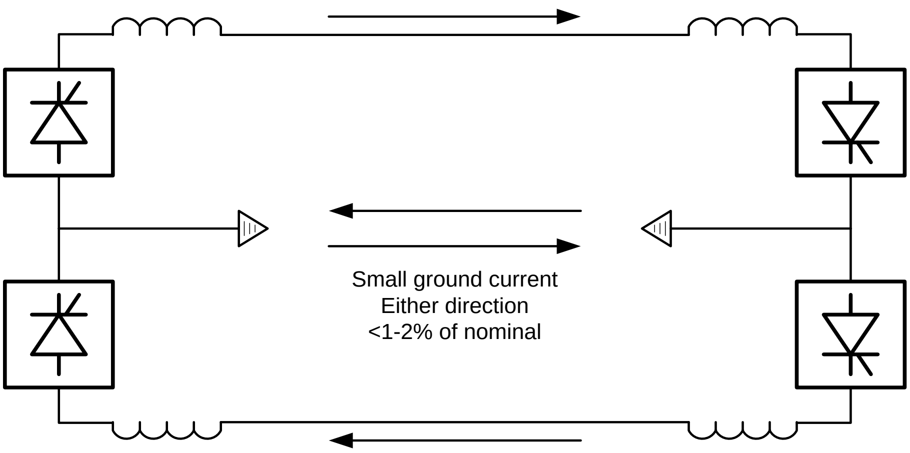


Figure 1.2 - Bipolar Configuration with Electrodes

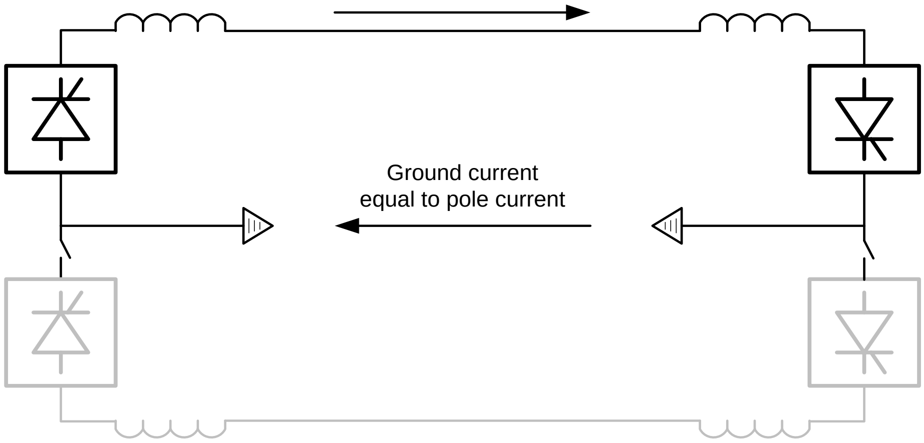


Figure 1.3 - Bipolar Configuration Operated as A monopole with Electrodes

In all the above figures the LCC symbol has been used. However, the same configurations would also apply for VSC systems.

Additional possible configurations and modes of operations include

a) Multiple pole configuration (e.g. Skagerrak scheme comprised of four poles) which operates to minimize unbalance earth return current. Homopolar operation (two poles at same polarity using ground as current return path) or high level unbalanced operation is possible if one or more of the poles are lost.

b) Bipole scheme with paralleled poles to achieve higher capacity for a pole, a loss of a converter pole can result in high level of unbalance.

c) HVDC Grid comprised of multiple converter poles connected to a meshed set of bipolar conductors which may have a single or multiple earthing points and a complete or partial dedicated metallic return conductor between the converter stations. Outage of any converter pole can result in high unbalanced current that may flow in the earth or in the metallic return conductors depending on the configuration.

2. TYPES OF ELECTRODES AND SELECTION OF TYPE OF ELECTRODE

2.1 TYPES OF ELECTRODES

Table 2.1 summarizes the typical types of electrodes.

Table 2.1 - Types of electrodes

Type	Active part in	Advantage	Disadvantage	Example/Figure
Land (Shallow Horizontal)	Surface soil	Generally located close to converter site Low electrode line and electrode power losses compared with neutral line.	May have high temperature rise, high potentials. potential for electro-osmosis. May not be rated for full time in operation in earth return	Nelson River BP1 Radisson (Shallow ring electrode) Figure 2.4
Land (Vertical)	Relatively shallow soil within 200m of the surface	Reduced area of electrode site compared to shallow horizontal land electrode	Obvious end effect of current releasing density.	Puer-Qiaoxiang HVDC Project, China Figure 2.9
Land (Deep Well)	Deep soil up to 1000m deep	Minimum area of land electrode site. Perhaps no electrode line near or in the converter station.	Obvious end effect of increased current density.	Changcuicun electrode site, Heyuan city of China Figure 2.10
Sea	Seawater	Low resistance to remote earth, thus low power losses. no temperature rise no risk for electro-osmosis	Must achieve low current density to avoid chlorine evolution.	Kontek, Bjäverskov Figure 2.13
Shore (Beach)	Soil saturated with seawater	Low resistance to remote earth, thus low power losses easy to exchange active parts	Tidal water level variation can affect characteristics. Subject to erosion in storms.	Skagerrak, Lövens Breddning Figure 2.15
Shore (Pond)	Seawater	Low resistance to remote earth, thus low power losses. Easy to exchange active parts	Requires construction of breakwater. Economic design favours high current density which results in high potentials.	Gotland, Massangä Figure 2.16

2.2 ELECTRODE SHAPES AND CONFIGURATIONS

There are large variations in geographical, geophysical and technical properties of electrode sites and HVDC system requirements differ from one system to another. Therefore, a variety of electrode shapes, and configurations have been developed. In general, some degree of adaptation to the site is always needed and thus completely symmetrical shapes are seldom realized.

2.2.1 Land Electrodes

Land electrodes are categorized into three types depending on the depth of burial and the configurations as described below.

Shallow horizontal electrodes – generally buried in the surface in trenches with coke ground beds as shown in Figure 2.1. This type of electrode can be configured in many geometric shapes including linear electrodes (Figure 2.2), single ring electrodes (Figure 2.3), double ring electrodes, triple ring electrodes, and elliptic electrodes or any other shape as dictated by site constraints.

Shallow electrode types have advantages because of economy in construction. A circular ring configuration is preferred due to uniform current distribution, but linear or irregularly shaped electrodes can also be constructed. A linear electrode can be branched in order to adjust to the site and use the site area in an optimal way. Linear and branched electrodes require the use of a bigger volume of coke and also larger metallic element size in the outer ends due to increased current density.

Concentric circular or irregularly shaped horizontal electrodes are sometimes applied where land cost is high and land acquisition is difficult.

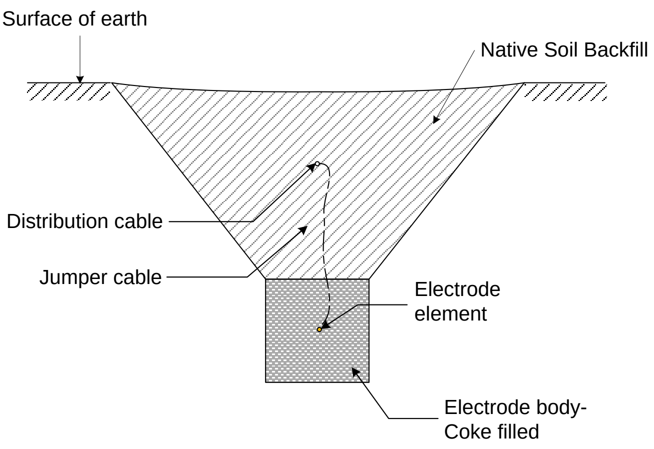


Figure 2.1 - Shallow Horizontal Land Electrode

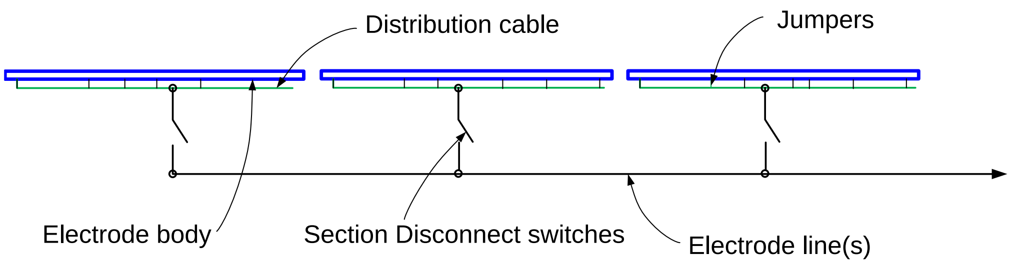


Figure 2.2 - Line Electrode

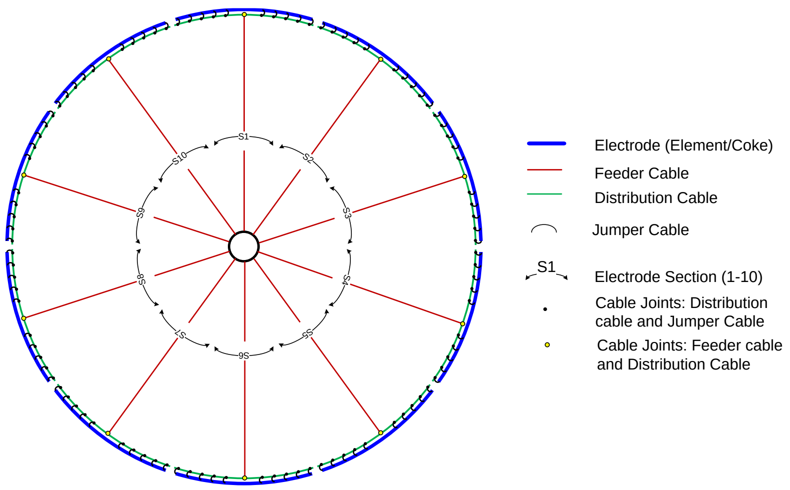


Figure 2.3 - Ring Electrode Arrangement

Figure 2.4 - Land Electrode (Manitoba Bipole 1 – Radisson)

Vertical electrodes - have been used to depths of up to 200m in order to reach a layer of lower resistivity and higher moisture content than that found near the surface, and to decrease the risk of interference at the site area as shown in Figure 2.5. As with shallow electrodes the vertical elements can be arranged in many geometric patterns such as linear, circular, rectangular, and grid.

The electrode wells would normally be backfilled with coke, see Figure 2.6. However, a mixture of graphite and bitumen could be used in dry conditions to make contact to low resistivity structures such as graphite deposits.

Figure 2.9 shows another example of a vertical electrode as used for the ±800kV HVDC Puer-Qiaoxiang Project with a rated current of 3125A. Due to limitations in the available drilling technology, the max diameter of the single vertical electrodes is about 558mm, and the depth is not larger than 200m.

Deep well electrode – This type of electrode would be applied if the geological conditions are such that there is a soil structure in which there is relatively high resistivity in the upper layers of the soil but the deeper soil structure has low to very low resistivity. With current drilling technology the depth of the well could length could be extended to about 1000m.

The low resistivity, of the deep soil layers promotes the rapid current dispersion deep underground and would help reduce electric potential and gradients at the surface. This can reduce the risk of corrosion due to exchange of current between the soil and buried facilities.

Typically, 3 to 5 deep-well electrodes would be connected in parallel arranged either a linear or polygonal configuration. Individual wells can be over 1000m deep and can carry up to 1000 A. Arranging the wells in a regular polygonal shape can help reduce the imbalance current between the deep well electrodes but the effect may be reduced if the soil resistivity is not similar for each well. Figure 2.10shows a regular triangle arrangement of deep-well electrodes with 1000m well depth with wells spaced 100m apart. Feeder cables are used to distribute the current to the metallic electrode elements at different depths in the well. Petroleum coke would be used to provide the electrical interface between the metallic elements and the soil thus reducing the corrosion of the metallic elements and reducing the current density at the electrode-soil interface. The gas produced by heat or electrolysis can block current flowing through the coke and needs to be vented using a perforated pipe running the full length of the electrode.

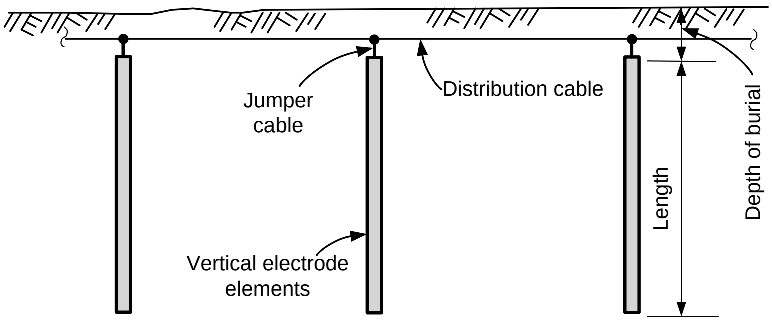


Figure 2.5 - Vertical Electrode (placed in a line, ring, or arbitrary arrangement)

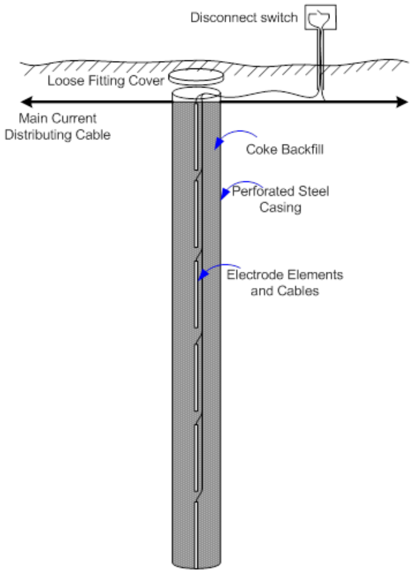
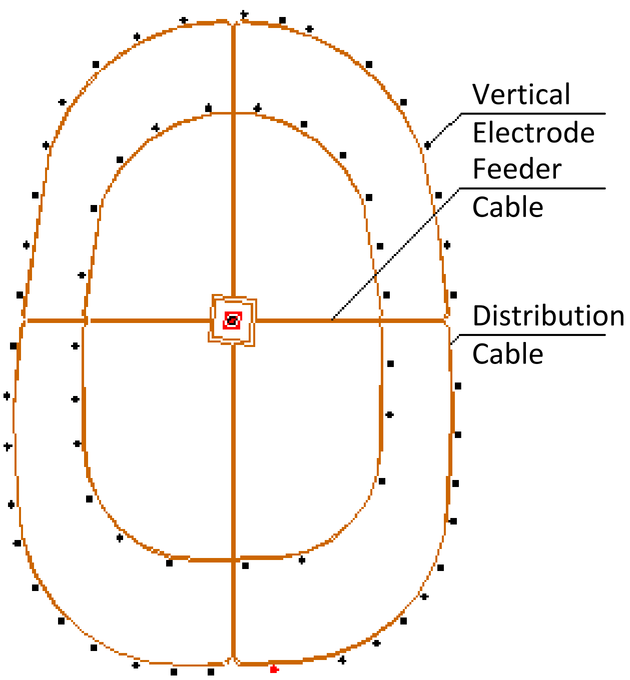
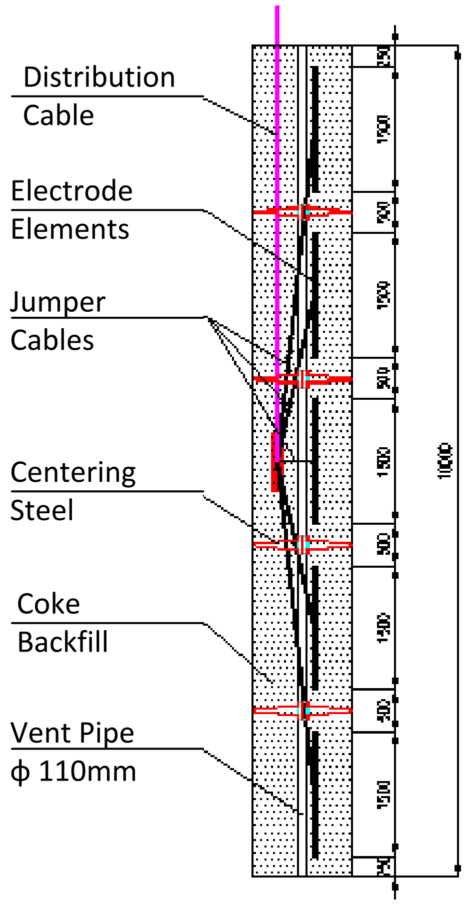


Figure 2.6 - Vertical land electrode

Figure 2.7 - Assembly of sub-electrode element FOR Vertical Well type Electrode

Figure 2.8 - Completed sub-electrode assembly before inserting Vent pipe and filling with coke





Electrode Shape adapted to site

Layout of irregular double ellipse
Outer ellipse major/minor axis:250m/170m.
Inner ellipse major/minor axis:175m/120m.
Total number of Vertical electrode: 61.
Outer / Inner ellipse: 38/21.
Distance of each Vertical electrode: 20m;
Length of vertical electrode:30m
Depth of Buried: 5m

Figure 2.9 - Vertical Electrode of ±800kV HVDC Puer-Qiaoxiang Project with Rated Current 3125A

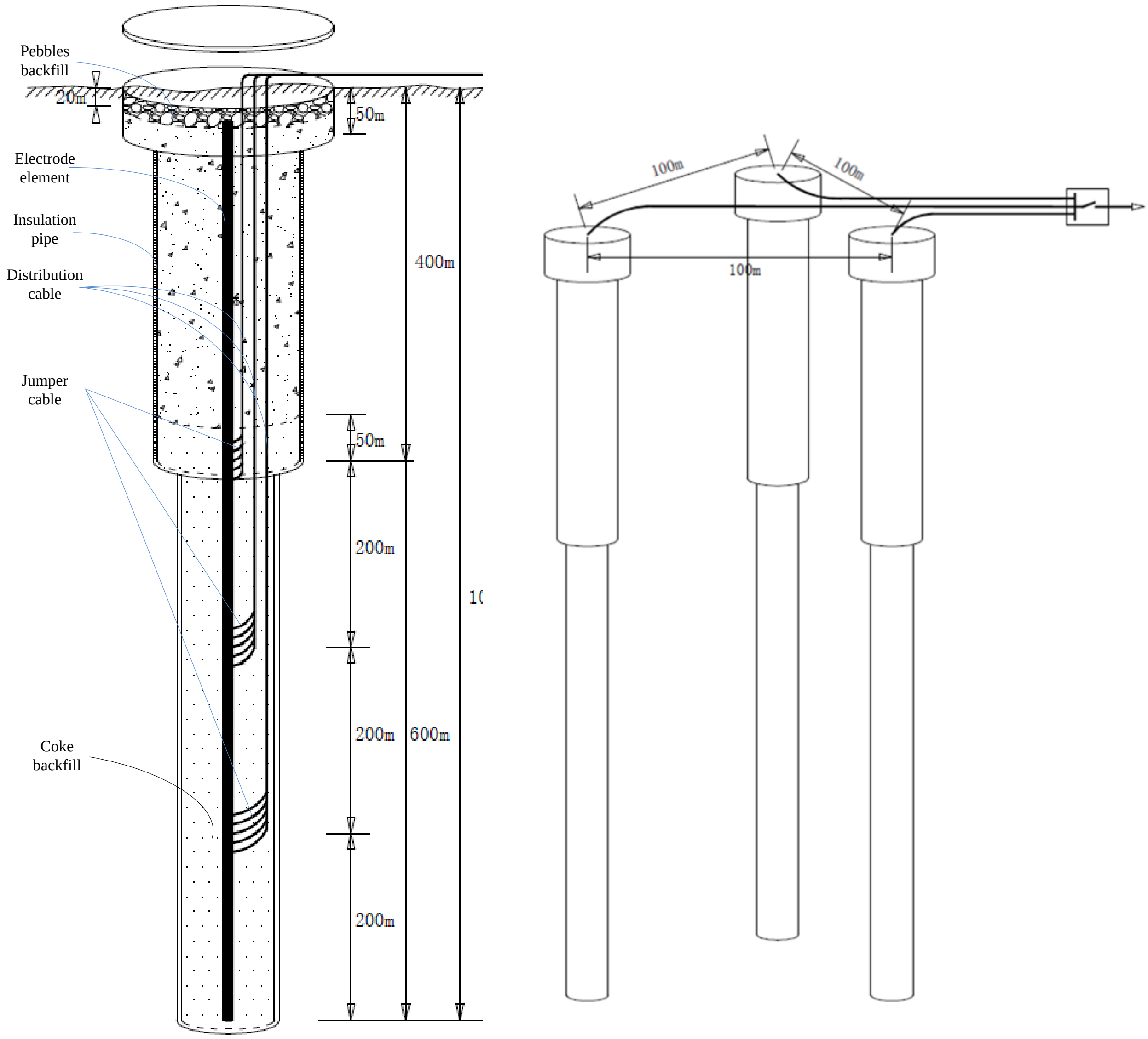


Figure 2.10 – Arrangement of Changcuicun Deep Well Electrode

2.2.2 Sea Electrodes

A sea electrode is an electrode located away from the shoreline in a body of water. Sea electrodes may be placed in the sea with or without barriers if the current density is low enough to limit the electric field within acceptable limits. Figure 2.11, Figure 2.12 and Figure 2.13show different types of sea electrodes. Figure 2.11 and Figure 2.12 show an electrode without barriers constructed using an expanded titanium mesh net placed directly on the sea bottom in a concrete frame. Figure 2.13 shows electrodes placed inside a protective wooden structure which also acts a barrier to divers and marine animals.

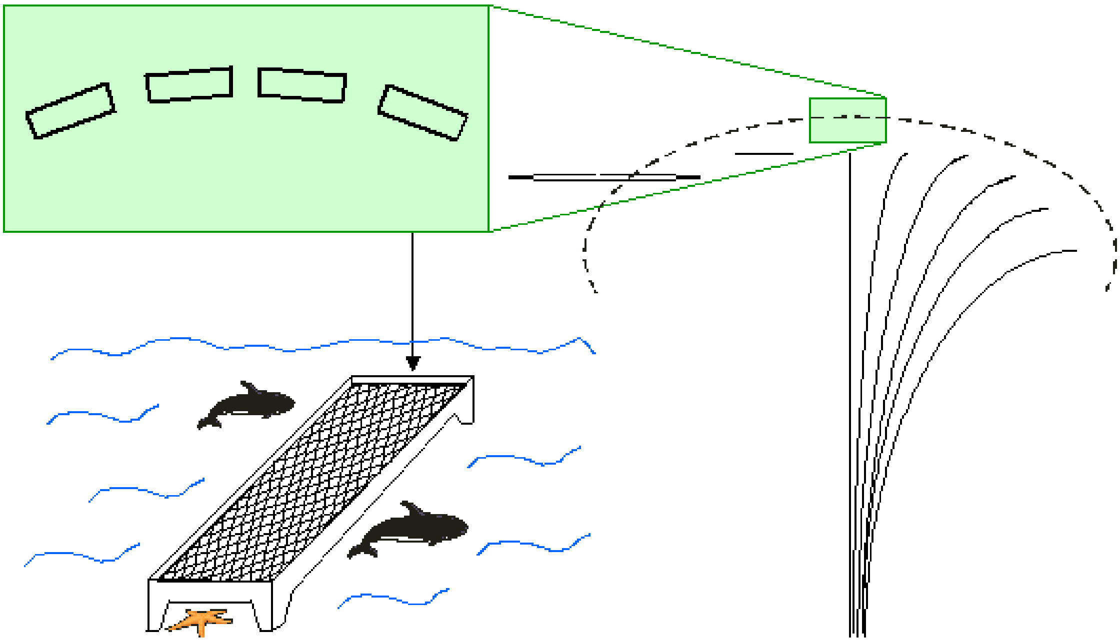


Figure 2.11 - Sea Electrode with Titanium Net

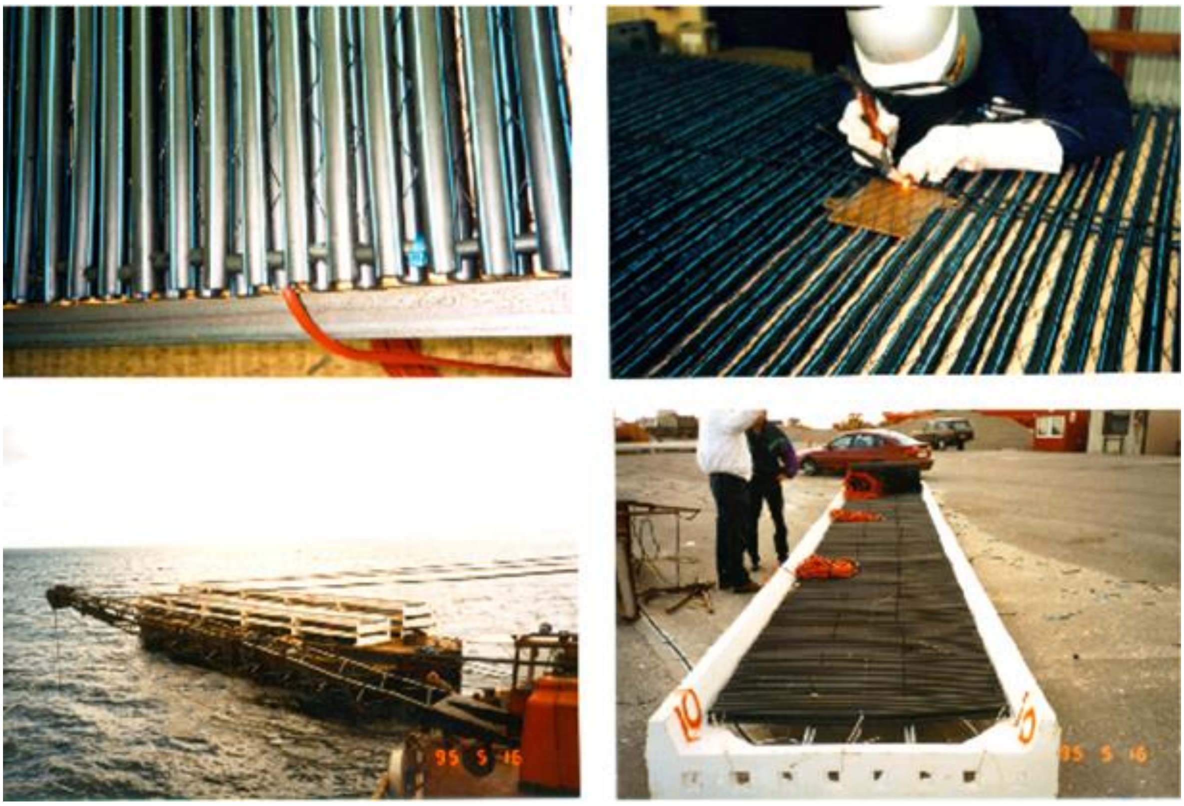


Figure 2.12 - Titanium Net Mounted in Concrete Frame

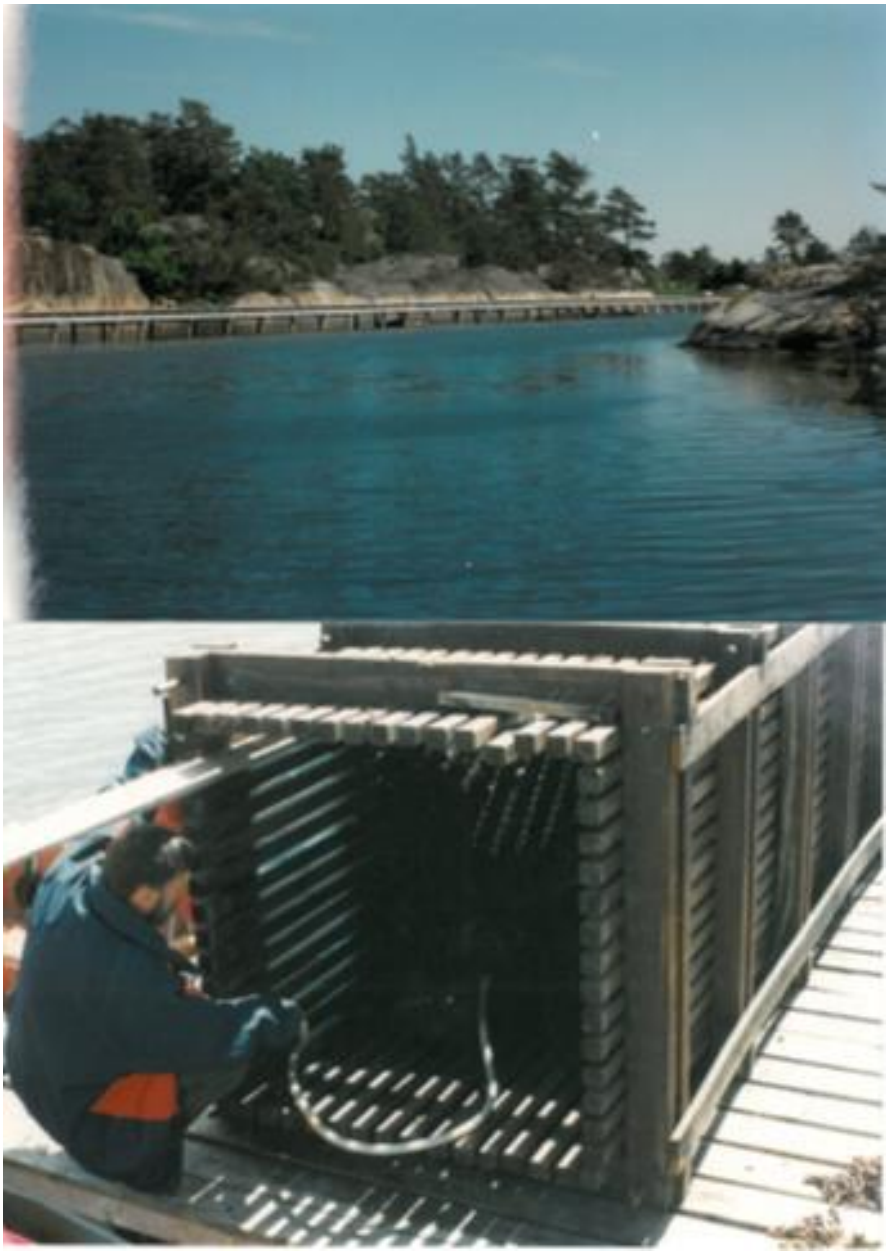


Figure 2.13 - Sea Electrode Graphite Sub-electrode in Coke in Wooden Cage

2.2.3 Beach Electrodes

A beach electrode is an electrode located on the shore above the high tide water level but with the active part of the electrode recessed into the beach to a depth below the minimum sea level so that it makes contact with the seawater seeping into the beach material, but not directly with open sea. Typical arrangements of beach electrodes are shown in Figure 2.14 and Figure 2.15.

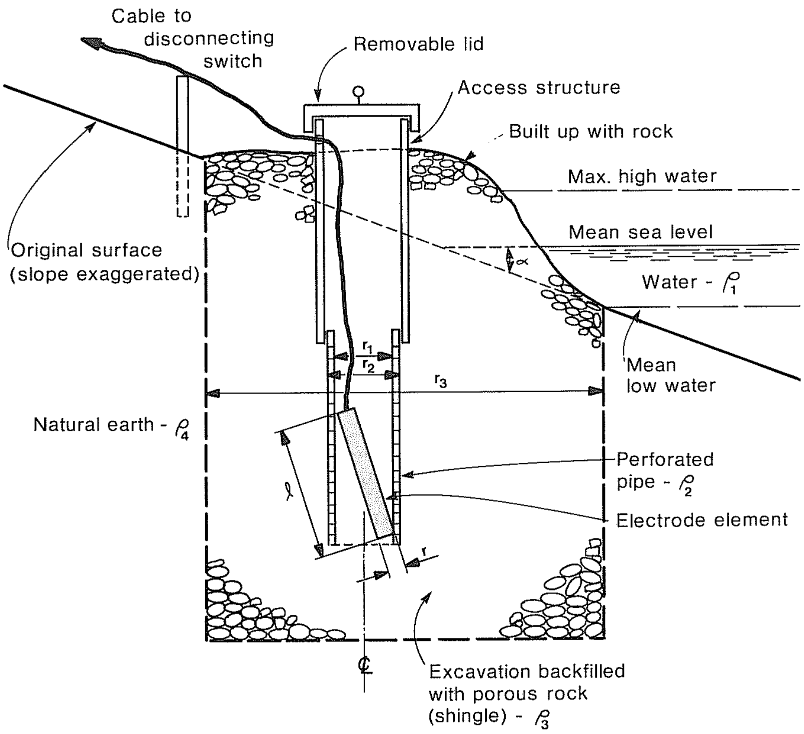


Figure 2.14 - Profile View of Beach Electrode in Shallow Well [1]

Figure 2.15 - Beach electrode in coke with covers to avoid Mixing of coke and soil

2.2.4 Pond Electrodes

A pond electrode is an electrode located on the sea shore with the active part directly in contact with seawater below the low tide water level and confined within a small area which is protected against possible wave and ice damage by a breakwater. Figure 2.16 and Figure 2.17 show examples of pond electrodes.

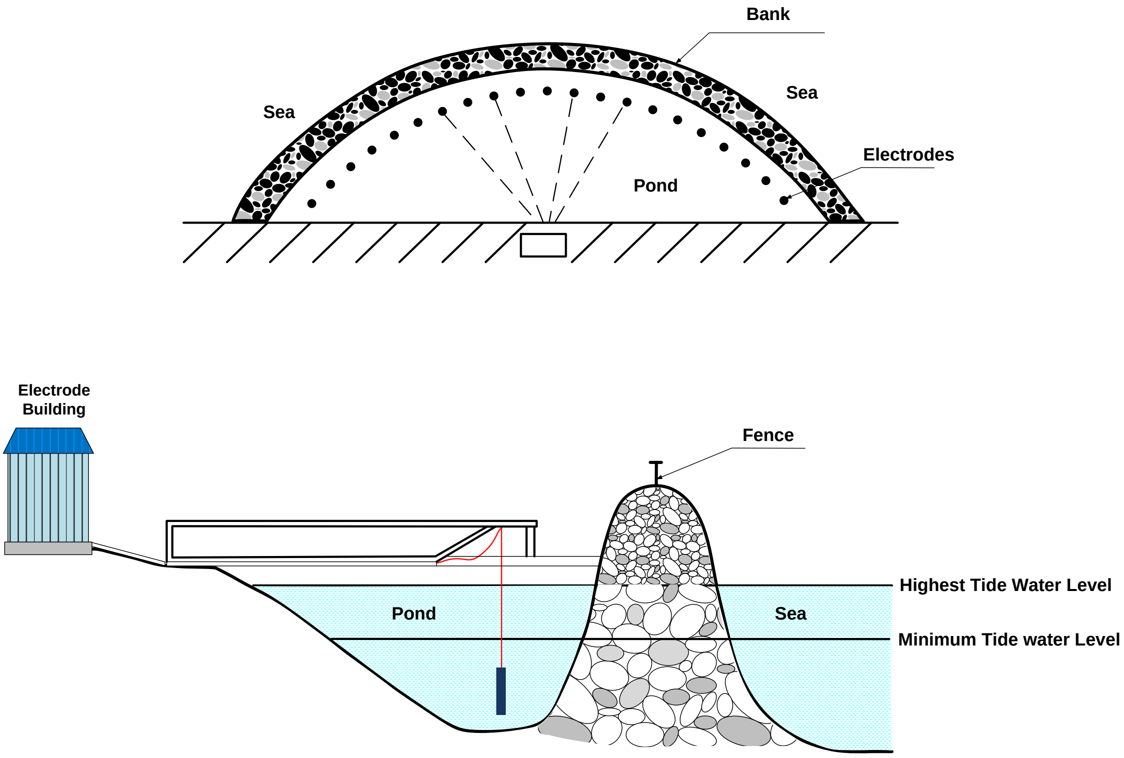


Figure 2.16 - Conceptual Plan and Profile Views of a Pond Electrode

Figure 2.17 - Pond Electrode with Sub-Electrodes Placed Directly in Seawater with Wooden Fence to Avoid Transfer Potentials

2.3 SELECTION OF ELECTRODE TYPE

Selection of the electrode type is a critical step during ground electrode design. It can be a complicated process as, in the general case, many electrode types would be possible near a given converter station. It usually requires technical and economic comparison of the options to select a safe, reliable, economically feasible, and ideally the most environmentally friendly type.

In selecting the electrode type the designer should consider the following factors:

a) The distance between the converter station and the prospective electrode site
b) The predominant soil resistivity in the vicinity of the converter station
c) Operational duties of electrode operation
d) Limitations on permitted operating duration
e) Operation and maintenance philosophy
f) Expected cost
g) Possible limitations on land use
h) Safety at the electrode site
i) Total number of infrastructure elements that could be adversely affected

If the converter stations are relatively close to the sea and the expected electrode operational duty is high or continuous, then sea or beach electrodes are a preferred technical option due to the low resistivity of seawater compared to soil. If there is a long distance between the converter station and the sea, a land electrode would be required. This can be challenging if the geological conditions consist predominantly of high resistivity bedrock and no part of the lower strata consists of some type of low resistivity material, in which case there may be no other choice than constructing a long electrode line to the seashore.

One possible differentiating factor in favour of land electrodes could be local regulations or laws which may restrict the maximum permitted duration or Ampere Hours of electrode operation. For electrodes with low duty or no requirement for continuous or long-time operation with high ground current, or with operational time restricted by legislation, land electrodes may be preferred due to lower cost.

Vertical types of land electrodes may have some advantages especially where the surface soil is not suitable for shallow electrodes. The active part of a vertical electrode would be below the ground water table or in a selected soil layer with adequate moisture levels. The vertical well may sometimes be drilled to a predetermined depth to take advantage of low resistivity soil or brackish water conditions. As the hydraulic pressure of water increases with the depth, the risk of electro-osmosis decreases and the boiling point of water increases allowing a higher current density to be used compared with a horizontal type of electrode placed only a few meters down in the ground. A vertical electrode will in general create lower surface potential gradients and the electrode resistance to remote earth would usually be lower for the same length of active element. The drawback is the drilling and casing cost which can be significantly higher than digging costs for shallow electrodes.

The type of electrode should be considered in parallel with the site selection process and design criteria, which are covered in Chapter 3 and Chapter 5, respectively.

3. ELECTRODE SITE SELECTION CRITERIA AND PROCESS

3.1 GENERAL ASPECTS OF SITE SELECTION

3.1.1 Process of Finding Candidate Electrode Locations

Finding a suitable location for an electrode requires both fact-finding and field investigations. The process should initially focus on acquiring information that would help in quickly eliminating unsuitable areas and in the prediction of electrode performance and environmental impact in promising areas. The results from each step in the process can influence the course of the succeeding steps. It can therefore be difficult to plan the entire process in detail beforehand.

A typical flow diagram of the different steps in the site selection process is presented in a flow chart in Figure 3.1.

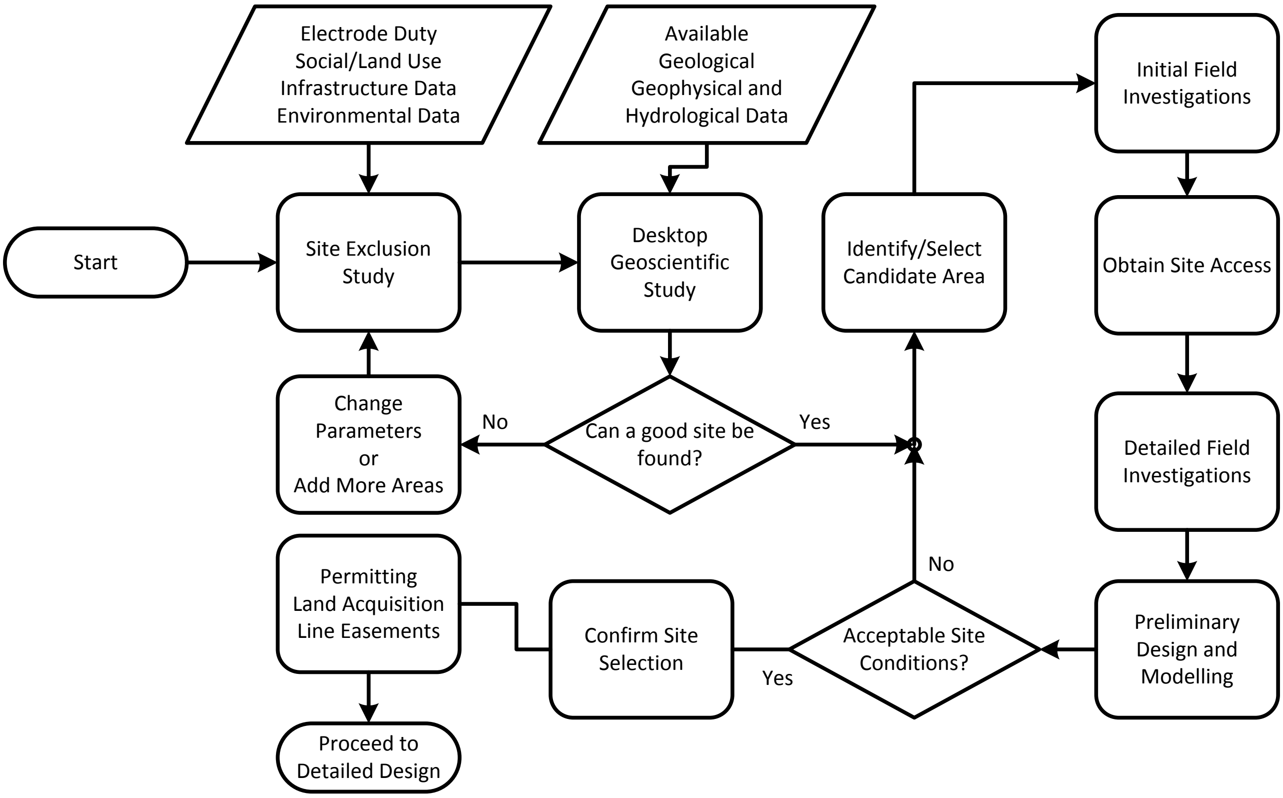


Figure 3.1- Flow chart for Site selection process

This chart should be seen as a generalized framework. Each project is unique and some of the different activities in the site selection process might be carried out in a different order. Some steps might not be realizable and therefore omitted and other processes not shown in Figure 3.1 may be required. Since the outcome of the process is not known beforehand, a reasonable approach is to identify a number of possible candidate locations in the early steps and then narrow down the number of prospective sites as work proceeds.

The exact order in which the electrode selection activities are carried out may vary slightly depending on the type of location that is being sought and the amount of information that can be found during the initial steps. Since the process is iterative and the outcome can be difficult to predict, it is important to start the site selection process at an early stage of the HVDC project. Different steps in the process are described in the sections below.

3.1.2 Site Exclusion Process

The first step in determining appropriate locations for electrodes is to conduct a site exclusion study. Such a study would make use of social and environmental data for existing land use or planned infrastructure. The study would assist in identification (at a high level) of inaccessible or inappropriate areas and would allow elimination of areas where electrodes could definitely not be implemented.

The site exclusion study will be useful to focus the project team into defining the criteria for appropriate study areas before extensive testing is done at prospective sites. The information gathered and the criteria that are formulated would also be useful as the basic inputs into environmental impact assessment (EIA) processes. The following high-level information would be needed as input to such a study:

a) Areas where electrodes would definitely not be allowed to be built.

b) Areas where electrodes might be allowed to be built but with a high cost or undesirably high environmental impact

c) Areas where the converter stations and buried or underwater infrastructure are to be located.

d) Preliminary indication of whether suitable right-of-way can be acquired for the electrode line (or cable).

Geospatial information tools and Geographic Information System (GIS) databases are useful for carrying out such studies. Information such as human settlement and land use information, land cover, protected areas, environmentally sensitive areas, etc. can be obtained from authoritative sources such as governmental organizations, professional associations, etc. The data sets can be loaded into a GIS application as spatial layers. Exclusion criteria can be developed and, areas either suitable or unsuitable for electrode location, can be identified as illustrated in Figure 3.2.

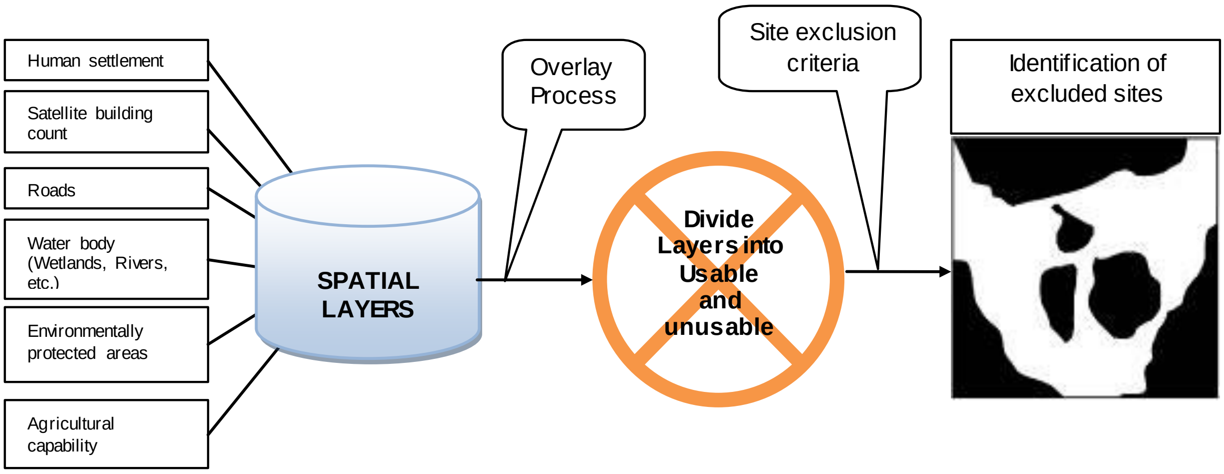


Figure 3.2 - Site exclusion process in a Geographic information system

The site exclusion criteria can be based on technical requirements, actual information and assumptions if detailed information, such as converter station location, is unknown. The criteria should include, for example:

a) Exclusion zones that are environmentally sensitive such as habitat or nesting area for rare or endangered species. This could include boundary or buffer areas around the directly excluded areas, for example, a safety buffer region of for example 2 km could be required.

b) Exclusion zones around other electrical, telecommunication or pipeline infrastructure.

c) Exclusion zones around the converter station sites. Electrode station should not be located too close to the converter stations to avoid corrosion to the buried structures in the station and to ensure that saturation of grounded transformers will not occur. The required separation distance can initially be estimated using rule of thumb guidelines but, if the site is being seriously considered, should be more accurately determined.

d) Factors that would exclude a particular site like human settlements, culturally or archeologically sensitive areas, highly productive agricultural areas, industrial areas, rivers, mines, urban areas, main roads, bridges, and docks.

e) Limitations on the maximum distance to the electrode site. For example, depending on techno-economic factors, it may be required to limit the length of the electrode line to a maximum distance away from the station. It is assumed that the cumulative costs of the electrode line will become more prohibitive the further the electrode site is from the converter station.

f) Exclusion zones for sea electrodes could include important fishing areas, fish farms, harbours, beaches and other tourist centres, shipping routes etc.

g) Exclusion zones should also apply to areas with possible, but not yet exploited, mineral resources, oil or gas fields, freshwater reservoirs, areas for wind farms etc.

h) Areas which are subject to flooding or other environmental hazards.

Some of the above site exclusion criteria will be hard and inflexible and, where these criteria apply, it would not be possible develop an electrode. Some other criteria may be soft or fuzzy, and the area in question could have some aspects which are not suitable for an electrode or which may require greater mitigation of possible interference but might still be selected if no other area with suitable geological and technical conditions is available.

Soft criteria can be assigned different weights or costs depending on their importance. A total cost surface can then be calculated in the GIS software. The cost surface can also be used in initial searches for suitable electrode line routes.

The importance of the data sets in the site exclusion study would typically be ranked with reference to each other. To do this, it would be necessary to formulate assumptions on the relative importance of each data set relative to another. A pairwise comparison technique could be used for the analysis.

In cases where no sites with suitable geophysical and geological characteristics can be found in the areas that remain after completing the exclusion process, it would be necessary to revisit the process and possibly adjust or relax some of the soft exclusion criteria.

3.2 TECHNICAL, ECONOMIC AND TIME ASPECTS OF SITE SELECTION

There are a number of factors related to different aspects of the HVDC system that may constrain the selection of an electrode site. Most of these factors are also covered in other chapters of this document since they also affect the choice of electrode type and the design of the electrode. The different factors are therefore only briefly described here.

3.2.1 Duration of Operation in Monopolar Mode

The requirements on the electrode site are dependent upon for how long the HVDC link will run in monopolar mode and the amount of current that will be injected into (or drawn from) the ground at the electrodes. Corrosion of buried metallic objects will be of less concern if the electrode is not operated continuously. Thermal and electro-osmotic effects at land electrodes would also be less problematic if the electrode is used intermittently rather than in continuous operation.

3.2.2 Rated and Overload current

The magnitude of current that will be injected into or drawn from ground will determine the electric potential rise around the electrode during operation. This will in turn determine the minimum distances to transformer stations and other sensitive infrastructure.

3.2.3 Converter Station Locations

The electrode will have to be located far enough from the converter station to avoid corrosion or saturation of grounded transformers. The cost for the electrode line will tend to favour shorter distances between the converter station and the electrode. However, it should be kept in mind that the extra costs that could result from choosing an inappropriate electrode site can be greater than the additional cost for a longer electrode line to a better electrode location. The location of the converter station may also make some electrode locations impractical or costly if the electrode line has to pass very rough terrain, densely populated areas, or wide rivers, etc.

3.2.4 Line Servitudes or Right-of-way and Land Acquisition

It must be possible to acquire, within an acceptable time frame, servitudes, right-of-way or other permitting for the electrode line. The acquisition of land for the electrode site for reasonable cost and within acceptable time must also be possible.

3.2.5 Environmental and Other Permits

It can be difficult to get acceptance for shore electrodes or sea electrodes close to the shore in some areas. The process of negotiations with landowners and other stake-holders, legal proceedings, possible appeals and court rulings can take a very long time. It is therefore essential that this process is initiated as early as possible. It may, in some cases, be necessary to exclude an electrode site if the process of permitting and land acquisition is expected to take too long.

3.2.6 Possible Impact on Infrastructure

The current injected into the ground may cause problematic electrical gradients that could affect grounded transformers, single-wire-earth-return (SWER) lines, pipelines etc. The electrode should not be located too close to such facilities. The minimum separation distance is however, a function of the earth resistivity and in most cases cannot be determined without detailed study, although approximate numbers may be assumed. The minimum separation distance may also vary over the area around the converter station due to differences in earth resistivity.

The possibility of transferred potentials should be considered for electrical infrastructure especially facilities entering the electrode site such as telephone lines, station service supplies and wire agricultural fences. Transferred potential can result in safety concerns if there is a single ground point or corrosion of the grounds if there are multiple ground points. The electrode current causes an upward or downward shift in the ground potential around the electrode. This potential difference between different points on a long metallic structure may cause current flow between a grounded facility at higher potential and a remote ground at lower potential. The ground point at higher potential will then act as a secondary cathode which can create potential gradients in its vicinity that can cause corrosion of objects that would not normally be affected by the primary electrode current.

The impact of electrode on infrastructure is covered in more detail in 4.

3.2.7 Constructability and Accessibility

The construction of land electrodes involves the use of excavators, drill rigs and heavy trucks. The electrode site must therefore not be located in unacceptably rough terrain or in swampy ground that cannot support heavy machines. The cost of construction of roads must be considered if an electrode site at a remote location is selected.

The construction of sea electrodes may be complicated at deep water, strong currents, high waves and rough and uneven sea-floor terrain. Protected bays on the other hand might be unsuitable if there are very strong restrictions on chlorine emission.

3.2.8 Permitted Potentials and Potential gradients

The maximum allowable electrical potential rise and potential gradients at different critical locations should be defined based on safety criteria and potential impacts on other infrastructure.

3.3 GEOPHYSICAL, GEOLOGICAL AND HYDROLOGICAL ASPECTS OF SITE SELECTION

3.3.1 Land Electrodes

3.3.1.1 Influence on the magnitude of the electric field by geophysical factors

An electrode must be located in such a way that electric potential gradients are at acceptable levels at sensitive infrastructure some distance away from the electrode. The electric field gradient at points some distance from the electrode (the far field) depends on the magnitude of the current, the distance from the electrode and the resistivity distribution or the soil structure. The shape and local arrangement of the electrode does not have a measurable impact at a distance that is large in comparison to the physical size of the electrode.

The effective resistivity of the earth may vary three or four orders of magnitude between areas of different geological conditions and the resistivity distribution is therefore a critical parameter in the selection of an electrode site. The resistivity down to a depth that is comparable to the distance between the electrode and the observation point must be considered. Problems with stray currents due to electric potential gradients may occur at tens of kilometers away from an electrode. The resistivity earth's crust and the upper part of the mantle of an area extending to perhaps 100 km or more from the electrode site must be considered in such cases.

Unfavourable conditions with high resistivity bedrock are common in areas dominated by solid crystalline rock such as granite or gneiss. Such rock types may dominate in areas of geologically stable continental crust. The thickness of the crust is usually around 30 to 45 km in such areas and the resistivity of the upper part of the crust may be of the order of 10000 Ω•m. The resistivity of the lower crust and the upper mantle is usually lower. Approximate resistivity ranges for different types of geological formations are given in Figure 3.3.

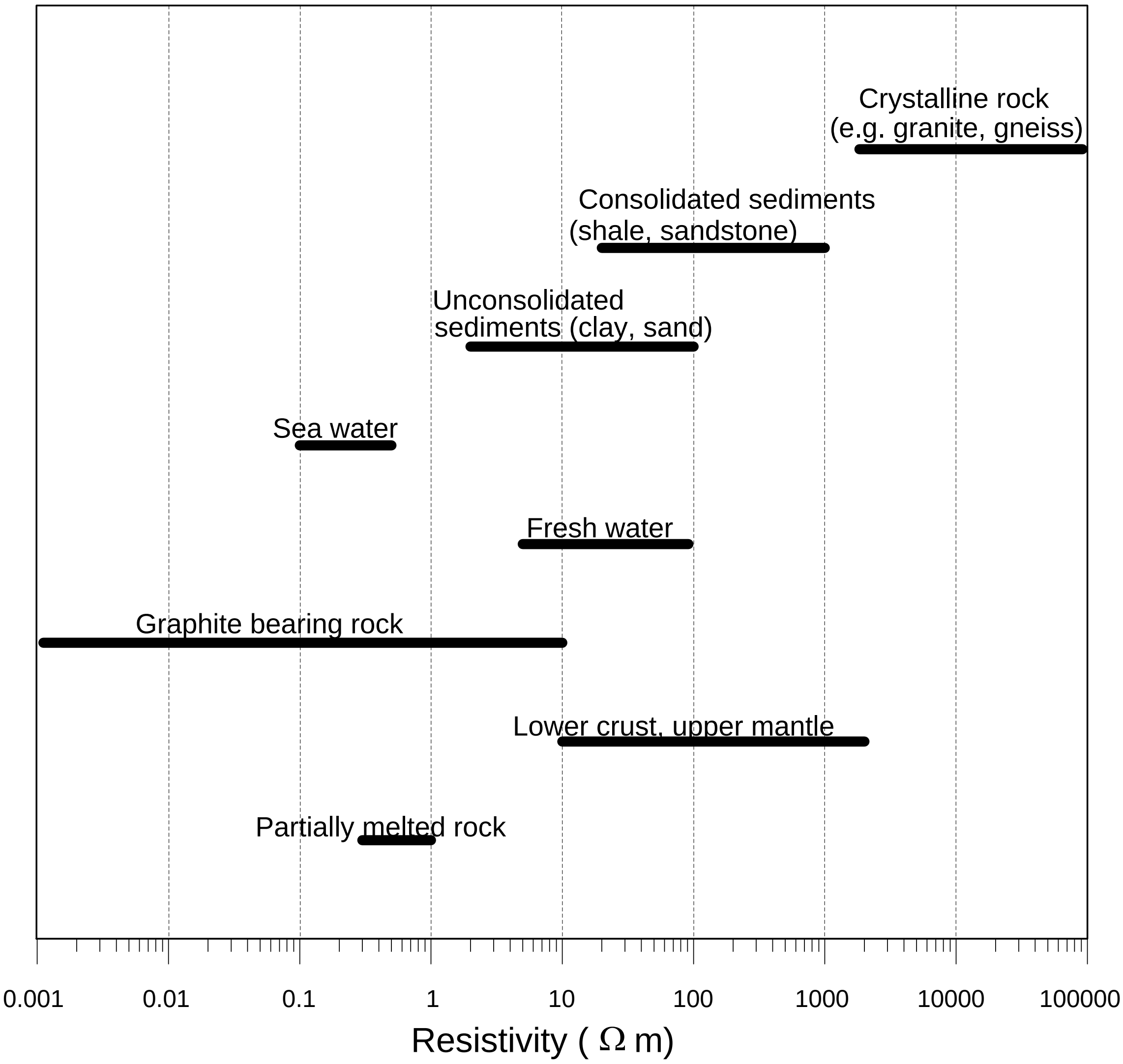


Figure 3.3 - Approximate resistivity ranges for different types of geological Formations

Favourable conditions for electrodes with low resistivity to significant depth may be found in certain geological formations such as deep sedimentary basins, rift zones, areas with active volcanism and areas with graphite bearing rock.

Prediction of electrical gradients far from an electrode requires good knowledge of the deep earth and variations in shallow resistivity of the geological formations in the area around the electrode. The deep earth resistivity of different geological units can be estimated based on known geophysical properties or by measurements using indirect techniques such as magnetotelluric measurements.

3.3.1.2 Influence of geophysical factors on electrode performance

General criteria for good electrode performance are

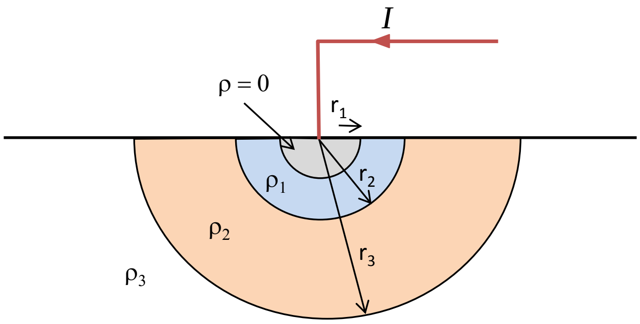
a) the resistance to remote earth should be low

b) the electrode availability should be high

c) the current differences between electrode elements should not be excessive.

The performance of an electrode is influenced both by the local soil immediately adjacent to the electrode as well as soil materials that are further away. An electrode placed in a thin layer of low-resistivity soil cover underlain by high-resistivity rock will have high resistance to remote earth.

This can be illustrated by an simple example shown in Figure 3.4. The resistance of this electrode relative to a remote reference can be calculated based on a model consisting of concentric hemispherical shells.



$$R = \int_{\infty}^{r_1} -\frac{\rho \cdot dr}{2\pi r^2} \qquad \text{for this case:}$$

$$R = \frac{1}{2\pi} \cdot \left(\frac{\rho_3 - \rho_2}{r_3} + \frac{\rho_2 - \rho_1}{r_2} + \frac{\rho_1}{r_1} \right)$$

Figure 3.4 – Simple electrode model consisting of concentric hemispherical shells

The central grey portion in Figure 3.4 represents the local electrode construction with negligible potential drop within the electrode structure corresponding to approximately zero resistivity. The electrode is situated in a low-resistivity volume (blue) consisting of unconsolidated sediments. This volume is in turn surrounded by a high-resistivity shell (orange) that would represent hard-rock basement. If we assign the values: ρ_1 = 50 Ω•m, ρ_2 = 20000 Ω•m, ρ_3 = 500 Ω•m, r_1 = 300 m, r_2 = 2000 m, r_3 = 10000 m, then the calculated resistance of the electrode is 1.3 Ω. It is then interesting to note that the electrode resistance is almost unaffected by parameters r_1 and ρ_1. The resistivity of the host material closest to the electrode is of minor importance for the resistance (changing ρ_1 to 10 Ωm will only decrease the resistance by 1.4%. The conclusion is that an electrode placed in a sedimentary basin (or in seawater) will have low resistance only if the basin (or water body) has large dimensions (laterally and vertically) and if the resistivity of the underlying basement material is not extremely high.

The model in Figure 3.4 can also be used to calculate electric potentials and potential gradients. The potential gradient just outside the electrode is directly proportional to ρ_1 and inversely proportional to r_1. The host material resistivity and the size of the electrode are therefore important parameters for electric potential gradients close to the electrode.

Figure 3.5 shows a more typical geological structure consisting of horizontally stratified layers but the calculations are more complicated. We can assume an example with the same parameter values as for the hemispherical shell model above, but with r_1 = 0 (point source), h_2 = 300 m and h_3 = 10000 m. With an injected current of 1000 A, the electric potential rise at 10 km distance would be 38 V. If ρ_2 is set to 5000 Ω•m, the potential at 10 km distance would be reduced to 23 V, i.e. to 60% of the first value.

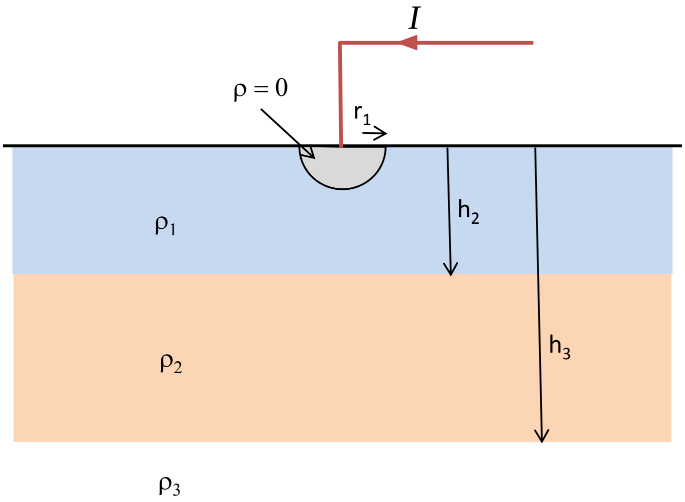


Figure 3.5 – Electrode model consisting of horizontal layers

The conclusion is that the potential rise at large distances from the electrode is dependent on the resistivity at large depths, even in case where the electrode has been placed in a fairly thick low-resistivity surface layer. This may also be true for sea electrodes if the seawater is shallow around the electrode and the current cannot readily dissipate into deep-water areas nearby.

Ohmic losses will raise the temperature in the soil near the electrode. The temperature must not be allowed to rise above the boiling point of the water in the surrounding soil. The temperature rise is a function of the current density, resistivity, thermal conductivity, pore-water convection and the time of operation of the electrode. Electro-osmotic effects may cause pore-water flow away from the anode (or towards a cathode). Water flow away from an anode can increase the resistivity of the soil immediately adjacent to the electrode resulting in increased thermal losses and in turn increased temperature rise. If the electrode is located below the water table, the electro-osmotic flow may be balanced by hydraulic return flow at steady state. Problems with electro-osmosis are therefore less likely in material of significant hydraulic conductivity and with hydraulic head which favors water flow back towards the electrode.

Electrode resistance to remote earth, thermal heating effects and electro-osmotic effects are dependent on the design of the electrode. A large electrode with large contact surface to the host material is less likely to have problems but will also be more expensive. A proper selection of electrode site might therefore be cost saving.

Current sharing between sub-electrodes or electrode elements will be uneven if the resistivity varies significantly in the host medium of the electrode. The current sharing in a shallow electrode design might change seasonally due to variations in moisture content. A vertical electrode design using boreholes will have uneven current sharing in the boreholes if there are strong resistivity contrasts between different horizontal layers in the ground. Current density will be increased where the borehole passes though low-resistivity layers and reduced where the borehole passes though strata or regions with higher resistivity. The differentiation between low-resistive layers and higher resistivity layers will usually be difficult to resolve with surface based geophysical measurements and an accurate picture may require that resistivity be determined by drilling and logging test boreholes.

3.3.2 Sea and Shore electrodes

For sea electrodes, it is important to keep electric fields low to avoid effects on the sea animals. The current density must also be kept low to avoid unacceptably high chlorine emissions. The low resistivity of salty or brackish water will usually keep electric fields at low levels around sea and shore electrodes but significant electric fields can occur if a sea electrode is located in a shallow water environment underlain by high-resistivity solid, crystalline rock. The seawater will almost act as one single large electrode volume in such cases and high electric gradients can be created perpendicular to the shore line at quite large distances away from the electrode. Thus, it is important to select sites with rapid transition to deep water and direct access to the open sea.

3.4 PROCESS OF GEOPHYSICAL AND GEOLOGICAL INVESTIGATIONS

3.4.1 Geoscientific Desktop Study and Definition of Candidate Areas

The purpose of a geoscientific desktop study is to compile geological and geophysical information from publicly available files into a regional model of relevant parameters for the selection of candidate locations. The amount of information and the level of detail will vary considerably from one area to another. Typical information can include but is not limited to:

a) Geological maps – they are usually available at different scales such as national geological surveys. The maps may be accompanied by text descriptions.

b) Deep probing geophysical measurements – they could include magneto-telluric surveys from scientific investigations or from geo-thermal exploration. The image in Figure 3.6 shows a vertical section that explains magneto-telluric data acquired around the Gerus electrode of the Caprivi Link [8]. The electrode is located offset from the survey profile but at a position corresponding to the ELG005 station shown in the figure. A low-resistivity structure is seen that extends to the deeper parts of the earth's crust.

c) Airborne geophysical data – this may be available from some national geological surveys and mineral exploration or ground-water projects. Magnetic and radiometric data are most common but electromagnetic data that gives direct information about the resistivity of the ground might also be available. Figure 3.7 shows results from airborne measurements in Finland with 200 m line spacing [9]. Red and purple colours correspond to low-resistivity structures in the ground. The banded patterns are related to graphite bearing rock of low resistivity.

   The Gerus electrode of the Caprivi Link is one example of an electrode that was located in this type of geological environment. Figure 3.8 shows results from helicopter-borne measurements at Caprivi, Namibia [10][11]. The resistivity at approximately 15 m depth below surface is shown. The Zambezi electrode of the Caprivi Link is located approximately at 24.2°E/17.7°S, just outside the surveyed area. A vertical section from the same survey is shown in Figure 3.9. That survey line is located around 3 km from the Zambezi electrode. The validity of the investigation depth of the method was around 50 m.

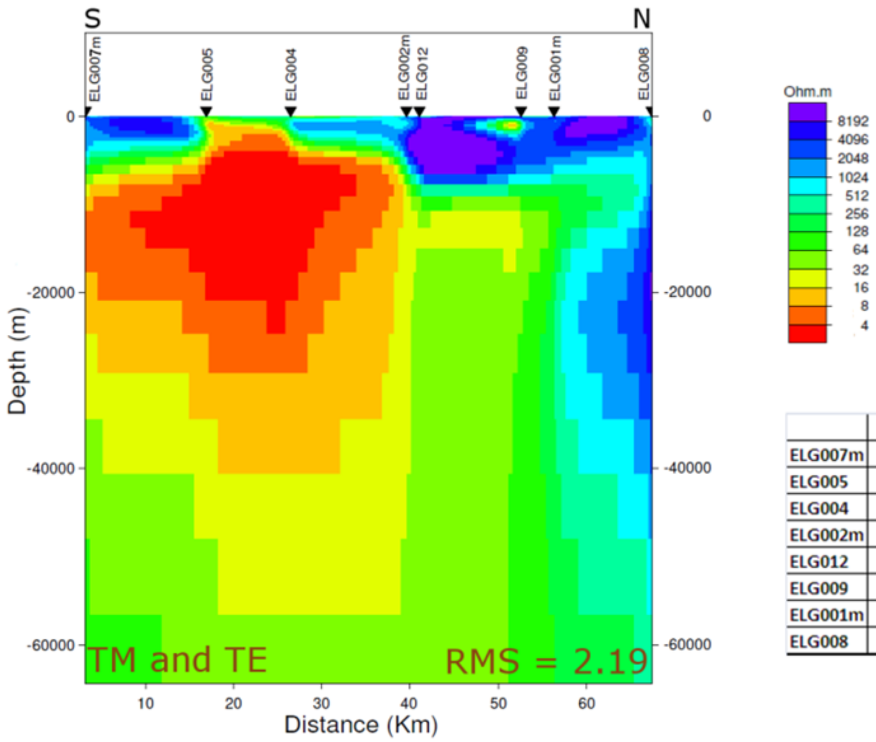
d) Mineral or oil exploration data - earth resistivity measurements from exploration purposes are proprietary and unavailable in most cases. However, some countries require that exploration companies lodge their data at some public archive when an exploration permit is abandoned. It might be possible to acquire such data at low cost.

e) Geothermal data- information about geothermal activity, hot springs, thermal gradients etc. may be found in various sources. Elevated heat-flow through the earth's crust is usually related to low electric resistivity.

f) Ground water data - some countries keep public archives of wells for ground water exploration and production. The information can include ground water level, water salinity and electric conductivity. This information can be used to locate areas with shallow ground water level so that a low-cost electrode design might be possible.

g) Marine geological maps – these are available in many countries. If such information is not available, it might be possible to infer geological conditions at close range from the coast-line from geological maps of neighbouring land areas. Detailed bathymetric data might be difficult to access since such information often is treated as classified. Special permits will in most cases have to be arranged. Coarse information about water depths can be found on sea charts.

Information that is relevant for the site selection process should be extracted from available sources of information. The results may be very detailed or quite coarse depending on the available information and might require further processing for presentation in a desktop study report. The report should point out general areas where it should be possible to locate an electrode, although it might not be possible to determine specific locations. The report should also include information about what information, if any, is missing for the next steps in the process to be carried out. Recommendations should be given regarding complementary field investigations.



	RMS	TM-SS	TE-SS
ELG007m	1.62	1.17	1.52
ELG005	1.41	0.50	0.48
ELG004	2.11	3.42	1.08
ELG002m	2.25	0.91	0.58
ELG012	2.39	0.86	0.36
ELG009	3.18	0.82	1.37
ELG001m	2.40	1.04	0.72
ELG008	2.01	2.15	2.07

Figure 3.6 - Typical Resistivity ProfiLE Provided by magnetotelluric survey

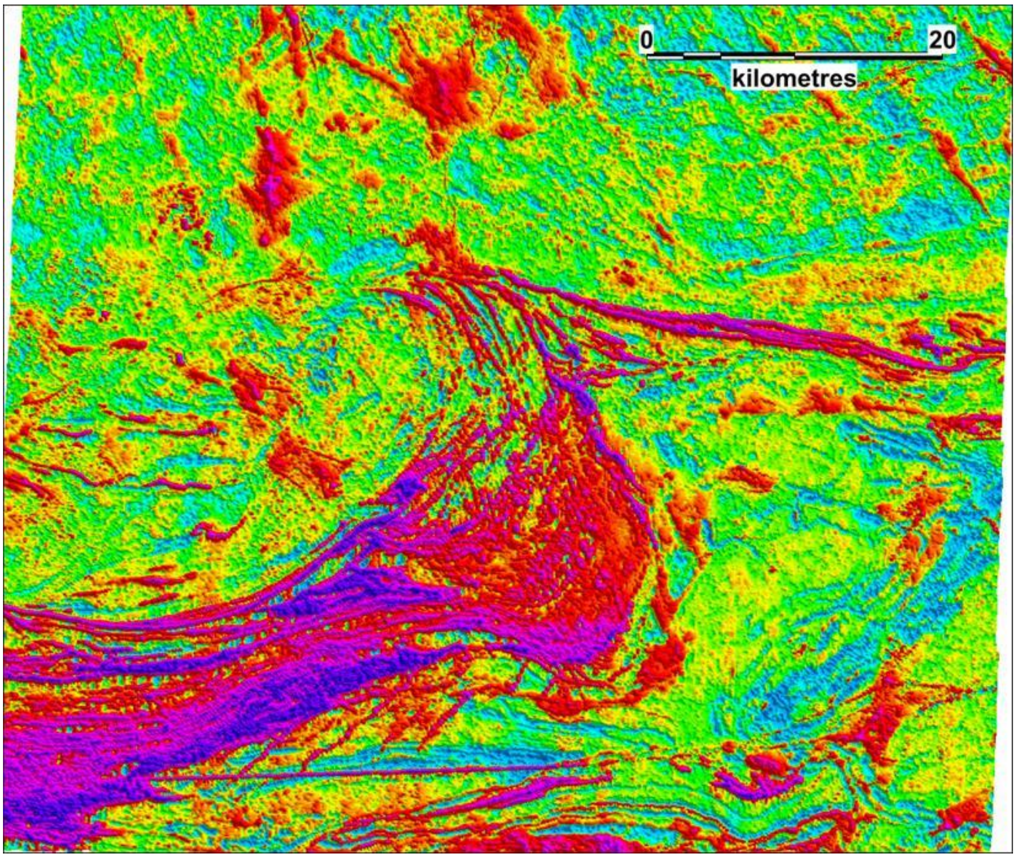


Figure 3.7 - Airborne electromagnetic measurements in Finland that highlight low-resistivity graphite bearing structures (red-purple) in the ground [9]

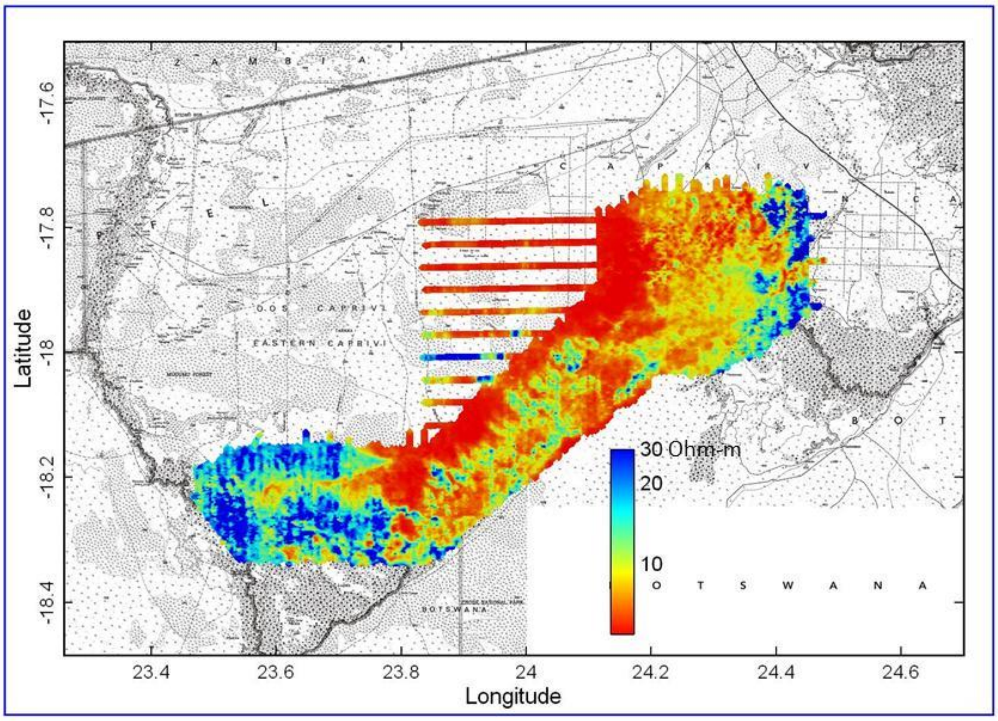


Figure 3.8 - MAP showing helicopter-borne geophysical results from Caprivi, Namibia [10],[11]

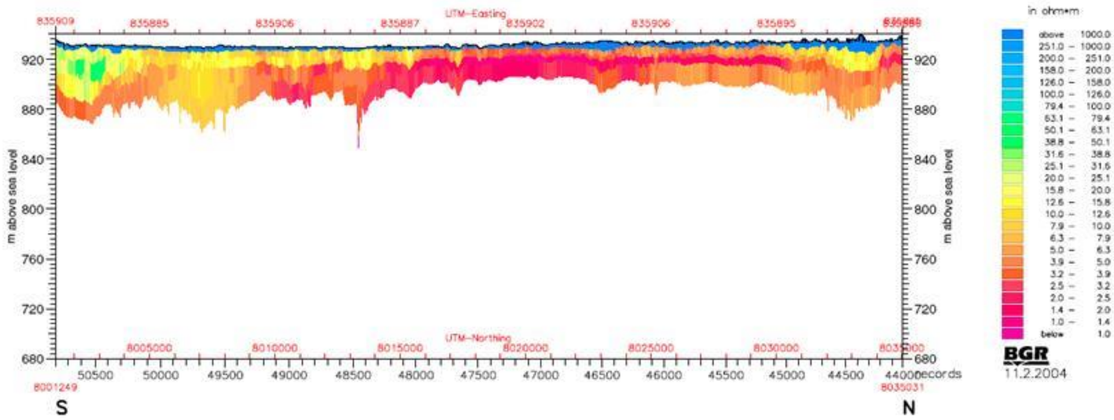


Figure 3.9 - Vertical section based on one of the flight lines from the Caprivi helicopter-borne survey of Figure 3.8

3.4.2 Initial Resistivity Model

Areas around some planned converter stations might host sensitive infrastructure and some areas can have geological conditions that can already be expected to be unfavourable at an early stage. In such cases, it is advisable to construct a tentative resistivity model of the ground based on the outcome of the desktop study alone. The complexity of the model will then be a function of available data and the resistivity with certain geological units being perhaps completely unknown. Values may then be assigned based on experience from other places with similar geological conditions. The model can be used to predict the magnitude of the ground potential rise and the electric field as a function of distance from a tentative electrode position. The predictions should be treated as indicative only if the model is based on uncertain and/or inferred parameters.

An example of a regional resistivity model based on open-source geological and geophysical data is shown in Figure 3.10 (exaggerated vertical scale) [12]. The size of the model is 70x70x40 km but only the top 3.5 km of model is shown in Figure 3.10. The Fågelsundet sea electrode is on the Swedish side of the Fenno-Skan Link. The Dannebo converter station is located at Forsmark close to the Forsmark nuclear power plants. The distance from Fågelsundet to Forsmark is 25 km. The bedrock in the area is dominated by granite with high resistivity on land (estimated to 14300 Ω•m). The resistivity is lower below the Baltic Sea due to brackish and salt ground-water in the granite-dominated bedrock. The brackish-fresh groundwater interface dips towards the land side. Bathymetric data have been used to set the thickness of the low-resistivity shallow brackish seawater layer in the model. The potential rise due to current injection at the Fågelsundet electrode was calculated with a finite-difference program and the results are shown in Figure 3.11. The potential gradient is estimated to be about 0.005 V/A or 5 V/kA at Forsmark. It is also noted that the potential gradient is higher on the sea compared to that on the land side at the same distance from the electrode. The electric field is also perturbed compared to a homogeneous ground case so that the potential gradient tends to be perpendicular to the shore line.

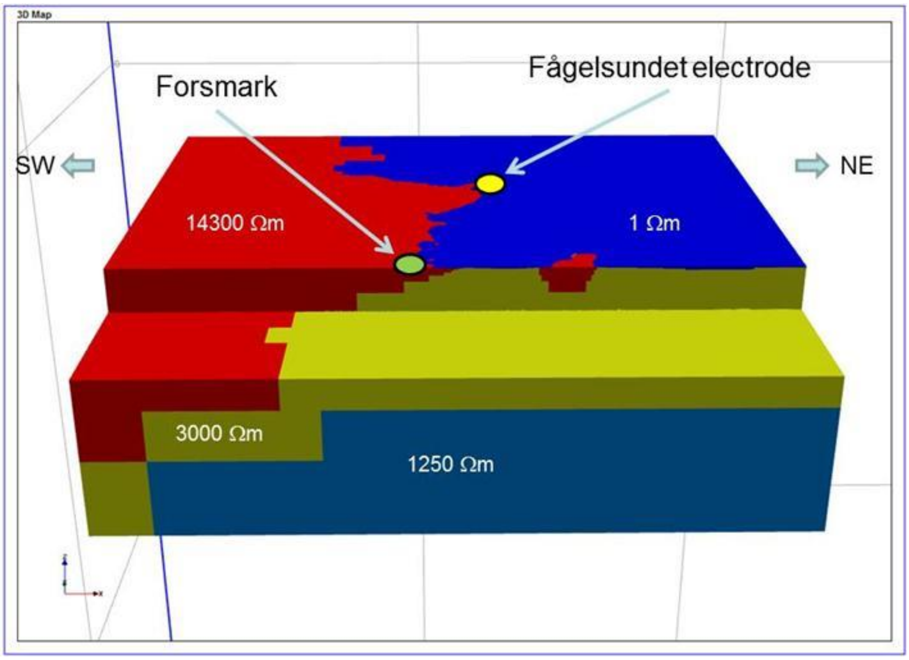


Figure 3.10 - Regional resistivity model around the Fågelsundet electrode based on open-file data [12]

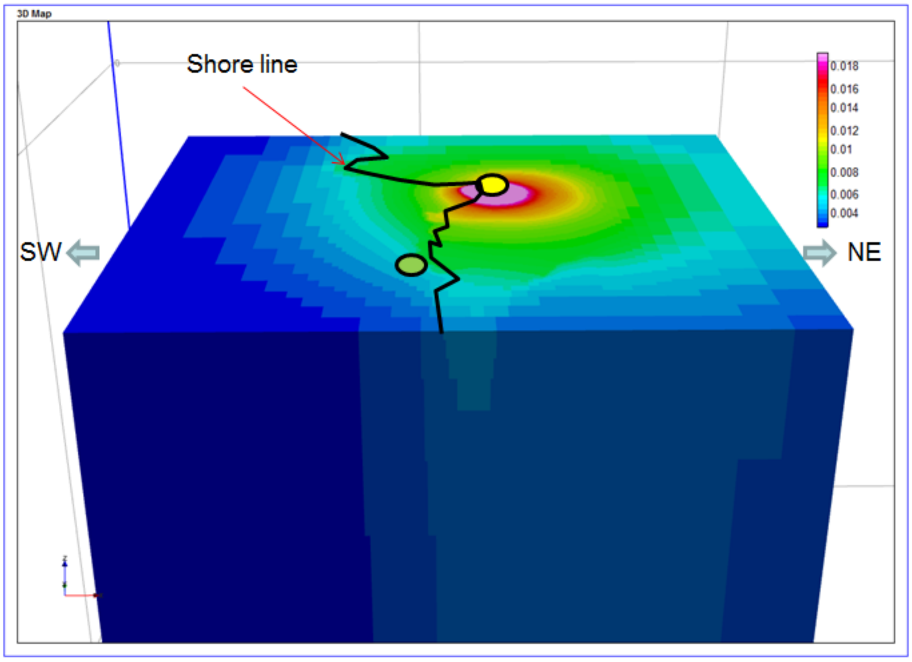


Figure 3.11 - Calculated potential RISE due to current injection at Forsmark (Figure 3.10) into the resistivity model [12]

3.4.3 Initial Field Investigations

In many case, a geoscientific desktop study will not be able to establish the resistivity at large depth. The desktop study and initial resistivity model should determine if such information is necessary for the site selection and if so a magnetotelluric survey should be carried out. However, it is possible that the electric fields may in some cases fall to insignificant values (for example around a sea or shore electrode) at such short distance that a deep probing survey may not be necessary.

The distribution of survey stations for a magnetotelluric investigation will be dependent on the geology of the area and can vary from scattered stations to systematic profile measurements across significant geological structures. The magnetotelluric data should be interpreted with care. The interpretation should be compatible with known geology and with reasonable resistivity values. Magnetotelluric survey stations need not be placed exactly at the possible electrode location since this often requires access to private properties. Instead, they can be placed at positions on public land that do not require permits or where such permits are easy to arrange.

Initial field investigations should also include site visits for geological reconnaissance mapping. The site visits should focus on determining information and parameters that are essential for the electrode design and construction. This will include rock and soil types, soil particle size, soil moisture levels, possible depth to ground water table, land access, impediments to constructability, environmental factors etc.

In cases where it is evident that the site selection will be difficult based on information from the desktop study, deep probing geophysics and field visits, it might be wise to carry out a helicopter-borne geophysical survey as shown in Figure 3.8 and Figure 3.9). Such a survey will cover a large area to a reasonable cost and permitting is usually not a serious issue.

Initial field investigations for sea electrodes can include sonar or echo-sounding investigations of sea-bottom topography and morphology.

Initial field investigations should also identify possible obstacles for electrode line routing and construction.

3.4.4 Site Selection

Candidate sites for an electrode should be selected in areas that have passed the site exclusion process and where appropriate geological conditions can be expected based on the geological desktop studies and initial field investigations. The process for the selection will be dependent on the geological environment and the type of electrode that is contemplated. It is generally a good idea to select a number of candidate sites since some of them might be disqualified later based on the results of detailed site investigations.

Trench based land electrodes should preferably be located in areas with shallow ground water. Locations with high-resistivity rocks at shallow depth should be avoided even if they are covered by low-resistivity soil. Fine grained clay soils should be avoided if the electrode will be used in anodic mode, since problems with electro-osmosis might occur. Topographic maps, well data, satellite imagery and airborne photographs are useful datasets in the selection of locations with presumably shallow ground water.

Deep well electrodes comprised of vertical boreholes should be located in areas with fairly thick cover of alluvial sediments and permeable sedimentary rocks. The groundwater should be at reasonably shallow depth to avoid the necessity of drilling deep holes. Drilling may also be complicated by unconsolidated sediments since holes might collapse.

3.4.5 Permitting, Land Acquisition, Line Servitudes

Detailed field investigations will in many cases require landowner and stakeholder permissions. Many types of geophysical and geological investigations might therefore be limited to selected sites where such permissions have been arranged.

The permitting process can take considerable time. It is therefore essential that the entire site selection process is started early enough so that the site selection does not degrade into a process where the permits can be arranged quickly enough.

The final selection of electrode site will require land acquisition. A servitude or right-of-way must also be arranged for the electrode line. Servitudes might already exist for the HVDC line or for some AC line from the converter station that can be used for at least part of the electrode line.

3.4.6 Detailed Field Investigations

Detailed site investigations with geophysical methods should be carried out in order to test if candidate sites fulfil the requirements for an electrode location. Testing of candidate sites on land might require boreholes in some cases.

Electrode sites can be tested with resistivity measurements. Profile measurements using multi-electrode system will enable two or three-dimensional modelling of the data whereas soundings such as Schlumberger array will be adequate if the geology is known to be horizontally stratified and with small lateral variations in electric properties. The investigation depth should not be too small in comparison with the physical dimensions of the expected electrode design. The acquired data together with magneto-telluric data should be detailed enough and with sufficient investigation depth so that a resistivity model can be compiled to estimate the electric field around electrode.

Resistivity measurements with detailed resolution for near-surface layers should also be carried out if a shallow land electrode design is considered. For large sites, a number of survey profiles should be taken close to where the trenches of the planned electrode will be located. An example of the results from such a survey with around 10 m investigation depth is seen in Figure 3.12. The data were acquired at the Zambezi electrode site of the Caprivi Link. A highly resistive layer surface with around 3 m thickness indicated that a trench electrode would be an unsuitable alternative. The very low resistivity below 3 m depth favoured a design based on vertical drill holes that could be kept quite short.

Interpretation and modelling of resistivity measurements is a not unique process as it is dependent on the assumptions and understanding. Great care should be taken so that the data used in modelling is realistic and compatible with other geological information.

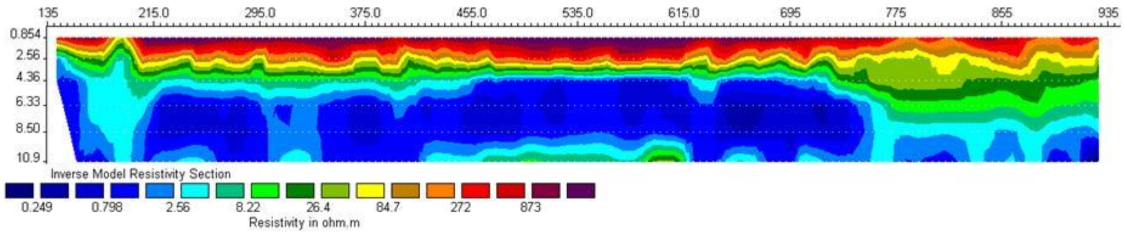


Figure 3.12 - ground SHALLOW resistivity profile (courtesy of NamPower)

Knowledge about hydraulic parameters might be important in some situations to identify potential problems such as electro-osmosis. Information about aquifer properties can be gained by magnetic resonance soundings (MRS) or by drilling boreholes.

Detailed field investigations for sea electrodes should investigate factors like sea currents, sea-bottom roughness and sea-bottom soil conditions. Morphological and geological investigations can include side-scan sonar, sub-bottom profilers and echo-sounders. Bottom conditions should also be investigated by divers and/or with under water vessels and documented by camera. Soil sampling can be carried out with grab-samplers or box-corers. Resistivity measurements are possible for sea electrodes, at least in shallow water areas, however more complicated than on land. The resistivity may also be measured on undisturbed soil samples from the seabed.

3.4.7 Detailed Resistivity Model

The initial resistivity model can be updated based on the data from detailed field investigations at the candidate sites. Separate models would be prepared for all candidate sites unless some locations can be excluded immediately due to unsuitable properties. The soil volume would be discretized into some mesh suitable for numerical modelling. The electric field due to injected current can then be calculated.

3.4.8 Preliminary Design and Electrode Modelling

At this stage of the site selection process it is usually possible to foresee what kind of electrode type will be most suitable and a preliminary design can be made. A preliminary electrode design can be used to establish tentative dimensions that would result in step and touch potentials within acceptable limits.

An example of the predicted potential for a tentative electrode design can be seen in Figure 3.13. The tentative design is based on a double ring of vertical boreholes. The potential is around 330 V at the active part of the electrode holes and the maximum ground potential rise is around 300 V.

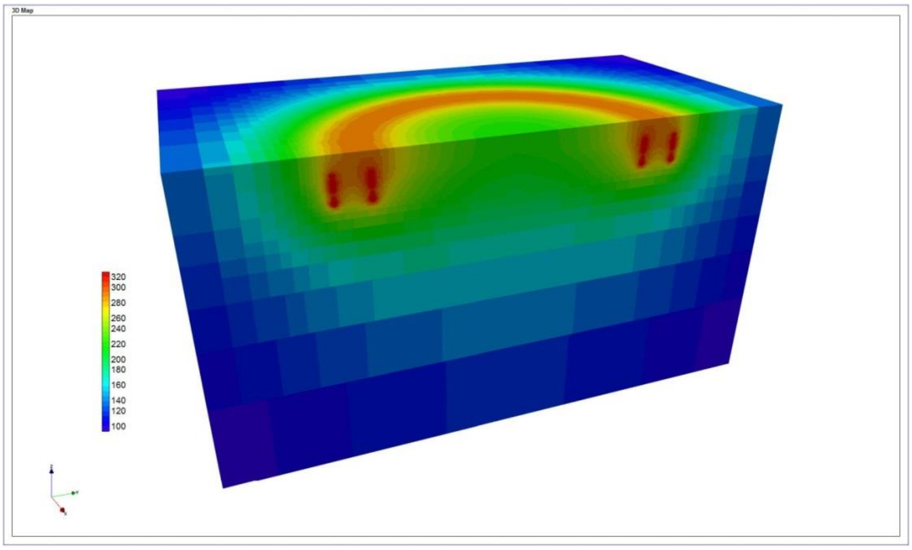


Figure 3.13 – Results from modelling of a tentative electrode design

The preliminary model can be used to check if the electrode site is likely to have acceptable properties. The estimated potentials can be compared with requirements for electric potentials and potential gradients at sensitive infrastructure. Estimated potential gradients at the electrode can be compared with maximum permitted step and touch potentials.

3.4.9 Borehole Investigations

Additional investigations would be made at the site that has been selected for the electrode.

Test boreholes will most likely be necessary before the electrode design can be finalized. The boring can be carried out with percussion, reverse circulation (RC) or core drilling. The choice of drilling technique depends on the geological environment, information that is required from the borehole investigation and the availability of drill rigs. There is also a difference in cost between the different techniques.

Several types of geological investigations are possible with test boreholes depending on the geological situation, the expected type of electrode design and availability of equipment and contractors. Possible investigations include:

a) Geological mapping of core or drill chips.
b) Defining the water table levels or piezometric ground water surface and monitoring of seasonal changes.
c) Performing pump tests in order to get in-situ estimates of hydraulic conductivity.
d) Sampling of groundwater and measurements of conductivity, pH etc.
e) In-situ resistivity logging with an induction probe.
f) In-situ resistivity logging with a galvanic probe. The galvanic probe requires that the hole is water-filled. Galvanic probes have better resolution for high-resistivity layers whereas inductive probes have better resolution for low-resistivity layers.
g) Soil sampling with e.g. a Denison tube. Measurements of electric resistivity, hydraulic conductivity, electro-osmotic permeability, porosity and thermal properties may be carried out on the samples.
h) Thermal response tests, giving in-situ estimates of thermal conductivity

In-situ resistivity measurements are always recommended. In-situ resistivity logging with inductive probed will provide detailed information of the resistivity down the hole if a metallic casing has not been used. An example of induction probe measurements from a vertical borehole are shown in Figure 3.14. The measurements are presented as electric conductivity for two different transmitter-receiver separations. The maximum value corresponds to a resistivity of 2 Ω•m. Natural γ-radiation was also measured down the hole. Variations in radiation are mainly due to the relative abundance of potassium (K_{40} isotope). Clayey layers are expected to contain more potassium than sandy layers.

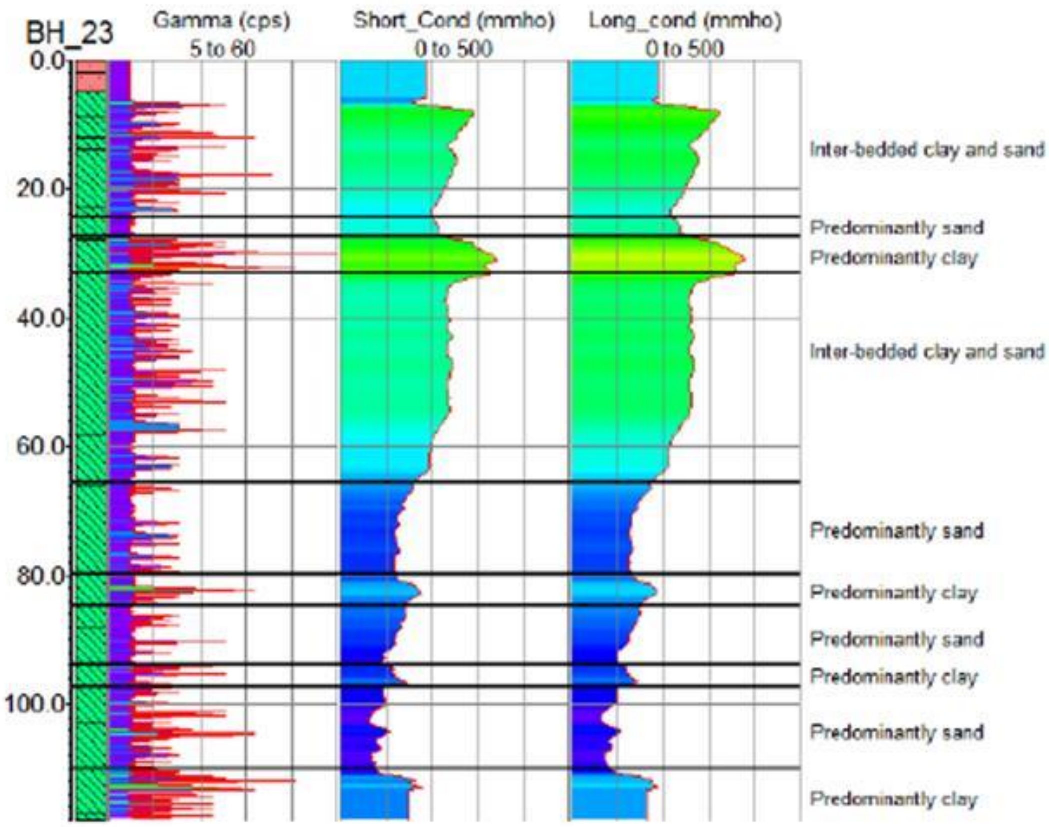


Figure 3.14 – Results from down-hole electric conductivity and gamma radiation logging from a test hole at the Zambezi electrode site of the Caprivi Link

For a borehole based electrode design, test boreholes will provide valuable information about stability and water influx that is necessary in the planning of how to lower electrode elements into electrode holes and backfill those holes.

3.4.10 Test Electrodes

Modelling of geophysical survey data can be a non-unique process and it is important to check independent data sources or independent test results so that a reasonably correct resistivity model can be established for the area surrounding the electrode site.

Measurements with a test electrode can be used to verify if the resistivity model is sufficiently accurate, at least to a depth that corresponds to the investigation depth of the test electrode and its associated remote electrode. The resistivity model may be updated to fit the measurements if there are discrepancies. The model should be compatible with all survey data.

The possibility of utilizing investigation boreholes as test electrodes should always be considered. A test electrode can be made by lowering a number of connected steel rods down a borehole and connecting them to a DC or low-frequency AC current source. The advantage of a low-frequency ac injection rather than a dc source is that it would be easier to discriminate between the signal due to the test source and background levels due to telluric currents at long distances from the injection points. The output current of the test source should preferably be high enough to enable measurements of the electric potential a few km away from the test electrode.

It is possible to construct a test electrode if no borehole is available. Steel rods can be driven into the ground or be buried in a pit. It might however be difficult to inject sufficiently high current to facilitate measurements with such a test electrode if the surface soil has high resistivity.

4. IMPACTS OF ELECTRODES

4.1 INTRODUCTION

Site location for ground electrodes is a non-trivial issue as local techno-economic variables and environmental issues may hinder and/or complicate the site location possibilities.

Besides any obvious visual, construction and electrode line impacts, there are less evident environmental impacts caused by operation of an electrode which injects dc current into the earth for extended periods. The degree of such impact and the size of the area influenced are dependent on the magnitude of current injected, average the time of operation during a year, the resistivity and other physical properties of the soil, and the most importantly the siting of the electrode relative to objects or infrastructure that may be impacted.

For AC grids, the main concerns related to ground currents operation are safety aspects and operational problems. However, for HVDC ground electrode currents, due to the extended period the current may be injected into Earth (which could last several months or longer), other environmental problems may appear. The types of impacts are mainly the following

a) DC current flowing out of metallic structures may cause **corrosion** at the theoretical Faraday corrosion rate. This is of specific concern for large buried metallic structures such as unprotected pipelines or large metallic structures in contact with the ground such transmission lines with grounded shield wires, bridges and other large facilities such as harbour infrastructure.

b) DC current may cause saturation in transformers with grounded neutrals.

c) DC current may cause transferred potentials in large metallic structures due to the ground **potential rise** and associated **surface potential gradient**. Thus, long metallic fences and radial irrigation systems can become safety risks.

d) DC current may cause **chemical reactions** in contact with the conductive media (seawater or moist soil), which may produce gases or other chemicals.

e) DC current for long periods of time may cause **soil overheating** close to the active parts of the electrode, which may alter the conductive media properties and the physical properties of the soil adjacent to the electrode.

f) DC current for long periods of time may cause **ground water heating**, even up to the boiling point, close to the active parts of the electrode, which may alter the surrounding environment.

The design of the electrodes may have certain environmental impact, but its influence is mainly local and can be influenced by the design of the electrode. It is therefore necessary to differentiate between two types of environmental impact:

"Local impact", where the design of the electrode has a direct influence, and

"Remote impact", where electrode siting has the major impact.

Although electrode operation may have environmental impacts, these can often be minimized or mitigated by proper selection of the electrode site, in the case of remote impacts, and by proper design, in the case of local impacts, some mitigation measures can be taken into account if any of the following phenomena occur.

Electrodes can also have an indirect positive environmental impact by providing a low resistance return path. This results in lower power losses, which means that the extra energy required to provide these losses does not have to be generated. Similarly, the size and mass of transmission line towers and hence cost may be reduced if they do not have to be designed to carry a metallic return conductor.

Environmental issues related to operation with ground return and mitigation measures for potential interference are summarized in more detail in Table 4.1

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Table 4.1 - Electrode Impacts and Mitigations

Issues	Environmental impact	Area of impact	Primary Physical Variable that defines the impact	Mitigation Measures [13][14]
General:				
Effects on existing and new metallic underground or earthed infrastructure in the vicinity of the electrode	Ground rise potentials may cause disturbances in telecommunications circuits: telephone, railway signalling systems.	Extended	Electric Potential and ripple magnitude affecting grounding systems.	Sectionalize railway line by creating electrical isolation gaps in the railway tracks. The disturbances in telecommunications circuits can be mitigated by replacing the metallic conductors and metallically shielded fibre optic cables with fibre optic cables having plastic shielding. Radio communication can also be considered. Other electronic solutions may be considered by electronic experts.
Effects on existing and new metallic underground or earthed infrastructure in the vicinity of the electrode	Current through metallic infrastructure cause corrosion of buried metallic structures: pipelines, cables, fences, telephone lines and railway tracks. Other large and nearby metallic infrastructure like bridges, grounding or cathodic protection systems of buried tanks may be affected if they are close enough to the electrode.	Extended	Current Density through metallic infrastructure, times number of hours of operation in the electrode's lifetime.	Onshore pipelines: insulating joints Sectionalize fences or replacing steel poles with wooden poles. Sectionalize railway line by creating electrical isolation gaps in the railway tracks. Passive or active Cathodic Protection systems should be considered and/or adjusted, if they already exist.
Effects on existing and new metallic underground or earthed infrastructure in the vicinity of the electrode	Ground rise potentials may cause dangerous touch potential, due to long potential transference.	Extended	Electric Potentials between two points.	Potential transference on telecommunications circuits can be mitigated by isolating them from ground in the electrode surrounding. Sectionalize fences or replacing steel poles with wooden poles. Protect large radial irrigation systems by restricting the size or sectionalizing to reduce the length of large conductive sections
Effects on existing and future electrical infrastructure (HV, MV and LV lines, transformers)	HV and MV lines For earthed metal and wooden tower structures with shield wires DC currents can flow in the shield wires and may cause corrosion of the in-ground earth leads or rods. The amount of	Extended	Total current injection and current density through grounding systems times number of hours of operation in the	HV and MV lines For existing HV and MV lines the shield wire could be isolated for the sections of the line that is within the area of influence. To ensure adequate protection of the power line against lightning, the shield wire can be connected to the tower via a low voltage surge arrester or leave insulated and

Table 4.1 - Electrode Impacts and Mitigations

Issues	Environmental impact	Area of impact	Primary Physical Variable that defines the impact	Mitigation Measures [13][14]
	current that will flow depends on the potential difference between towers and the characteristics of the soil. For wooden tower structures that are not earthed no problems are foreseen.		electrode's lifetime.	provide horns to make easy current extinction after lightning. Similar mitigation measures could be implemented for future lines.
Effects on existing and future electrical infrastructure (HV, MV and LV lines, transformers)	Transformers Solidly earthed transformers provide a return path for DC currents through lines (phases) between two substations. DC currents in a transformer may cause saturation of the transformer and/or protection operations. For non-solidly earthed transformers this is not a problem	Extended	Total Current Injection though neutral circuits.	Transformers The DC current can be limited to acceptable levels by the addition of a resistor or a capacitor in the transformer neutral. A surge arrester can be connected in parallel to the resistor to ensure that insulation levels are not infringed. Adding series capacitor in the phases. Isolating transformers in low voltage distribution systems.
Land and Shore Electrodes:				
Electric fields	Possible danger to humans and animals due to high step and touch potentials close to the electrode site.	Local	Electrical Potential and/or electric field in soil.	Adjust size and burial depth to achieve acceptable levels of step and touch potentials Design to ensure low current densities; a large electrode surface.
Land Electrodes:				
Soil around electrode site	Possible heating, drying out and gas emission in the soil close to the electrode site due to electro-osmosis (movement of water away from anodes thereby reducing moisture levels). If this phenomenon is uncontrolled, the soil may run dry and its properties may be permanently change and the electrode could be permanently damaged.	Local	Current Density in the active parts of the electrode times maximum operation time of the electrode.	Irrigation of the soil to prevent drying out if and when required. Burial of the electrode in coke to ensure current transfer by conduction through the coke to the soil. This will also achieve low current densities in the ground which will assist in avoiding electro-osmosis or heating problems.
Sea Electrodes				
Electrolysis products from anodes	Electrolysis products like hypochlorite, chloride, hypobromite,	Local	Current Density in the active	The amount of chlorine can be reduced only by proper design:

Table 4.1 - Electrode Impacts and Mitigations

Issues	Environmental impact	Area of impact	Primary Physical Variable that defines the impact	Mitigation Measures [13][14]
	bromide, chloroform and bromoform may be formed. Environmental concerns relate mainly to marine flora and fauna		parts of the electrode.	Maintaining a low pH-value at the electrode surface by ensuring sufficient seawater exchange Decrease current density in the water by increasing electrode surface/size Use of favourable electrode materials.
Water temperature rise	Possible heating and even up to boiling point of the contact water. Environmental concerns relate mainly to marine flora and fauna that may be in contact with the electrode	Local	Current Density in the active parts of the electrode.	The heating risk can only be reduced by design measures such as increasing electrode size to reduce current density.
Electric fields	Impact on divers, fish and marine life	Local	Electric field	The electrode could be buried in the seabed. The electrode area could be fenced off for fish and marine life Decrease current density in the water by increasing electrode surface/size Active parts of the electrode can be secured within concrete boxes.
Magnetic fields	Impact on fish and marine life Magnetic compass deviation in shallow waters due to magnetic fields from a single cable carrying high current	Local/Extended	Magnetic Field	Related to a single electrode cable. Not easy to mitigate unless the HVDC cables can be laid near each other. Avoid marine routes. A shore electrode will reduce the impact from a single cable to the electrode, but the effect on humans/ marine life must be considered. Electrode cable and HVDC cables with opposite currents may be closely laid.

4.2 IMPACTS ON INFRASTRUCTURE

4.2.1 Impacts on Buried Metallic Objects

Metallic objects in the ground, or in contact with the ground, can be divided into three categories:

a) Non-insulated objects such as metal that are directly and continuously in contact with the surrounding soil.
b) Objects coated with insulating material such as polyethylene and normally cathodic protected.
c) Earthing grids of substations which are interconnected by overhead shield wires and, if there are transformers with grounded neutrals, though the ac line conductors (AC Grid).

4.2.1.1 Impact on Non-Insulated Buried Metallic Objects

Examples of non-insulated objects are outer shields or armour of cables with a conducting layer, lead or steel armouring, in contact with the soil or, in the case of submarine cables, in contact with the water. Bare metallic pipes for water supply, buried tanks and sheet piling in harbours are also examples of buried bare metallic structures.

Depending on the orientation of the metallic object, its length in the direction of the field and the strength of the field, which depends on soil properties and current injected, 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 determine the impact, it is useful to calculate the current density on the affected object, often expressed in $\mu A/cm^2$ ($1\mu A/cm^2 = 0.01\ A/m^2$). Formulas and methods for calculation of current density, are given in references [1] [2] [4] [5]. Swedish professor S. Rusck [6] discussed the quantification of corrosion due to stray dc currents as early as 1962. Professor Rusck concludes that a current density of $1\mu A/cm^2$ could be permitted for unprotected iron. This corresponds to a rate of corrosion of 0.01162 mm per year removed from the surface of an iron object. This effect would need to be adjusted in proportion to the Ampere-hours of operation of the electrode. Dr. Kimbark [2] also gives comprehensive consideration of corrosion due to pick-up and discharge of dc ground current. Another remarkable approach, based on the definition of a corrosion time constant, was developed by Uhlmann [40]. This approach shows the advantage of allowing the estimation of corrosion in a simpler way when the electrode is operated on a very infrequent basis, such as in the modern bipolar plants.

Apart from dc ground currents, metallic unprotected objects in the ground would corrode for "natural" reasons such as local differences in soil composition along the metallic object, contact with dissimilar metals or soil chemistry, and natural telluric currents which also cause potential differences in the soil and cause current to enter and leave the metallic objects. The impact of natural telluric currents can be greater than the impact from an electrode station at distances greater than about 66 to 110 km away from the electrode station. Kimbark [4] arrives at a similar conclusion.

If an HVDC electrode is located near ac or dc land cables or submarine cables, it is important to investigate the corrosion risk to the cable armouring, which is normally not electrically insulated against the surrounding soil or seawater.

The most obvious and least complicated "protection" for in-ground of in-sea metallic infrastructure against stray currents from electrode operation can be achieved by locating the electrode a distance of a number of kilometres (as a general guide >10km from the ground electrode) away from objects that may be subject to corrosion. Distances closer than 10 km should be investigated in detail prior to construction. An example of a smaller separation distance that appears to work is the main cable of the Kontek scheme and the cathode station Graal-Müritz outside Warnemünde with a separation of only 5.5 km. Coincidentally, the main cable for another scheme, the Baltic Cable, passes the Kontek cathode at a distance of 7 km also apparently without concern for excessive corrosion. However, each case is different and the risk should be studied for each case.

Generally, for bare metallic objects, it is assumed that there is continuous contact with the surrounding soil along the object, that is, the whole 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 zinc 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 due to the greater current density attributable to the concentration of dc current should be investigated.

4.2.1.2 Impact on Insulated Metallic Objects

Long 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 electrically separate sections. Each section is equipped with a device for cathodic protection, generating a voltage which is measured against the surrounding soil through a Cu-$CuSO_4$ half cell and is about -1.0 V. The preferred voltage level may vary according to soil composition in a range between - 0.85 V and -1.1 V. But under anaerobic conditions (lack of oxygen) the margin is limited to about ± 0.05 V. If the voltage is "too positive", there is a danger of discharge of current, which means corrosion. If the voltage is "too negative", hydrogen embrittlement of the steel may occur at a faulty spot. Faulty spots are often unavoidable pinholes in the coating, due to imperfect production, or damage during installation or afterwards.

When a section of an insulated pipeline has to cross a ground potential field due to an electrode, the largest difference between 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, additional insulating joints would be required. The work of inserting further insulating joints in the pipeline may require outages of the pipeline for several days. To avoid expenses, especially those connected with outage of the pipeline, the required pipe to soil potential can sometimes be maintained by introducing new cathodic protection or modifying existing cathodic protection installations.

Examples of mitigations applied to buried pipelines are provided below:

a) Current compensating (cathodic protection) devices are running successfully on a major Swedish gas pipeline which passes the electrode station Risø (the Konti-Skan scheme) at a distance of about 10 km.

b) In Denmark, the uprating of electrode current for the Skagerrak scheme, from 1000 A to 2300 A, required the installation of two additional insulating joints. Current compensating cathodic protection stations were required to be installed on a 508 mm (20 inch) main gas pipeline, at a total cost of about USD 600,000. The gas pipeline is located within 6 km of the electrode station at Lovns.

4.2.1.3 Potential Impact on an AC Grids

The impact of the ground current on AC grid can be illustrated in a simplified way as shown in Figure 4.1.

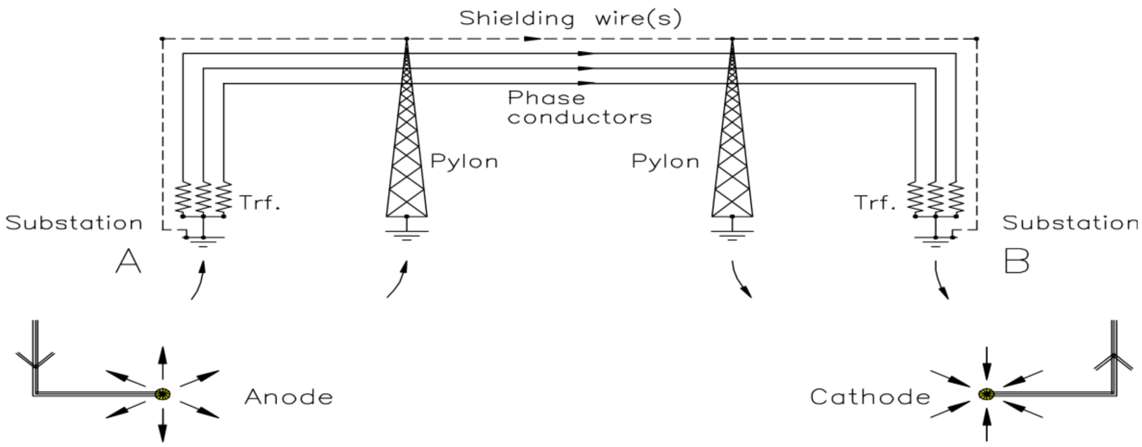


Figure 4.1 – Overview of ac connection exposed to a Field from two electrode stationS

If the shield wires of the line are continuous from A to B, part of the current that is picked-up flows in these wires and may be discharged at other towers further along the line where the ground potential is lower. Intermediate pylons closest to the anode pick up the most significant fractions of current, while pylons closer to the cathode discharge corresponding fractions. The situation is similar to the continuous metallic pipe or cable, which over the total line length is divided into a cathodic zone (left) and an anodic zone (right on the drawing). The principal risk is corrosion of the anodic points where current leaves the grounding grids of the towers. This can be very problematic especially in the case of guyed towers. This may be mitigated using the approach of Prof. S. Rusck by limiting the maximum current density to lower than 1 μA/cm^2 and by installing insulators in the guy wire.

Some of the current emanating from the anode partly enters the earthing grid of substation A and flows into the grounded neutrals of the transformer and along the phase conductors towards substation B, where the current is discharged via the earthing grid, and flows to the cathode. The dc component in the overhead line is independent of the ac phase current. This dc current can have two consequences:

a) Saturation of the grounded transformers if the dc current is too large, and
b) Corrosion of the ground grid of the station nearest the cathode.

The dc component through the transformer windings causes a constant magnetising of the core. This magnetising current is superimposed on the symmetrical ac magnetising current and causes a unidirectional offset on the flux, which may lead to saturation of the core. The magnetizing current waveform is distorted mainly due to the presence of 2nd harmonic current.

This vulnerability of transformers to dc magnetising current is different for different core types. Transformers can withstand some level of neutral dc current. This should be checked in discussion with transformer manufacturers and information on withstand levels should be requested when transformers are procured. Single phase 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 dc 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 dc current excitation, because the dc flux is developed only to a small degree due to the high magnetic reluctance of the air gaps from the top yoke to the bottom yoke.

Unfortunately, converter transformers are often of the single-phase type, depending on price, transportation limits and to reduce the cost of spare units. 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, single phase transformers are commonly used, 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.

As was the case for bare metallic objects, an effective means to avoid for dc ground current excitation of transformers is to locate the electrode station beyond a minimum distance from any vulnerable substation, including the converter station. Another measure that can be considered is the installation of blocking capacitors or resistors between the neutral connection of the transformers and the substation grounding grid.

Reactors with magnetic cores, for compensation purposes, are not at risk of dc 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 single phase or three-phase, with three-legged or five-legged cores.

When analysing the possibility of saturation, the grid configuration is usually much more complicated than the simplified arrangement indicated in Figure 4.1. A detailed resistance network containing the different stations, the mutual interconnections between stations and the resistance in transformers, resistances of the station ground grids to earth must be set up, and the flow in the different branches calculated. Generally, the degree of saturation is not serious for most small grid transformers (< 200 MVA), because they are normally three-phase, three-legged. Large single phase units and large three-phase units, which are often five-legged to reduce height in order to facilitate transportation are most at risk and should be individually evaluated for possibility of saturation.

New Zealand has published information on a serious case of saturation due to ground current from the southern electrode station at Bog Roy [7]. The converter station Benmore, is only 8 km from the electrode station. The close proximity combined with unfavourable underground resistance at a relatively shallow depth and a relatively large ground current of the 2000 A rating produce a ground potential rise voltage at Benmore of about 84 V, which causes current flow in the ac system towards substations with lower ground potential rise. As it is the magnitude of dc current flow in the transformers which is of concern, the problem was addressed by limiting stray dc current flow in the neutrals of the converter transformers to a maximum of 5 A by introducing resistances in the transformer neutrals, at the Benmore converter station, and at eight other nearby substations.

Although the problems were serious and the solution extensive, it was found to be more attractive than moving the electrode to the coast of the ocean, this being about 100 km from the present electrode station at Bog Roy.

DC excitation of power transformers caused by stray currents due to electrode operation is similar to geomagnetically induced currents which is a much-studied phenomenon. More information about the impact of dc currents on transformers is provided in [15].

4.3 IMPACTS ON THE ENVIRONMENT

4.3.1 Compass Deflection

The flow of dc current through cables and conductors, as well as through the sea and soil will create magnetic fields. The intensity of the magnetic fields will be greatest in the near vicinity of the electrode, and the contribution of these current will diminish as one moves away from the electrode. The horizontal component of the induced magnetic fields can cause a deviation from the earth's magnetic field and may be a source of compass error for ships navigating in the proximity of the electrodes, especially for sea, shore and pond type electrodes. However, the current through the seawater induces a magnetic field at the surface that is normally weak due to the low current density in the body of water.

The magnitude of the magnetic field at a point depends on the location of the point relative to the current carrying conductor/body, the magnitude of the current and the relative permeability of the medium in which the point is located. The current flow in the sea from electrode operation will produce a magnetic field, decreasing in intensity as it moves away from the electrode, and therefore a zone of magnetic influence around the electrode can be established.

For a particular location of interest, the induced magnetic fields resulting from electrode operation can be calculated and summed with the magnetic field of the earth at that location to determine the resulting vector components and angle of deviation in the resultant magnetic field. Compass deviations are further described in [16].

For a shore pond electrode, the induced magnetic field from the electrode cables and elements will be greatest near the breakwater and the resultant magnetic field will be a function of the cable layout, including the routing of cable leads to the electrode elements.

4.3.2 Chemical Aspects

In any electrolytic process, there will always be chemical reactions because the materials in the soil (more precisely the substances diluted in the ground or seawater) will be decomposed and/or may react with each other or with the metallic components in the electrode to produce new chemical compounds [17].

In an anodic process in ground water of very low or zero salinity, O_2 (oxygen) is evolved, which is generally not considered problematic because the atmosphere contains about 20% O_2. With increasing salinity, the evolution of Cl_2 (chlorine) will become more dominant, but there will still be a substantial evolution of O_2 even in high salinity seawater. The sum of evolved gases must follow Faraday's law of electrolysis, which says that the mass of decomposed material is proportional to the electric charge exchanged between the electrode and the number of Ampere-hours.

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 has given the following information concerning the anode for the Baltic Cable, electrode station at Smyge:

"At the salinity of this site (about 0.8 per cent) the rated current 1364 A produces Cl_2/O_2 in relative amounts 30/70 per cent. 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 30 per cent. At 50 per cent of the rated current, the selectivities for Cl_2/ O_2 are about 17/83 per cent, and at 20 per cent of the rated current 9/91 per cent. The absolute rate of evolution is 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. Thus, the obvious method to diminish evolution of chlorine is to use low current densities, which means electrodes of large sizes."

The chlorine selectivity of the titanium mesh varies with the composition of electrode material and tends to increase with:

- Higher salinity
- Lower pH
- Higher potential and current density
- Lower water temperature

It is not clear if all electrode materials follow the same trend as titanium mesh. If transfer of current to water is by means of small-sized sub-electrodes with small surface area, for instance SiCrFe-rods directly in water, it would not be 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 also dependent on the actual composition of the anode materials. A point which needs discussion and research is whether the surface area of a coke volume 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 is also noted that if Cl is evolved at 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 materials. 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 (e.g. 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" 9130 kg/kA· yr. If the intention or license of operation limits the electrode to a short time duty, an electrode of this simple type would last for many years. Deep non-noble metallic rods electrodes would tend to be "eaten up" from the bottom, because the current density is expected to be largest at the bottom ends of the vertical electrodes.

H_2 (hydrogen) is evolved in gaseous form in the cathodic process. 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 would be 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. Experience with sea electrodes running only in cathodic mode indicates that the cathodic process results in chalk-like substances being deposited on the electrode surface. These deposits are not harmful to the electrode surface, but may increase resistance and then heating. If this heating is too accentuated, the deposit may even be blasted off due to steam explosions inside the deposit.

Changing between anodic and cathodic operation 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 polarisation. The sum of polarisation voltages in a pair of electrodes can easily reach about 2 V, which represents a voltage drop, which would result in a corresponding power loss.

When a polarised pair of reversible electrodes is inversed, the polarisation, starting with the "wrong" direction, will at first 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 less tolerant, because a layer of SiO_2 on the surface bursts causing pitting. However, if sufficient material is installed any pitting that occurs may not significantly affect service life of the electrode.

Likewise, titanium and coated titanium, which withstand the harsh anodic condition extremely well, are very sensitive to polarity reversal and cannot 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 indicated that research is going on to develop metallic electrode materials with enhanced cathodic current capability.

4.3.2.1 Effects on Flora and Fauna

Hypoxia, water stress, and mechanical impediments to root growth all change when the water content of the soil is altered[31]. The drying of soil as a result of the flow of DC ground currents may affect the plant growth depending on the soil structure and the plant type. [29]

The maximum threshold of soil temperature at the electrode-soil interface is typically considered as 85°C and temperature levels above this threshold can result in steam formation [30]. When the steam is trapped inside the soil it might develop excessive pressures that might lead to the explosion of the electrode.

Electro-osmosis refers to the moving of water by the electric current; water tends to move away from the anodic electrode during this process. Soil around earth electrode may dry relatively quicker and proximity of electrodes to land used for crop farming should be avoided. Drying of soil plays a role on leaf growth, it restricts leaf expansion and initiation [31]. Photosynthesis is less affected than leaf growth. Heating of soil also reduces the moisture content of the soil. No information has been found relating the duration of heating of the soil.

A large variety of organisms have been shown to respond to geomagnetic cues, including: magnetotactic bacteria [19], protists [20], gastropods [21], crustaceans [22], insects [23], bony fish [24], amphibians [25], sea turtles [26], birds [27], and migratory whales [28]. The environmental concerns to marine flora and fauna related to sea electrode were expressed in the past.

Magnetic fields in the sea are not related to the electrode itself, but an effect of current flow in monopolar operation with only one HVDC cable. The same problem will appear in case of two bipolar dc cables following separate spaced routes [14]. Several studies have been done to evaluate the impact from sea electrodes and the major results show that no environmental impact should be expected if the electrodes are designed properly. More discussions on the environmental impact are included in Chapter 5 Section 5.1.4 and 5.4.3.

4.4 IMPACT STUDIES

After choosing a potential electrode site, an interference and environmental impact study should be carried out to investigate the extent of the possible interference of electrode operation on the surrounding facilities and natural environment.

As discussed in Chapter 3, electrode siting criteria vary, and both techno-economic criteria and environmental restrictions are considered as part of the constraints of finding a suitable site. An interference study is important to investigate if a potential environmental impact is a restrictive condition in the selection between one site and another, or if their potential consequences can be either avoided or mitigated, or if such consequences are so minor and can be ignored.

4.4.1 Data for Impact Studies

The following types of data should be collected to investigate and estimate the real effects of dc current injection at a specific electrode site:

a) Geological/Geophysical survey to establish rough resistivity magnitudes and to identify where there are big differences in resistivity between different types of rocks or soils. This last property is important, because it determines the current paths through the earth, and therefore the possible interferences.
b) Shallow resistivity survey.
c) Deep resistivity survey.
d) Soil thermal properties for the design considerations which can be done in a later stage.
e) Potentially affected facilities such as LV, MV, HV transmission lines with grounded transformers and their characteristics, metallic pipelines, long fences, large radial irrigation

systems, buried metallic installations close to the electrode, other physical infrastructure, telecommunication cable lines and antennas, etc.

f) Surrounding marine life in the case of sea electrodes.

g) Seawater resistivity survey in the case of sea, beach and land electrodes which are close to the sea.

h) In the case where fresh water is in contact with seawater, the resistivity survey should consider resistivity versus depth, because fresh water tends to go to the surface while salt water sinks to the bottom.

i) Climatic statistics to cover variations in soil properties during the year.

j) Electrode Current ratings and duties:
   i) Ampere-hours per year,
   ii) Transient operating condition
   iii) Short-time operating condition
   iv) Nominal continuous pole current rating
   v) Inherent continuous pole current rating
   vi) Maximum transient line pole fault current
   vii) Maximum pole short-time converter overload current

Interference phenomena due to electrodes are a complex problem because multiple variables are involved and it is often difficult to measure them accurately. Very small considerations and simplifications can be done a priori, because of the potential large area of influence of the impact and especially if the geographical characteristics are too heterogeneous. That is why mathematical tools have to be used if the environmental impact survey requires more precise quantification. This data can be used to build a three- dimensional model of the soil/geological features, infrastructure and electrode. Finite element and/or other mathematical tools can then be used to determine possible interference effects.

An interference study can be as detailed as the designer wishes and the available tools and information allow. It is difficult to say a priori what amount of detail has to be considered in the model before it can be considered as adequate. The designer may need to do several iterations before defining the final model of the problem and making conclusions. Experience, good judgment and sufficient iterations or sensitivity studies can lead to reasonable conclusions. Due to the nature and the scale of the problem and current environmental restrictions, no project should be treated as the same as another.

4.4.2 Physical Variables to Study

The nature of the behaviour of current injection can be represented by Maxwell's Equations [37]. In this case, this behaviour can be represented by a simplified variant called Electrokinetic Model. On the other hand, the environmental impacts are mainly defined, according to their nature, by different components of the equation in the same domain as follows:

a) The impacts caused by potential transfer are defined by electric potentials.
b) The impacts caused by dc current flux through metallic surfaces are defined by current density.
c) The impacts caused by total current injection through metallic objects, are defined by current flux.

These three variables are closely related to each other but it is important to understand that different possible environmental impacts are defined and may be analysed and quantified better by considering one factor at a time. In other words, each type of environmental impact has specific variables of interest. Thus, it is important to choose the right methods and tools to study a specific impact. Complicated mathematical tools, like Finite Elements, may work better to quantify some variables while other calculation techniques may be better to quantify other factors.

If a precise quantification of current flux and electric field is needed, it is recommended to use mathematical tools that impose or ensure current conservation in the calculations, in order to calculate precisely "where the current goes" instead of "what are the effects of the current injection (like potential rise)".

With respect to the interpretation of the results, the potential rise curves that may be estimated in an interference study, it is important to acknowledge that large values on the electric potential in a certain point may not matter if safety is not compromised and the current flux does not directly impact infrastructure. It is important to communicate to the non-engineering community that it is the current is that causes the problems for infrastructure not the potential rise. Potential rise and potential gradient may cause safety concerns.

The following factors should be taken into ac account when planning to quantify the impact of interference:

a) Developing a representative resistivity model for a large area to the required depth is a difficult task, due to the large amount of data, and to the uncertainties that are inherent to the data and because of the anisotropy of Earth's crust.

   Nevertheless, the behaviour of the current flux (not the absolute value) will mainly depend on the differences in soil conductivity rather than in the absolute values. This can be proven by simulations with adequate and accurate soil resistivity model. This makes important to make a special effort in the definition of accurate **relative conductivities**, especially in terms of where large changes or variations occur, rather than more precise resistivity values. Geological surveys and measurements should take this into account and focus on it.

b) Before mitigation measures are considered, the installations of concern (such as pipelines, bridges, railroads, distance to grounded ac transformers or cables) should be checked for the presence of telluric currents which may be generated by tidal flows, or by potential differences between land masses (especially for long cables of 100km or more). Such pre-existing telluric currents may be greater than the calculated stray DC electrode ground return currents. If so, electrode interference may only represent a small incremental addition to existing conditions.

c) In a mathematical model, a commonly asked question is: "What is the extent of the study area and location of the 0[V] boundary condition in the model?". One typical distance to impose is 100 km, but this value may not be sufficient to ensure good results. To be sure that an imposed distance is sufficient, it should be verified once simulations are run that the maximum value of the potential gradient near the boundary is close to zero, specifically it should be close to solver's tolerance. In the event that the gradient is large, the model size should be extended.

The designer should keep in mind that the actual impacts will only become known after the electrode has been constructed and operated at full current and measurements have been taken and analyzed. This is because any interference study is a complex problem, especially considering that the resistivity model will always be an approximation. The quantity of variables and the difficulties of exactly measuring all of them, make it impossible to the practice to calculate potentials and current flows with a high precision before the construction and the commissioning.

Due to this relatively high degree of uncertainty in the modelling it is useful to construct a test electrode or only part of the full electrode and operate this at reduced current. Test electrodes providing a sufficiently large area of influence may not be easy to build because the test current injection must be between two points that have an equivalent distance of the interference zone of the electrode. This means a minimum distance of at least several kilometres between one point and another and may require building of transmission lines between the two injection points. If the project budget and time schedule allows and if transmission and distribution lines are available to do this kind of test, it would be possible to take measurements that can confirm the modelling results or adjust the model and electrode design if required.

Either way, verification tests using test electrodes can be very expensive and difficult to realize especially if it is necessary to construct new transmission lines to allow injection between the ground electrode a sufficiently remote location so that the field around the electrode will reflect the actual behaviour. The impact and interference of HVDC electrode are further discussed in Chapter 5.

5. ELECTRODE DESIGN ASPECTS

5.1 GENERAL DESIGN CONSIDERATIONS

The function of a ground electrode is to transfer the HVDC system current from a metallic overhead or insulated conductor into the earth. It does not serve as protective ground for the HVDC scheme or for equipment. The ground electrode design must address the following aspects:

a) Safety
b) Physical design criteria and constraints
c) Potential environmental impact
d) Potential influence of electrode operation on other facilities
e) Practicality of building an electrode at the site

These aspects would be addressed in the design roughly in the sequence indicated above. As with site selection process the design process may need to be adapted or modified for individual designs. A conceptual flow chart of the design process is shown in Figure 5.1.

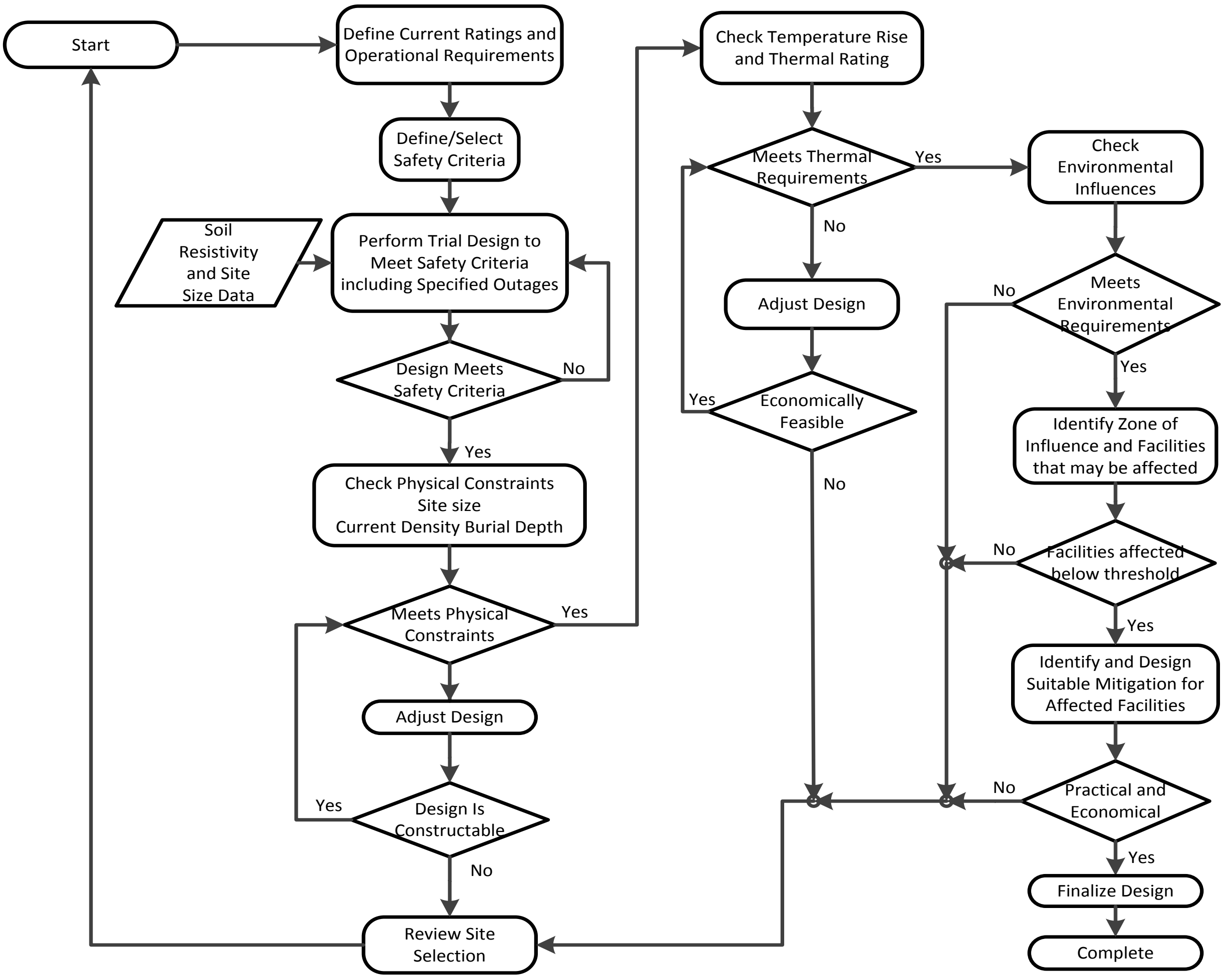


Figure 5.1 – Conceptual flowchart of Electrode design Process

5.1.1 Safety Requirements for Humans and Animals

The safety requirements of a ground electrode can be summarized in a single objective as follows:

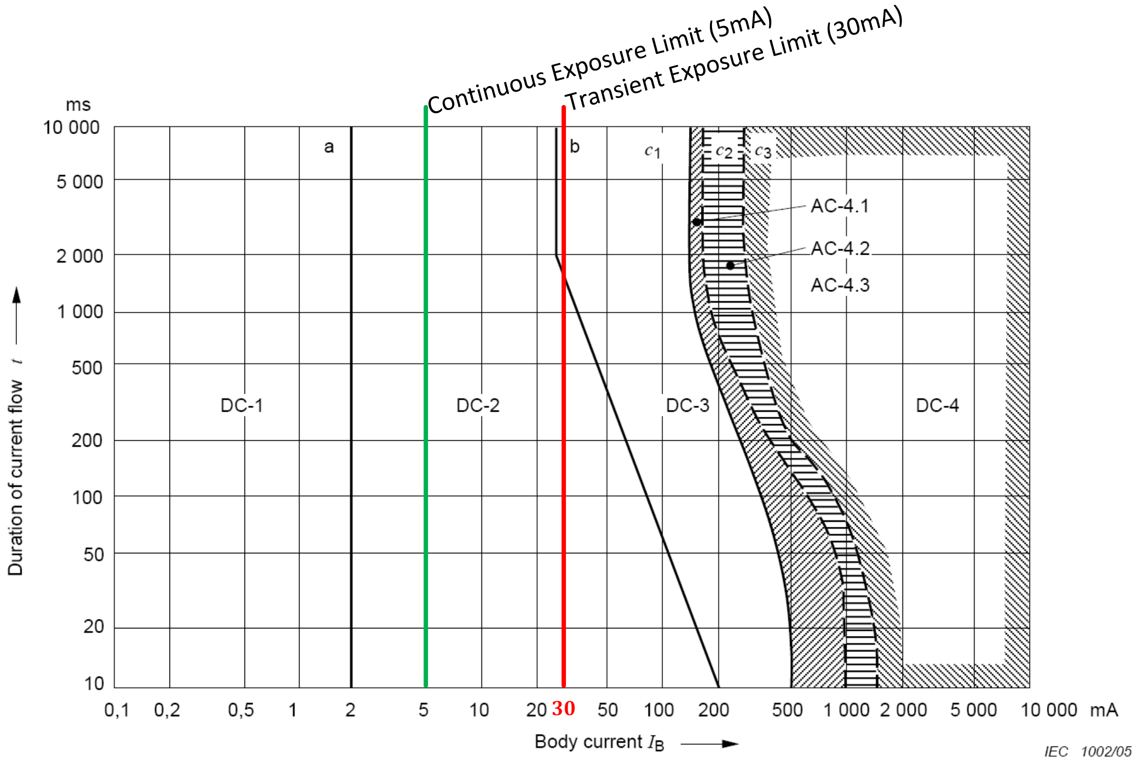
"The operation of the electrodes must not result in unsafe conditions for people or animals either in publicly accessible areas or within controlled areas accessible only to authorized maintenance workers."

This general objective requires consideration of the full range of possible operating modes of the electrode and consideration possible conditions and facilities within the areas that can be influenced by the electrode in operation.

The operational conditions considered for safety fall into two categories:

a) conditions which can persist for 10 seconds or longer which, for safety purposes, are considered to be continuous, and
b) transient conditions which would persist for less than 10 seconds. In the case of a dc transient line fault the transient overcurrent would persist for only about 50 ms until the current line protection and current controller will reduce the fault current to zero.

The criteria for these two time frames are different since the tolerance of the human body to current is time dependent [33]. The Figure 5.2 reproduced Table 13 and Figure 22 from IEC 60479-1 indicates the tolerance of the human body to dc current.



Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects
DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
DC-4 [1)]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	DC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50 %
1) For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feet and for upward current. For other current paths the heart current factor has to be considered.		

Figure 5.2 – Proposed Safety Criteria based on Limits Published in IEC 60479-1[34]

The criteria that are selected to be used for safety design limits for the earth electrodes are superimposed on Figure 5.2. The green line is the proposed criterion for steady state (continuous operation) conditions and represents a perceptible but tolerable level of current while the red line is the suggested transient exposure limit. The red line represents the lower threshold of let go current and which could be unpleasant but would still be much lower than the threshold of fibrillation as indicated in the curves labelled c1 through c3 of Figure 5.2. In an LCC HVDC system, transient currents would not be expected to persist for more than about 50 ms due to very fast fault current reduction by the HVDC control systems.

The use of single values of current for the continuous and transient design limits rather than curves is for convenience and simplification of the design calculations. The single-valued limits are selected to provide significant margins to let-go current limits or fibrillation currents.

The sensitivity of adults to dc current has been studied and tested but there is very little data concerning children. It is known that the threshold of perception and let-go currents are lower in women than in men and children are expected to be slightly lower than women [33].

5.1.2 Safety Metrics and Criteria

Safety of humans and animals at an electrode site is of concern primarily within the area where the surface potential rise and the associated surface potential gradients resulting from electrode operation are high.

In the event that there are bodies of water within the area of influence of the electrode, the safety in the water and at the water/soil interface would require consideration of body currents in humans and animals that can enter or are normally present in the water.

Safety can be defined in terms of the following quantities (using the definitions from IEEE Std. 80 [39] and modifying them to reflect the special character and operating characteristics of HVDC ground electrodes).

a) Step Voltage
b) Touch Voltage
c) Metal-to-Metal Touch Voltage
d) Transferred Voltage or Transferred Potential
e) Potential gradient in water

All of the above voltage quantities need to be addressed when considering the safety of the earth electrode installation. However, the acceptable values ***are not based on voltage*** but rather on acceptable levels of currents within the human body (or in the bodies of animals).

Acceptable levels of current within the body are generally considered to be currents that are above the threshold of perception but which are below the let-go current level and well below the current that would result in fibrillation of the heart. These current magnitudes may be large enough to cause annoyance to the person or animal but would not be sufficient to endanger life or cause injury.

Generally, the safety criteria for electrodes are defined using acceptable levels of dc current within the body. The only exception to this is consideration of the maximum transient electrode fault current which has a short duration and can be characterized as an ac current or pulse current superimposed on a dc level. The tolerance of the body to current flow is a function of the frequency of the current and the acceptable values of dc current in the body are higher than the corresponding values of power frequency (50 Hz or 60 Hz) ac current.

For convenience in electrode design it is usually desirable to be able to work with voltage limits or limits on potential gradients which can be more easily calculated and verified by measurements. Consequently, safe or acceptable values of voltages and potential gradients are determined by working backwards from the acceptable levels of current in the body using assumed conservative values of contact resistance and body resistance.

Available software programs must be a capable of calculating the ***surface potential rise*** at and surrounding the site to an acceptable degree of accuracy and the criterion used should include sufficient margin so that after-construction design changes or remedial measures would not be needed to make the final installation comply with safety criteria. All of the safety criteria discussed can be derived from the surface potential rise and associated gradients.

Of the above criteria, only two may extend for significant distances into publicly accessible areas:

d) Transferred potential, and

e) Voltage gradient in water

Step voltages approaching the limits would normally be confined to within the areas of the earth electrode sites.

As the public cannot be protected from these effects by restricting access behind locked fences the calculated values need to be both predictable and conservative.

As noted earlier, actual limits of safety are related to current flows in the human or animal body but the criteria applied are voltages or potential gradients. The most limiting of the calculated values becomes governing for the design for safety purposes.

When calculating acceptable voltage criteria for electrode design it is necessary to make assumptions with respect to resistance of the body and the contact resistance between the body and the earth or energized object. There are some differences between IEC 60479 and IEEE 80 in this regard but the IEEE calculation methodology is easier to apply for body resistance and contact resistances in series with the body resistance as follows:

a) Hand and foot or skin contact resistances to metallic structures are equal to zero.

b) Glove and shoe resistances are equal to zero.

c) The value of resistance of the human body can be approximated by a single resistance with a value of 1000 Ω. This value is used to represent the resistance of a human body from hand-to-feet and also from hand-to-hand, or from one foot to the other foot. (i.e. RB = 1000 Ω)

d) The contact resistance of a foot to ground is taken to be the same as that of a metallic disc representing the foot. The foot is represented as a circular plate with a radius "b" of 0.08 m. The resistance from each foot to ground (Rf) is given as

$$Rf = \frac{\rho s}{4b} = 3.125 * \rho s \qquad (5.1\text{-}1)$$

The above assumptions are consistent with the assumptions made in IEEE Std. 80 relating to safety in substation design.

The value of body resistance for animals is in general different than for humans and the tolerable levels of current may also be different for different species of animal. However, the methods of calculation and the conceptual diagrams shown below are exactly the same for people and animals.

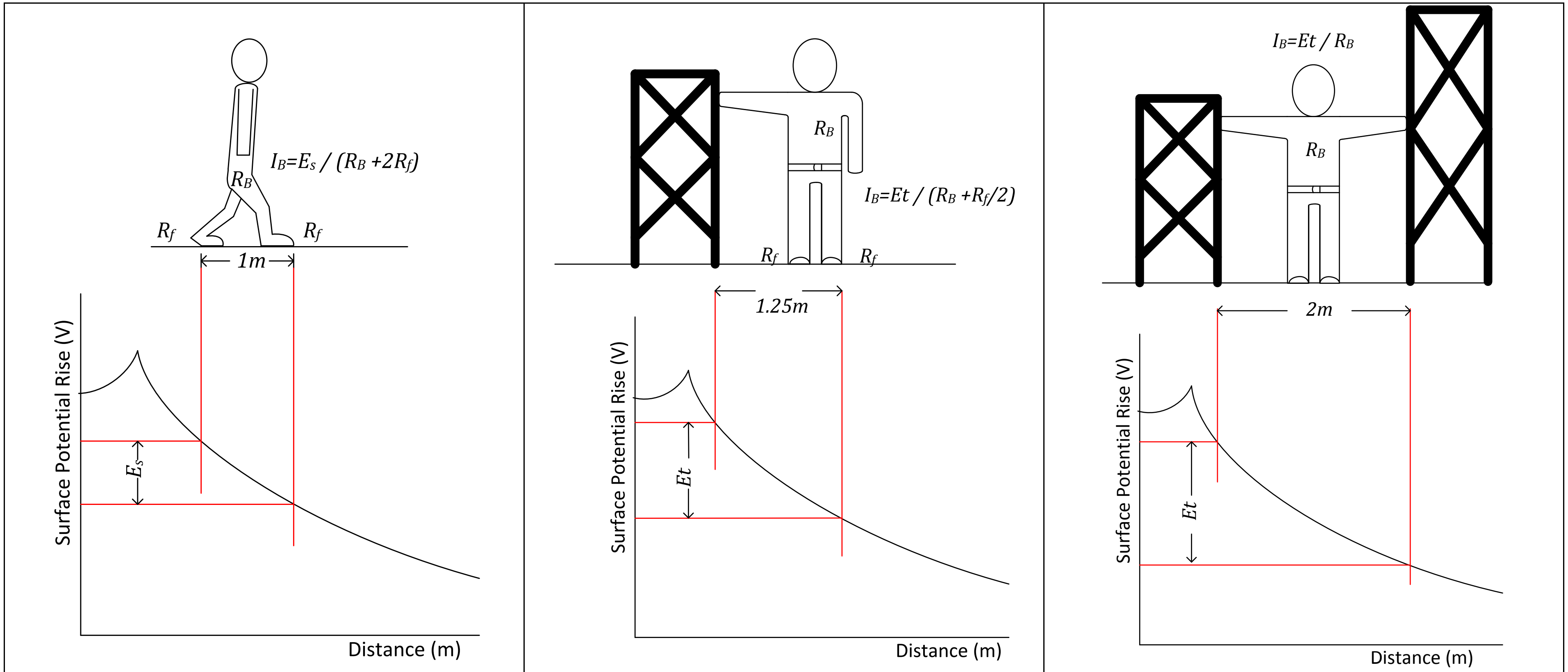
The following nomenclature is used in this section:

IBc –body current in continuous conditions (A)
IBt – body current in transient conditions (A)
RB – body resistance (Ω)
Rf – contact resistance between foot and soil (Ω)
Es – step voltage (V)
Esc – step voltage in continuous conditions (V)
Est – step voltage in transient conditions (V)
Et – touch voltage (V)
Etc – touch voltage in continuous conditions (V)
Ett - touch voltage in transient conditions (V)
Ewc – continuous voltage in water (V)
Ewt –voltage in water under transient conditions (V)
ρs – surface resistivity at the electrode site (Ω•m)

The distances generally applied for determination of acceptable conditions for step, touch, metal to metal and water safety are 1m, 1.25m 2m and 2m as illustrated in

Figure 5.3 and Figure 5.5. The designer may apply additional safety margins if desired. The distance is undefined in the case of transferred potentials as indicated in Figure 5.4.

Note that the calculations provide values of voltage and current ***not gradients***. The gradients can be determined from the voltages by dividing by the distances.



a) Steady state limit $Esc < IBc * (RB + 2 * Rf) = 0.005 * (1000 + 2 * 3.125 * \rho s)$ $Esc < (5 + 0.03 * \rho s)$	a) Steady-state limit $Etc < IBc * \left(RB + \frac{Rf}{2}\right) = 0.005 * \left(1000 + \frac{3.125}{2} * \rho s\right)$ $Etc < (5 + 0.008 * \rho s)$	a) Steady-state limit $Etc < IBc * RB$ $Etc < 5\,V$
b) Transient limit $Est < IBt * (RB + 2 * Rf) = 0.030 * (1000 + 2 * 3.125 * \rho s)$ $Est < (30 + 0.18 * \rho s)$	b) Transient limit $Ett < IBt * \left(RB + \frac{Rf}{2}\right) = 0.030 * \left(1000 + \frac{3.125}{2} * \rho s\right)$ $Ett < (30 + 0.008 * \rho s)$	b) Transient limit $Ett < IBt * RB$ $Ett < 30V$
(a) Step Voltage	(b) Touch Voltage	(c) Metal to Metal Touch Voltage

Figure 5.3 – Conceptual illuStration of step voltage, touch Voltage and metal to metal touch voltage and corresponding SAfety criterion

5.1.2.1 Step Voltage/Touch Voltage/Metal-To-Metal Touch Voltage

Step voltages should be limited to values that will not exceed the following criteria:

a). The step/touch voltage in publicly accessible areas under continuous operating conditions should not exceed a value that would result in body currents above the threshold of perception. (IBc<5 mA)

b). The step/touch voltage during short time and transient operating conditions and transient faults should not exceed a value that would result in body currents exceeding the lowest threshold of let-go-current. (IBt < 30 mA)

The step voltage, touch voltage and metal to metal touch voltage corresponding to these criteria as well as the expressions for acceptable step voltage under continuous and transient conditions are illustrated conceptually in Figure 5.3.

5.1.2.2 Transferred Potential

Transferred potential is a special case of touch voltage and thus the same body current limits and associated continuous and transient voltage limits would apply. However, in this case the distance can be any unspecified value.

Transferred potentials can be present on metallic objects or cables which are on the site and which may become grounded at one point and floating at another point. The concept of transferred potential is illustrated in Figure 5.4.

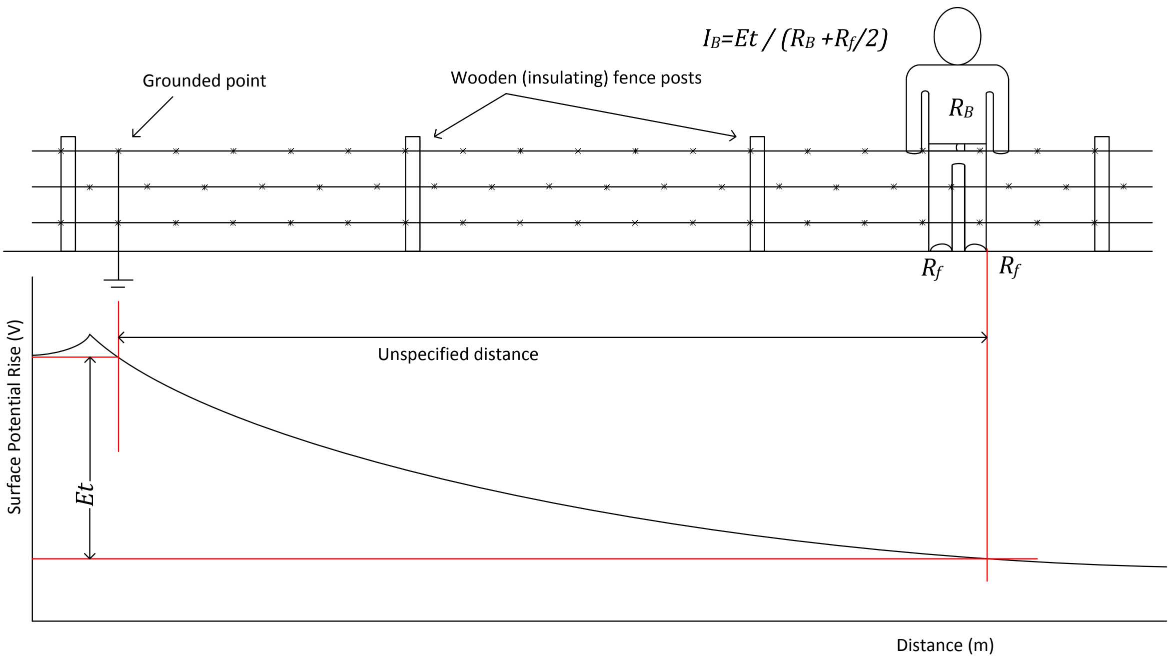


Figure 5.4 – Conceptual Illustration of Transferred Potential

Metallic cables entering or leaving the site or metallic fences near the site can also pose a risk of transferred potentials.

The resistance of the metallic object and the connection from the object to ground is assumed to be much lower than the resistance of the body (i.e. effectively zero). The resistance of the wooden fence posts is assumed to be infinite.

Mitigation of transferred potentials on fences is normally accomplished by sectionalizing the fence to limit the transferred voltage to safe levels. To avoid impractically small fence section lengths near the electrode, the criterion for transferred potential would be selected based on the transient current limit rather than the threshold of perception.

The risk of transferred potentials cannot be entirely eliminated by design but can be reduced by adopting the following design measures and procedures:

a) Restrict access to the site to personnel who understand the concepts and dangers of transferred potentials.

b) Development of "live-working" procedures for maintenance, which take into account and mitigate the risk of transferred potentials.

c) Provision of isolating transformers on metallic cabling entering or leaving the site transformers to prevent the transfer of potential to remote locations.

d) Provision of station service supply using a transformer that is not grounded on the primary side.

e) Avoid construction of metallic fencing in areas where the potential gradient is high. If it is necessary to cross an area with high potential gradient, insulating sections should be provided to maintain the transferred potential at an acceptable level.

f) Perimeter fencing, if provided, should roughly follow the expected potential contours of the electrode.

g) Even where provisions d) and e) above are followed, fence posts should not be made of steel but rather of concrete or fibreglass and the wire mesh or wire should be inspected regularly for corrosion and repaired if necessary.

The highest transfer potentials that can occur on the site would be equal to the difference between the maximum and minimum values of ground potential on the site. The maximum transfer potential will occur at the under transient and short-time overload current conditions.

5.1.2.3 Electrical Gradients in Water

Electrical gradients in water can cause current to flow in the bodies of humans that are swimming in the water. To ensure safety voltage gradients in water should be limited to values that will not exceed the following criteria:

a). The voltage gradient in publicly accessible areas under continuous operating conditions should not exceed a value that would result in body currents above the threshold of perception. (IBc<5 mA)

b). The voltage gradient during short time and transient operating conditions and transient faults should not exceed a value that would result in body currents exceeding the lowest threshold of let-go-current. (IBt < 30 mA)

The voltages corresponding to these criteria are illustrated conceptually in Figure 5.5. As the total voltage appears across 2 m the gradient must be limited to the total permissible voltage divided by 2. Thus the voltage gradients in the water should be limited to 2.5 V/m for continuous operating conditions and to less than 15 V/m under transient fault and short-time overload conditions.

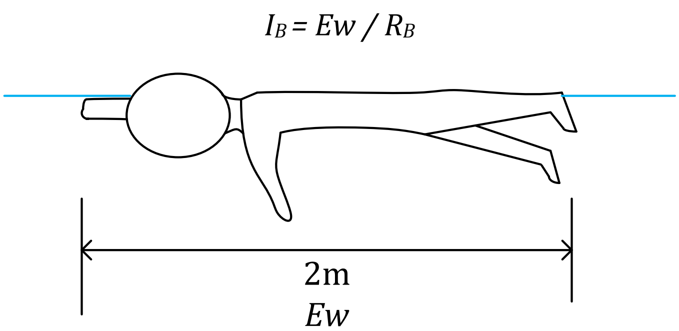


Figure 5.5 – Conceptual Illustration for Safety with Electrical Gradient in Water

This results in the following expressions for acceptable voltages across the body under continuous and transient conditions:

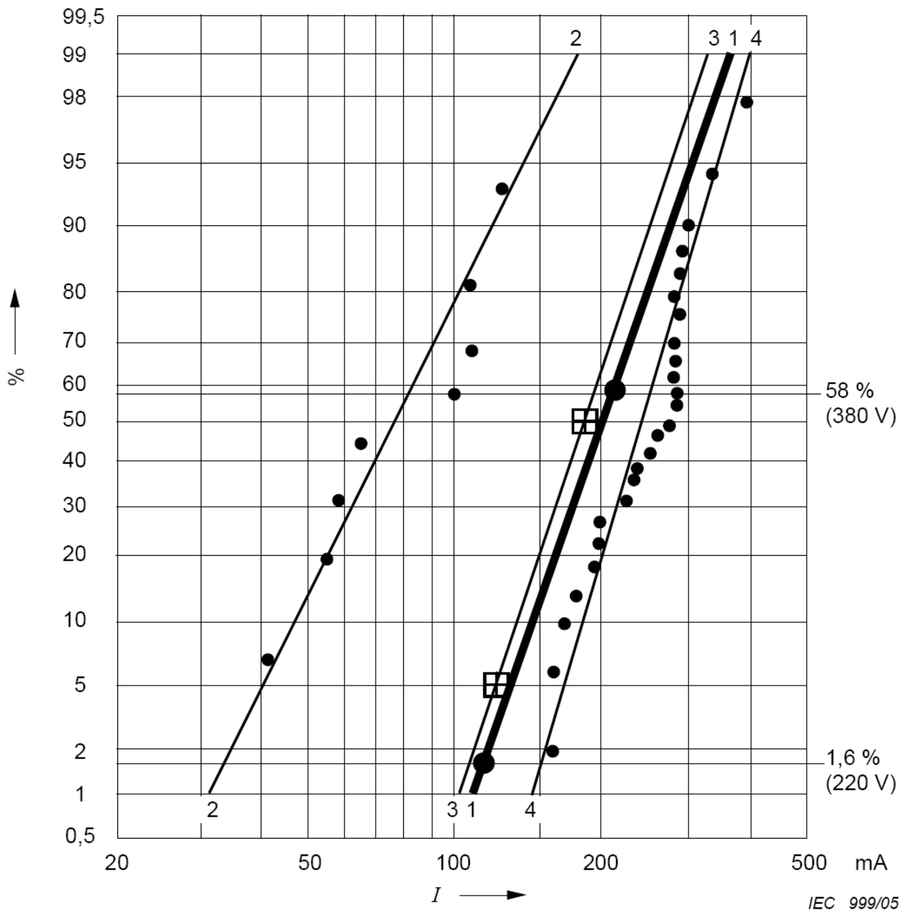
a) $Ewc < \frac{IBc*RB}{2}$, which can be reduced to $Ewc < 2.5V$

b) $Ewt < \frac{IBt*RB}{2}$, which can be reduced to $Ewt < 15V$

These limits are not dependent on water resistivity and the resistance between the water and skin is assumed to be zero. Thus the above values are directly applicable to publicly accessible bodies of water without modification.

5.1.2.4 Sensitivity of Animals to Electrode Operation

The sensitivity of animals to heart fibrillation due to current flow in the body is compared to humans in IEC TS60479-1[34] and IEC Std. 60479-3 [36]. Figure 5.6 shows the comparison as given in Figure 19 of [34].



Key

1 fibrillation data for persons calculated from statistics of accidents (U_T = 220 V, 1,6 %, U_T = 380 V, 58 %)

2 fibrillation data for dogs, duration of current flow 5 s

3 fibrillation data for pigs, duration of current flow t > 1,5 * heart-period

4 fibrillation data for sheep, duration of current flow 3 s

⊙ calculated values based on statistics of accidents (U_T = 220 V, 1.6 % and U_T = 380 V, 58 %, I_T = 110 mA and 220 mA respectively) (1)

⊞ statistical values of measurements with pigs (I (5 %) = 120 mA, I (50 %) = 180 mA)

(1) values corrected with the heart-current factor F = 0,4

Figure 5.6 – Comparison of Human and Animal Fibrillation Currents [34]

This figure indicates that ac (50 or 60 Hz) fibrillating currents for sheep and pigs are similar to those of humans while dogs are slightly more sensitive. Cows would also be expected to exhibit similar tolerance curves to sheep and pigs. Smaller animals such as birds have much smaller step length and smaller body size implying higher internal resistance and would be able to tolerate higher step or touch voltages for the same limits on internal body currents. Experiments have shown voltage differences (step or touch) as high as 18 V have no effect on production performance and behaviour of laying hens. Smaller birds are expected to be able to tolerate even higher voltage gradients. Much lower gradients are expected near operating electrodes and thus no impact on bird nesting would be expected.

In the electrode design process, the body currents resulting from touch, step and transferred potentials would be limited 5 mA continuously and 30 mA during transient conditions. The minimum ac currents known to cause fibrillation in some species of domestic animals are about ten times higher than these values as discussed in [36] and shown in Table 5.1. Thus, the values that would be used in electrode design are far below the fibrillation currents for either humans or animals and there would be no question of safety of animals during electrode operation.

Table 5.1 - Minimum Fibrillating Currents (50 or 60 Hz) for Animals [36]

Species	Average Weight		Minimum Fibrillating Current	
	Body (kg)	**Heart(g)**	**Average (mA)**	**Range (mA)**
Pig	79	300	240	170 to 270
Sheep	56	270	250	160 to 390
Calf	70	420	310	210 to 470
Pony	115	-	300	160 to 410

5.1.3 Physical design criteria and constraints

5.1.3.1 Electrode Operating Duties

For a bipolar transmission system electrode duties are based on the anticipated pole outage rates which result in the need for monopolar operation of the HVDC system, bipolar imbalance current under normal operation, system load factor, and planned operating configurations of the HVDC transmission system. These duties would have cumulative corrosion impacts on the surrounding infrastructure and result in loss of electrode element materials due to corrosion. The design of the electrode should be such that either the electrode elements would be able to sustain operation over the life cycle of the project or could be replaced at intervals when required. In general, operating duties would be minimized to limit the corrosion impact on the infrastructure within the electrode zone of influence.

The duties for a monopole scheme depend primarily on the following:

a) Maximum current rating and annual ampere hour duty

b) Life cycle of the project

c) The determination of a bipole or a multi-pole scheme duty involves a comprehensive review of modes of operation and associated ground currents, and any major contingencies. The parameters to be evaluated include,

d) Maximum current rating including short time and continuous overload during a monopolar operation

e) Life cycle of the project

f) Load factor during a monopolar operation, the load factor is contingent on the load demand.

g) Forced pole outage rate that results in earth return operation or high level of imbalance. It is normally specified as part of the converter or system specification and average outage time is considered based on published data

h) Scheduled pole outage rate that will result in earth return operation or high level of imbalance.

i) Reliability and availability of transmission line especially lightning performance which will result in earth return operation.

j) In steady state, a bipolar or multipolar imbalance current

k) Earth return operation during installation and commission stage.

l) Major equipment failures that can result in extended monopolar operation. (e.g, submarine cable or converter transformer)

In some jurisdictions, maximum earth return operation ampere-hour limits are imposed to minimize the corrosion impact on the infrastructure (e.g. pipelines). In some countries, earth return current is prohibited and therefore a dedicated neutral return or metallic return using the other pole conductor must be provided.

5.1.3.2 Project Life Cycle

The project life cycle of the HVDC scheme should be reviewed to define any future upgrades to be considered as part of the ground electrode design, and suitability of ground electrode infrastructure to operate at its rated current and to sustain environment in which it is to be constructed.

Provisions should be included in laying out the grounding elements and distribution circuits for any future capacity increase. The replacement of consumable elements (e.g., for pond type ground electrode) should be considered in developing the design details, if applicable.

Electrodes are also at risk from environmental events. Land electrodes must withstand wind and flood events. The sea and shore electrode infrastructure should be designed to sustain the worst case tidal and wave actions.

5.1.3.3 Reliability

The ground electrode and its connections to the converter station impact the overall reliability of HVDC scheme where ground return path is required for imbalance currents, continuous pole current or during a pole fault. The reliability of the ground electrode and electrode line is a key factor in the overall reliability of the HVDC scheme.

A ground electrode does not involve any moving parts and the probability of failure is not high if distribution circuits and elements are designed with adequate margins, and protected from the environment. However, some issues can be expected due to material tolerance and unknown field conditions (soil thermal capacity, and salinity of water) not factored into the design.

The reliability of a ground electrode can be increased if the installation is divided into sections with separate isolation disconnect switches for individual sections and arranging multiple conductor for connection to the converter neutral bus. This provides the means to isolate any defective elements to allow maintenance while the ground electrode is operating. Depending on the design, the outage of a portion of the electrode may limit the capacity of the scheme. The capacity constraint can be addressed if a redundant electrode subsection is included (e.g. an electrode requires 45 elements, by installing 54 elements in 6 subsections will facilitate operating at full capacity with one section taken out for maintenance).

A site monitoring system and a preventive maintenance program help to identify any evolving issues and theft/destruction of the infrastructure.

5.1.3.4 Polarity- Anodic and Cathodic Operation, and Element Materials

The polarity of a ground electrode is specified as either cathodic, which indicates current flow from the earth to electrode, or anodic, which indicates current flow from the electrode to the earth. For a scheme where current flow direction through the earth return path remains the same, the electrodes can be designed as one anode and one cathode as applicable. In case the direction of current flow changes periodically, the electrodes should be of the reversible type having capability to operate as an anode and as a cathode.

The ground electrodes associated with a bipole scheme are required to be reversible since the direction of bipolar imbalance and monopolar current under a pole outage current can reverse. Monopole schemes may have single function or reversible ground electrodes.

The polarity of a ground electrode is a key consideration in the selection of the element types. Also, polarity is the main factor in determining the chemical emission footprint of an electrode. The types of electrode element suitable for anode, cathode and reversible operation are discussed in Section 5.3, 5.4 and 5.6.

5.1.3.5 Current density

The current density at the electrode element surface must be selected so as to avoid electro-osmosis for land electrodes, and to reduce chlorine selectivity for elements in contact with saline water for beach and sea electrodes."

A maximum average current density in the range of 0.5 A/m^2 to 1 A/m^2 is recommended for land electrodes to avoid electro-osmosis and 6 A/m^2 to 10 A/m^2 for beach and sea electrodes to reduce chlorine selectivity for elements in contact with saline water.

Higher current densities can be used for pond electrodes where the access by people and animals can be restricted so that safety concerns are addressed. However, even here, lower current density would result in lower chlorine selectivity and reduced electrode consumption and both of these aspects should be reviewed for the type of elements used.

5.1.4 Potential Impacts on Environment and Infrastructure

5.1.4.1 Ground Potential Rise (GPR)

The dc current injected into the earth (anodic operation) or collected from the earth (cathodic operation) results in GPR at the electrode relative to the surrounding area. The magnitude and distribution of the GPR is a function of the current and the resistance of the electrode to the remote earth. The resistivity of the local soil or body of water and the grounding element configuration are the main determining factors of the GPR near the grounding site. Grounding elements with a large contact area will result in a lower maximum GPR, as well as a HVDC ground electrode installed in low resistivity soil or seawater will result in a smaller potential gradients or step voltages.

However, at a significant distance from the electrode outside the zone of influence, the GPR distribution will not be affected by local soil conditions or element arrangement at the grounding site. The remote earth resistivity determines the GPR distribution outside the zone of influence. The GPR distribution at the ground electrode location determines the step potentials and consequently safety. The electric fields resulting from electrode operation can have effects on the surrounding infrastructure, which are mainly electrical interference (applicable primarily for wye-grounded transformers and machines) and electrolytic corrosion (applicable for buried and immersed metallic infrastructure).

5.1.4.2 Electrical Interference and Corrosion Impact

The electrical interference of electrode in a system (mainly ac transmission and distribution, and dc transmission systems) has been described in details in 4.2.1.3. Preferably the location of the ground electrode should be selected to minimize electrical interference. Mitigation measures should be evaluated where a location away from the main transmission and distribution system is not viable.

Steep gradients along a metallic structure caused by the electric field from the grounding site current will cause corrosion where stray currents leave the structure (i.e., the anodic location or extremity of the metallic structure). Corrosion of metallic structures can be mitigated in different ways, such as adding more material to sacrificial anodes, introducing insulating joints, or providing impressed current cathodic protection (ICCP) systems.

5.1.4.3 Magnetic Field

The magnetic field from the electrode cables and element of a pond or a sea electrode can cause compass deviation or affect the magneto-sensitive species in the sea as described in 4.3.1. Typically, the magnetic field at a distance from the cable or grounding elements is weak and is not normally a design concern. The magnetic field should be quantified and the findings should be communicated for further assessment by transport authority and environmental assessment groups.

5.1.5 Constructability

A constructability assessment of the selected site would involve the following considerations:

a) Accessibility of the site by road, rail or water for transport of equipment and materials
b) The possibility of constructing the electrode line to the site
c) The site should be relatively level
d) The site should not be excessively wet or soft
e) The site should not be subject to flash floods or at risk of erosion or landslides

Similar factors would also apply for beach and pond electrodes.

5.1.6 Data Required for design

5.1.6.1 Current Ratings

The HVDC current that passes through the ground electrode is the main parameter by which a ground electrode is rated. The current passing through a grounding site is a function of the HVDC scheme design and its operational configurations. To ensure its electrical performance, the electrode must be sized adequately for the current while maintaining the electrode element current densities within the recommended limits. The operation and maintenance factors to be considered include maintenance on a subsection of the electrode during operation, and safety for access to electrode elements for inspection and maintenance.

The system currents (continuous, short-time overload, and transient) form the basis of the design for an electrode system.

The earth electrode current for a bipole scheme or a multi-pole scheme depends on the mode of operation of the scheme. For a balanced bipolar or multipolar operation, the ground return current is a small imbalance current on the order of 0.1 % of the rated pole current. Under a contingency of a pole outage, the earth return current could be equal or higher than the rated pole current. The earth current can be as high as 200% for a short duration to support the ac systems and, for designs with overload ratings, can continuously carry current higher than the nominal pole current. The ground electrode should be designed to meet the safety requirements for the **maximum transient electrode overcurrent**. Harmonics can flow through the earth return path for bipolar and monopolar configurations but are normally suppressed to low levels at the converter station by a dc filter and are not a factor in electrode design.

The magnitude of the earth return current associated with a dc line fault depends on the converter transformer impedance, dc arc resistance and grounding impedance of the line at the faulted location. The current is suppressed in a LCC scheme by control action and should be reviewed for ground electrode design. For a VSC scheme, the fault is cleared by isolating the converter terminal from the ac system or the dc system; the fault current should be evaluated for safety at the electrode.

5.1.6.2 Soil Physical and Chemical Properties

During the design of earth electrodes, the main physical properties of the soil on the electrode site should be measured during different seasons of the year in order to determine the electrical, thermal and physical parameters needed to model the site and evaluate the impact of the earth electrodes on the environment.

The main properties of soil are subject to seasonal variability as well as variability with depth and location on the site. These factors include:

a) Soil resistivity
b) Soil thermal capacity
c) Soil thermal conductivity
d) Soil highest natural temperature
e) Type of soil or rock material
f) Moisture content
g) Depth to water table
h) Temperature at electrode depth
i) Susceptibility to Electro-osmosis
j) Chemical properties

5.2 DESIGN METHODOLOGY

Electrode design involves consideration of the following factors all of which must be within acceptable limits or follow the guidelines as described in Section 5.1.

a) Safety (Step voltage, touch voltage, etc.)
b) Electrode dc resistance to remote earth
c) Thermal stability at specified current ratings
d) Design life based on corrosion of electrode elements
e) Current density

f) Current sharing between sub-electrodes
g) Potential interference with other nearby facilities

5.2.1 Simple Calculations

Ground potential rise, potential gradient and maximum step/touch voltage, and dc resistance to remote earth can be mathematically estimated for various types and shapes of electrodes for the soil resistivity of uniform, 2-layer or 3-layer distribution.

In accordance with industry practice, the current density is calculated as the injected current divided by the surface area of the coke to soil boundary. Normally, the current at the short time overload rating and with specified outage of sub-electrodes (if applicable) should be used for the current density calculation.

5.2.2 Simulations

Direct calculations using analytical expressions are usually used for calculation of step potentials and current density at the electrode-soil boundary. However, such methods are not sufficient if the soil in the immediate area of the electrode is not of uniform resistivity or when operation is required with outages of a portion of the electrode. Programs using finite element methods have been developed which allow the detailed modelling of soil structure near the electrode to establish the expected variation in step voltage or current density under these conditions.

In general, the soil resistivity structure would be modelled based on resistivity data gather using a number of established measuring techniques for different depths characterized as follows:

a) Shallow – tens of meters – by means of vertical electrical (Schlumberger or Wenner) or electromagnetic (nanoTEM) soundings;
b) Near-surface – hundreds of meters – by means of electromagnetic (TEM) soundings;
c) Deep – down to MOHO (crust/mantle interface) – by means of MT measurements.

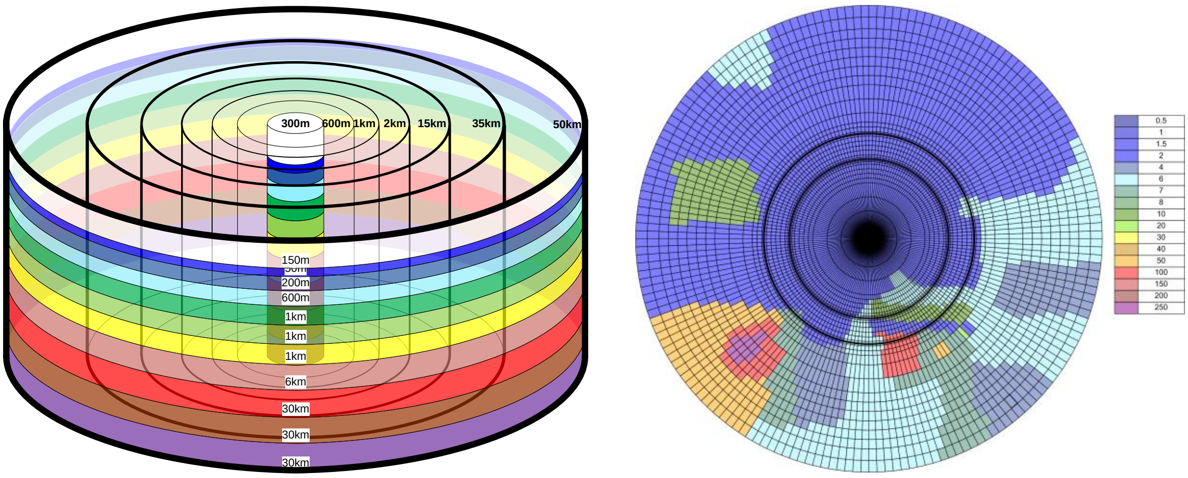
The soil resistivity model can be represented as a three-dimension structure either as a circular cylindrical volume or cubic volume. The 3D structure is normally divided into a number of elemental volumes with each defined with specified dimensions (radius, thickness and angle: r, z and θ the cylindrical coordinates, or width, length and height x, y and z). The resistivity of each elemental volume can then be individually assigned layer by layer.

Two kinds of earth resistivity model structures can be constructed:

a) Detailed and near-surface model – close to the electrode (up to two times its diameter) – using the data from the shallow and near-surface surveys; Shallow soil resistivity values as determined from the shallow site measurements can be used for the model of radius up to a few hundreds of meters and depths of 50-100 m.

b) Wide area model – covering the complete interference area, by means of a layered model – using the data from the deep resistivity measurement. Deep soil resistivity measured at selected electrode site is used for the local model of radius up to <5 km and depth of 100 m to 100 km.

Figure 5.8 shows an example of a resistivity model in circular cylindrical volume with area extended to 50km wide and 100km deep.



(a) A circular cylindrical volume resistivity model (7 circles x 11 layers)

(b) Resistivity assigned for soil near the electrode for the layer where the electrode is buried

Figure 5.7 – Example of circular cylindrical volume resistivity model

Detailed modelling near the electrode elements will ensure that the design including the backfill material such as coke is adequately represented to show the ground potential rise (GPR) potential gradients and current density near the electrode.

Less detailed modeling can be used as the distance from the electrode increases but the presence of low impedance areas such as a sea coast or rapid change in resistivity must be included. Figure 5.8 shows an example of top layer soil resistivity modelled in an area within 250 km of the electrode. The presence of seawater is clearly indicated by the blue area.

Sensitivity cases including the outage of sub-electrodes, variations in top soil resistivity representing seasonal variations and higher resistivity layers at deeper earth should be carried out to establish a range of conditions that could occur based on differences in assumptions with respect to the extent and depth of regions of different resistivity.

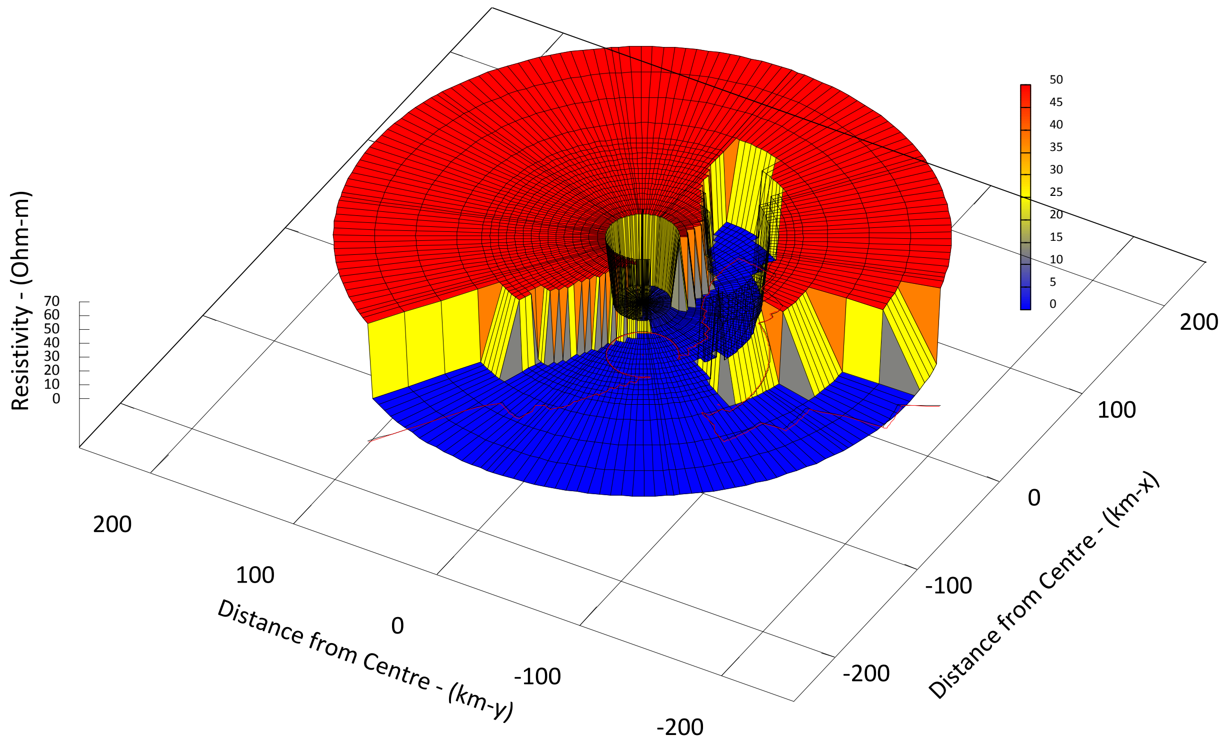


Figure 5.8 - Example of A Top Layer Resistivity as Modeled In Area Within 250km Of The Electrode

Example of calculated ground potential rise and potential gradients from an electrode with two shallow circular rings and outage of some of the segments are shown in Figure 5.9 and Figure 5.10.

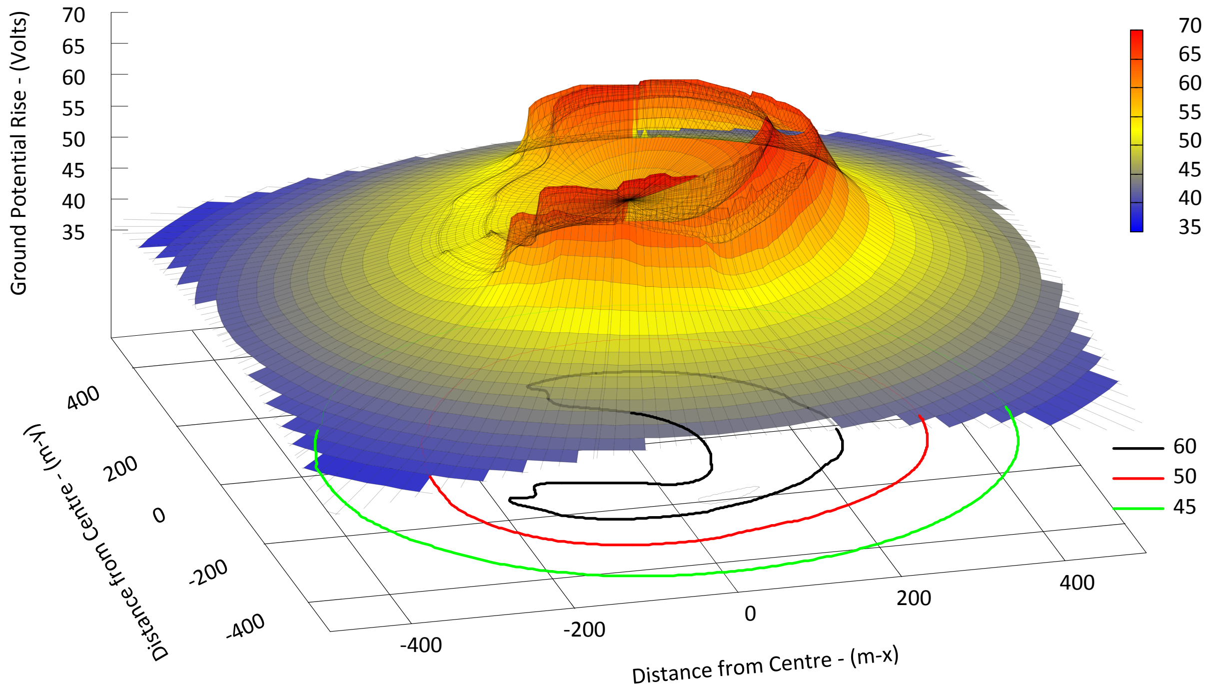


Figure 5.9 - Example of Calculated Ground Potential Rise near A Shallow Double Ring Electrode With A Portion of The Electrode Out of Service

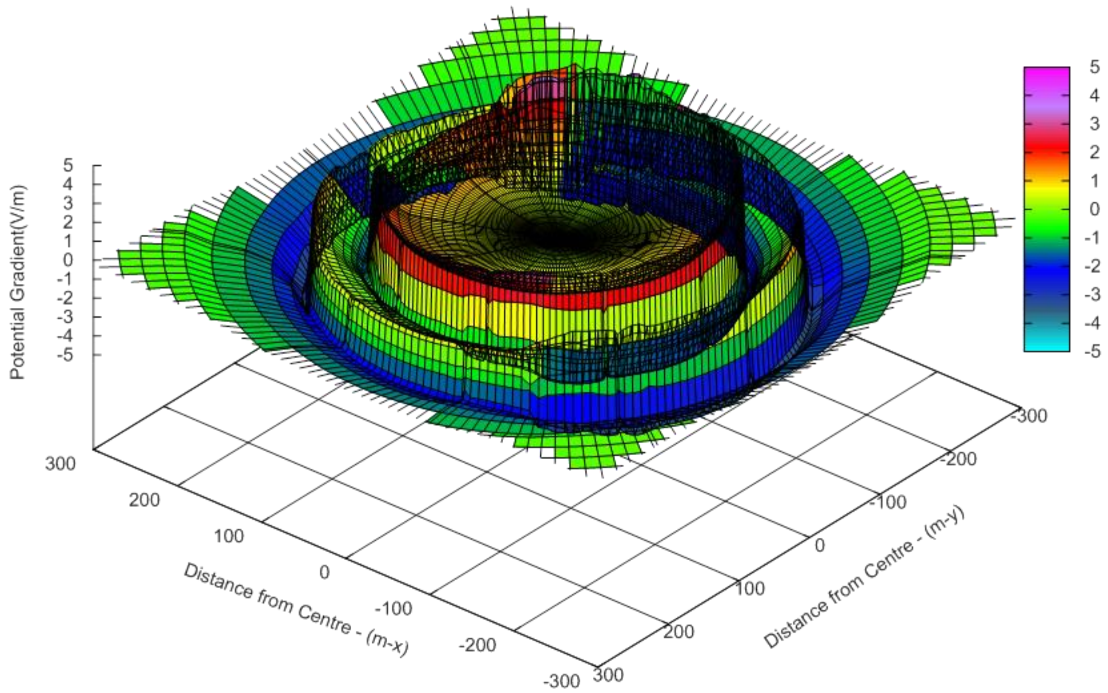


Figure 5.10 - Example of A Local Calculated Potential Gradient of A Shallow Double Ring Electrode

Figure 5.11 shows an example of the level of detail that is possible with the current generation of numerical electrode calculation programs. In this case a deep well electrode is proposed but coke backfill has been extended back up to the surface through a relatively high resistivity surface layer. The result is that there are dangerous step and touch gradients at the tops of the wells.

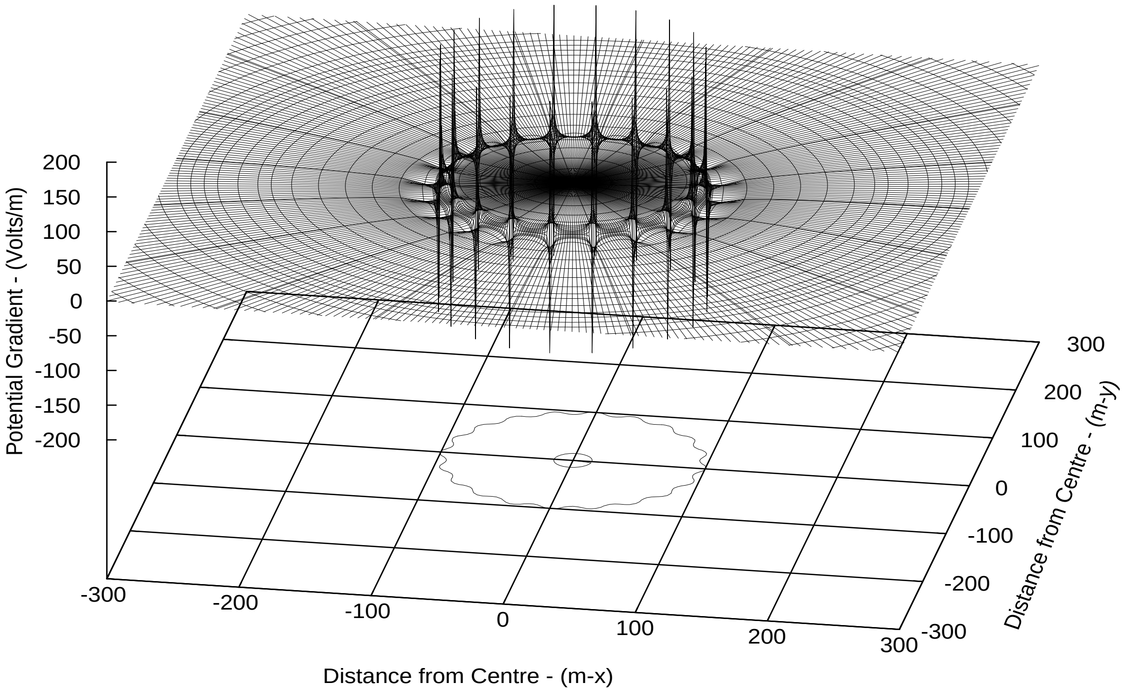


Figure 5.11- Example of Calculated Potential Gradients from A Ring of Deep Well Electrodes

5.2.3 Verification of Design

Tests should be performed after installation and during the commissioning of the electrodes to evaluate the performance of the electrode and to confirm the electrode design meets the specified criteria and requirements.

The electrode design verification measurements should include the following:

a) Electrode resistance to remote earth (all types of electrode)
b) Ground potential rise (all types of electrode)
c) Current distribution in sub-electrodes (all types of electrode)
d) Step and touch voltages (land and shore electrodes)
e) Potential gradients in water (shore and sea electrodes)
f) Soil temperature and moisture (land electrodes only)

The measurement results should be compared to the calculated and simulated design values. In general, it is not expected that the actual measurement results could ever exactly match the design. However, they should be similar to and show the same trends as the design values. If the measurements deviate significantly from the design especially in respect of safety, mitigation would be required before the electrode can be used.

Additional details of electrode tests are given in Chapter 8.

5.3 LAND ELECTRODES

5.3.1 Design Considerations

Land electrodes are generally located relatively close to the converter stations and would be buried close to the surface horizontally or placed in a vertical deep-well configuration to ensure contact with low resistivity soil.

In addition to the general design considerations and design criteria described in Section 5.1, a number of specific factors, such as soil heating, high potentials and electro-osmosis, must be taken into account during a land electrode design. The land electrode is normally not rated for full time operation in earth return.

5.3.1.1 Thermal Stability at Specified Current Rating

Temperature rise is a concern primarily for land electrodes either of shallow horizontal or vertical well configuration. Shore beach and sea electrodes would inherently have, or could be designed to have sufficient water exchange, to ensure that any heat evolved at the electrode elements would be removed without excessive temperature rise near the elements.

The current rating that is of primary concern for thermal design of land electrode is the continuous current rating. Generally, the durations of the short time overload current and transient overload current with durations of seconds to hours are too short to have any noticeable impact on the thermal rating of the electrode which would typically have a time constant in the order of hundreds of days. Thermal stability of the electrode system needs to consider the time duration of service at maximum continuous current to assure long term stable life of the completed systems.

5.3.1.1.1 Classical Calculation with Simplifying Assumptions

The thermal rating of the electrode is obtained by calculating the thermal time constant and the maximum temperature rise of the electrode using the following equations from Kimbark [2]:

The thermal heating time constant is calculated using the following equation:

$$T = \frac{v}{2\lambda}\left(\frac{R_e A_e}{\rho}\right) \qquad (5.3\text{-}1)$$

Where:

T	Thermal time constant (seconds)
ν	Heat capacity of the soil in (J/m^3·°C)
λ	Thermal conductivity of the soil (w/m·°C)
R_e	Resistance from electrode to remote earth (Ω)
A_e	Surface area of electrode (m^2)
ρ	Soil resistivity near the electrode (Ω·m)

The final temperature rise at the surface of the electrode is calculated using the following equation:

$$\theta_{max} = \frac{V_e^2}{2\lambda\rho} \qquad (5.3\text{-}2)$$

Where:

Θ_{max}	Temperature rise (°C)
V_e	Voltage of electrode with respect to remote earth (V)
λ	Thermal conductivity of the soil (W/°C)
ρ	Soil resistivity near the electrode (Ω·m)

As per Kimbark [2] and Uhlmann [40] the resistance value (Re) is calculated assuming uniform resistivity from electrode to remote earth, which is the same as the resistivity near the electrode.

The evaluation of the electrode thermal time constant and maximum temperature rise using the above equations is based on the following conservative assumptions:

a) uniform soil resistivity (ρ) and thermal conductivity (λ) for the entire earth which do not vary seasonally or change as the temperature of the soil changes. This is certainly never correct. The adopted practice is to use values for the soil parameters close to the electrode-soil interface;

b) the soil at the electrode burial depth is initially at a constant temperature and will not vary due to daily or seasonal air temperature variation;

c) the heat dissipated due to electrode operation remains within the soil and the heat loss into atmosphere above the ground is ignored;

d) the relationships expressed in the formula are independent of the geometric shape of the electrode.

In order to have the best possible foundation for the calculations, it is recommended that important parameters, electrical resistivity, heat conductivity, moisture content, natural ambient soil temperature at the burial depth of the electrode, precipitation, and every other parameter that has an influence in the soil, be monitored through a complete year to get information on seasonal variations. It must be considered if the period for the measurements has a normal or an abnormal character of for instance meteorological circumstances such as abnormally heavy rain.

In accordance with the above assumption, the formula for temperature rise is independent of the geometric shape of the electrode. In the following, a completely buried sphere (not a semi-sphere) is assumed 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:

$$\theta_{max} = I^2 \cdot \left(\frac{\rho}{4\pi \cdot r} \right)^2 \cdot \frac{1}{2 \cdot \pi \cdot \rho} = 0.00317 \cdot \frac{I^2}{r^2} \cdot \frac{\rho}{\lambda} \qquad (5.3\text{-}3)$$

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

$$\theta_{max} = I^2 \cdot \left(\frac{\rho}{4\pi \cdot r} \left(\frac{1}{r} + \frac{1}{2 \cdot h} \right) \right)^2 \cdot \frac{1}{2 \cdot \lambda \cdot \rho} = 0.00495 \cdot \frac{I^2}{r^2} \cdot \frac{\rho}{\lambda} \qquad (5.3\text{-}4)$$

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 2r 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 2r from the surface is 80 per cent of the potential on the sphere. The temperature just above the sphere has dropped, theoretically, to 96 per cent 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 with the atmosphere by convection and by radiation.

When calculating the temperature rise using these equations on some of land electrodes, unrealistically high temperatures rises of several hundred °C or even 3000-4000°C can be determined. The high temperatures indicate that these electrodes would not able to carry the rated current continuously, although they may function quite well when used for short time duty. Results of several hundred degrees °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 [4]. A correction factor of 5is suggested for continuous duty, which is to be applied 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 it is expected that there would be significant dissipation of heat to the atmosphere which would imply that a high correction factor is applicable. For deeply buried electrodes (50-500 m) a smaller correction factor than 5, but still greater than 1, could be considered. If no correction is applied to the theoretical formula, then the size of the electrode station will be larger than required and unnecessarily costly. Special attention should be given when applying the correction factor as it is dependent on the soil resistivity. The value of 5 is applicable when the soil resistivity is around 100 Ω·m.

5.3.1.1.2 Finite-Difference Calculation Method

Numerical methods based on the finite-difference method [41]-[45]. have been introduced to improve the estimates of the soil heating associated with the electrode.

Figure 5.12 illustrates the modelling of discrete nodes located inside a volume represented by Cartesian coordinates.

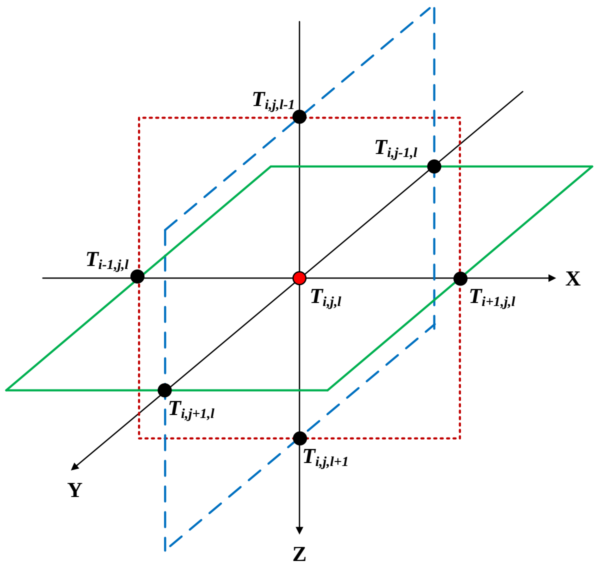


Figure 5.12 – Internal Node Located in XYZ planes

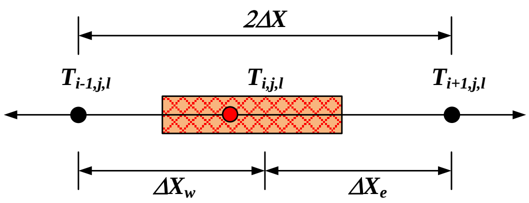


Figure 5.13 – Non-uniform Node Spacing

The temperature at any point of the soil can be determined by solving the Laplace differential equation of heat conduction as indicated in [44]

$$\nabla(k_T \cdot \nabla T) + g = d_s \cdot \gamma \cdot \frac{\partial T_{i,j,l}}{\partial t} \qquad (5.3\text{-}5)$$

With

$$g = \rho \cdot J^2 \qquad (5.3\text{-}6)$$

Where

k_T	soil thermal conductivity (W/°C·m)
g	heat dissipated by Joule Effect (W/m^3)
d_s	soil density(kg/m^3)
γ	specific heat capacity of soil (J/(°C*kg))
$T_{i,j,l}$	temperature(°C)
t	time (Seconds)
ρ	soil resistivity (Ω·m)
J	current density (A/m^2)

The node temperature for a non-uniform node spacing as shown in can be derived from the steady-state solution of Equation 5.3-5 using finite-difference method.

$$T_{i,j,l} = \frac{1}{\Delta}\left(\varphi_{e \cdot T_{i+1,j,l}} + \varphi_{w \cdot T_{i-1,j,l}} + \varphi_{n \cdot T_{i,j+1,l}} + \varphi_{s \cdot T_{i,j-1,l}} + \varphi_{o \cdot T_{i,j,l+1}} + \varphi_{u \cdot T_{i,j,l-1}} + \frac{g}{k_T}\right) \qquad (5.3\text{-}7)$$

$$\Delta x = \frac{1}{2}(\Delta x_e + \Delta x_w) \qquad (5.3\text{-}8)$$

$$\Delta y = \frac{1}{2}(\Delta y_n + \Delta y_s) \qquad (5.3\text{-}9)$$

$$\Delta z = \frac{1}{2}(\Delta z_o + \Delta x_u) \qquad (5.3\text{-}10)$$

$$\varphi_e = \frac{1}{\Delta x_e \Delta x} \qquad (5.3\text{-}11)$$

$$\varphi_w = \frac{1}{\Delta x_w \Delta x} \qquad (5.3\text{-}12)$$

$$\varphi_s = \frac{1}{\Delta y_s \Delta y} \qquad (5.3\text{-}13)$$

$$\varphi_n = \frac{1}{\Delta y_n \Delta y} \qquad (5.3\text{-}14)$$

$$\varphi_o = \frac{1}{\Delta z_o \Delta z} \tag{5.3-15}$$

$$\varphi_u = \frac{1}{\Delta z_u \Delta z} \tag{5.3-16}$$

$$\Delta = 2 \cdot \left(\frac{1}{\Delta x_e \Delta x_w} + \frac{1}{\Delta y_s \Delta y_n} + \frac{1}{\Delta z_o \Delta z_n}\right) \tag{5.3-17}$$

The boundary conditions to be satisfied by Equation 5.3-5 for soil temperature calculations are

a) The temperature of the soil is not affected at a distance sufficiently far from ground electrodes;
b) The dissipated heat escapes from the soil into the atmosphere by convection and radiations.

When the node is located at soil surface, Equation 5.3-7 changes to [45]

$$T_{i,j,l} = \frac{1}{\Delta'}\left(\varphi_e \cdot T_{i+1,j,l} + \varphi_w \cdot T_{i-1,j,l} + \varphi_n \cdot T_{i,j+1,l} + \varphi_s \cdot T_{i,j-1,l} + \varphi_o \cdot T_{i,j,l+1} + \varphi_u \cdot T_{i,j,l-1} + \frac{2 \cdot h_c \cdot T_{air}}{k_T} \cdot \frac{1}{\Delta x} + \frac{g}{k_T}\right) \tag{5.3-18}$$

Where

$$\Delta' = \Delta + 2 \cdot \frac{h_c}{k_T} \cdot \frac{1}{\Delta x} \tag{5.3-19}$$

With

h_c	heat convection coefficient (W/°C·m^2)
T_{air}	ambient air temperature (°C)
Δx	node spacing in X axis (m)

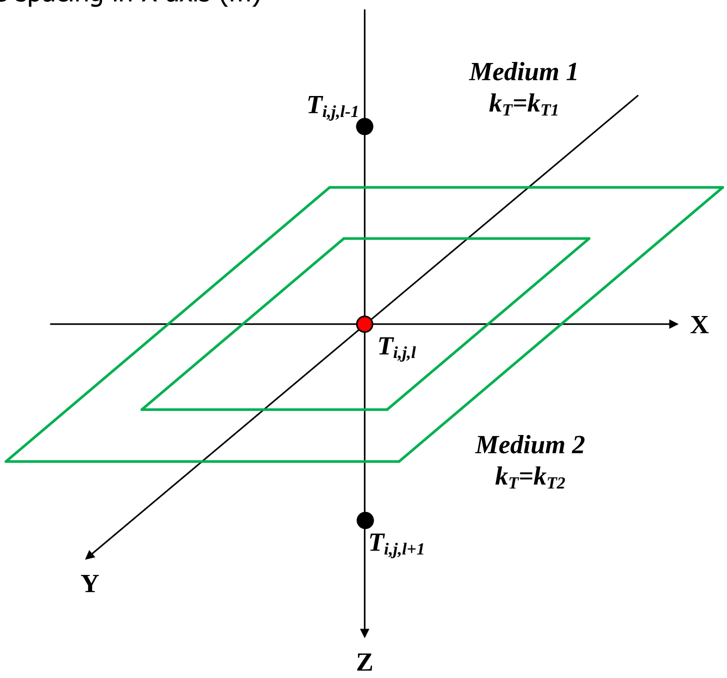


Figure 5.14 – Interface of Two Media With Different Properties

When the node is located at the interface between two media as shown in Figure 5.14, Equation 5.3-7 changes to [45]

$$T_{i,j,l} = 2 \cdot \frac{\left(\frac{(k_{T1}+k_{T2}) \cdot \varphi_e \cdot T_{i+1,j,l} + \varphi_w \cdot T_{i-1,j,l} + \varphi_n \cdot T_{i,j+1,l} + \varphi_s \cdot T_{i,j-1,l}}{2} + k_{T2} \cdot \varphi_o \cdot T_{i,j,l+1} + k_{T1} \varphi_u \cdot T_{i,j,l-1} + \frac{g}{k_T}\right)}{k_{T1}+k_{T2}} \tag{5.3-20}$$

The note temperature at time t+Δt and t is represented

$$T_{i,j,l}(t+\Delta t) = (\alpha \cdot \Delta t)\left(\varphi_e \cdot T_{i+1,j,l}(t) + \varphi_w \cdot T_{i-1,j,l}(t) + \varphi_n \cdot T_{i,j+1,l}(t) + \varphi_s \cdot T_{i,j-1,l}(t) + \varphi_o \cdot T_{i,j,l+1}(t) + \varphi_u \cdot T_{i,j,l-1}(t) + \frac{g}{k_T}\right)(1 - \alpha \cdot \Delta t \cdot \Delta) \cdot T_{i,j,l}(t) \tag{5.3-21}$$

With

α soil thermal diffusivity (m^2/second)

The node temperature in the soil at any time can then be solved from Equation 5.3-18, 5.3-20 and 5.3-21.

The finite-difference method illustrated above could be used to analyse the soil heating more accurately as it can take into account the effect of convection at soil surface, thermal conductivity and diffusivity of different mediums. The results demonstrated in [44] [45] show that the soil temperature rise calculation can be significantly influenced by heat exchange between soil and air as well as high thermal conductivity and diffusivity of the coke bed.

5.3.1.1.3 Maximum Temperature Rise for Electrode Design

The common assumption is that the soil temperature must be limited to, at most, the boiling point of water with some margin. 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 done. On the other hand, if the electrode is deep below 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.

5.3.1.1.4 Thermal Time Constant for Cooling

It should not be assumed that the thermal time constant for cooling of an electrode is equal to the time constant for heating. In general, it can take longer for an electrode to cool back to ambient temperature than it takes to heat up. Thus, when designing an electrode with a thermal rating less than maximum continuous pole current, the designer should assess the possibility of multiple events each causing significant temperature rise with short time intervals between events.

5.3.1.2 Moisture Content of Soil and Electro-osmosis

Operation of an electrode in anodic mode can lead to reductions in local soil moisture content and, in the event of operation at high current for prolonged periods with dry soil conditions, can cause accelerated drying and thermal runaway with potential to cause permanent damage to the electrode.

The decrease in soil moisture content is primarily due to electro-osmosis effects and increased evaporation due to temperature rise. If the soil moisture falls too low, and continued monopolar operation is necessary, it may be necessary to provide an external water supply to irrigate the electrode site. To minimize the amount of water required, the water would ideally be applied immediately adjacent to the electrode using buried irrigation pipes or, if these have not been provided, water should be introduced into seepage wells which allow the water to penetrate rapidly to the depth of the coke bed.

From the survey [3] many existing electrodes have a moisture content ranging from 2.1% to 37.7% of dry weight, and for some electrodes "saturated" is indicated. The Indian electrode stations Chapki and Dankaur have arrangements for adding water to the electrodes in case of very dry soil.

An electrode cannot be located in very dry environments, such as hard rock or dry sand.

It is virtually impossible to locate an electrode in a fresh water lake, like a sea electrode, because gradients against the surface at an electrode in fresh water can easily reach the values of 100-200 V/m, which is extremely high relative to the tolerance of fish to electric fields. 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 or lake water resistivity of 100 Ω m.

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). For the Rice Flats electrode of the Pacific Intertie, where the electrode is shallow and an operation of 80 hours/year with a current of 1800 A, 0.5 A/m^2 has been used as a design value. In the CU-project, both electrodes are deep and a continuous operation of 30 days with 1500 A, 2 A/m^2 would be possible.

Large land electrodes buried close to the surface should preferably be placed in flat terrain conditions, ideally with approximately equal depth to ground water level. If possible, the configuration of the electrode should be selected and located in such a way that natural precipitation is utilised to increase the moisture content of the soil around the electrode.

In the Danish shore electrodes, which are similar to land electrodes in their construction, about 5-8 A/m^2 is used. Adequate moisture levels are ensured by the location close to the sea, and electrode depth below the water level of the sea.

5.3.1.3 General Electrode Arrangements

With the results of shallow resistivity measurements, it is possible to define the electrode arrangement for the site. The selected arrangement could be horizontal or vertical depending on the stratification of the soil resistivity.

5.3.1.3.1 Horizontal Arrangements

These kinds of electrodes are also known as shallow electrodes, because the installation in the low soil resistivity is near the surface. A horizontal electrode may be shaped in many different configurations.

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. Figure 5.15 shows a typical single shallow ring electrode arrangement.

The layout consisting of one ring is advantageous in being symmetric, which makes it easy to obtain uniform gradient, all along the electrode circumference, if the soil resistivity does not vary substantially in the area covered by the ring.

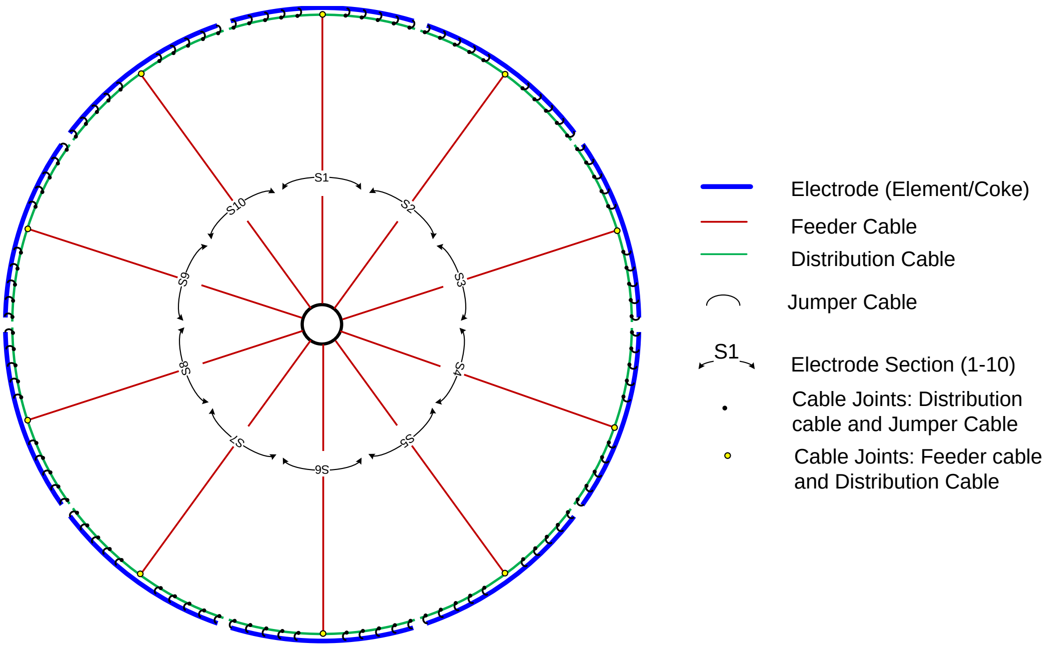


Figure 5.15 - Single Shallow Ring Electrode Arrangement with Ten Sub-electrodes

Continuous electrode trenches may be configured in two ways:

a) The coke and the metallic inner conductor cover the total length of the trench without interruption.
b) The coke string is uninterrupted, but the metallic inner conductor consists of shorter individual pieces.

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 mark a clear subdivision of the electrode so that individual sub-sections can be taken out for maintenance.

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 allow for the best possibility of equal current sharing. However, this point is typically not very important, since the resistance of feeding cable and inner conductor are not significant compared to the resistance of the electrode. 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 approximately uniform current density along the ring, this is certainly not the case for electrodes with extremities, such as linear or star types. Figure 5.16 shows current distribution per unit length in percentage on a line electrode assuming equal voltage along the inner conductor. The average is 1A/m over per unit length.

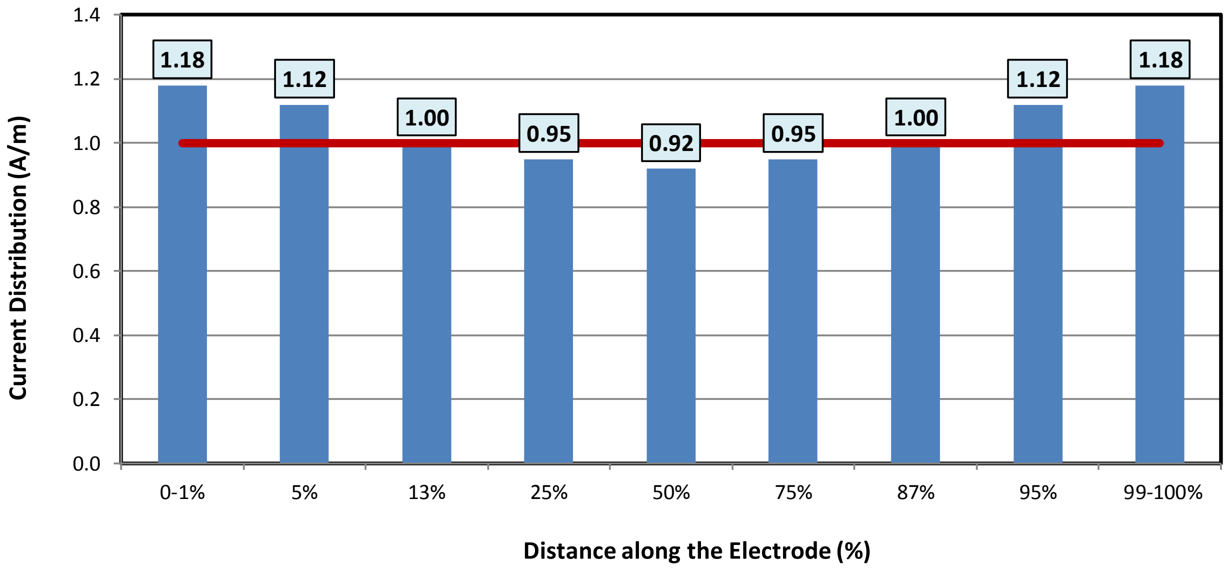


Figure 5.16 - Current Sharing per unit Length
(Reference: The computer program "CYMGRD", version 6.3 rev. 8 for Windows)

A method to reduce this unbalance 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 sub-electrodes take too much current due to low local resistivity.

The step voltage 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.

In general, the soil resistivity is not uniform. It is not uncommon that a design provides the lowest resistance but at the same time represents a non-optimal current sharing in both calculations and actual solution where a division into elements, sub-electrodes, 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.

5.3.1.3.2 Vertical Arrangements

A vertical arrangement may be preferable to a horizontal arrangement if a better conducting stratum is present at some depth below which a horizontal arrangement would be difficult to construct. This depth could be more than 5 meters. Vertical electrodes are also known as deep well electrodes.

These electrodes consist of vertical elements or wells; normally comprised of a column of coke/coke breeze, with an inner metallic conductor, which most often is divided into pieces.

Benefits of this kind of electrode, compared with a shallow electrode, are:

a) Generally, vertical arrangements need less space on the surface.
b) Normally, the step voltage on the surface is decreased by vertical arrangements as shown in Figure 5.11.

c) They are less susceptible to seasonal variations of moisture and temperature.

The drawbacks of this kind of electrode are:

a) Construction and materials are more expensive than horizontal electrodes. Also extra wells may need to be constructed because repair of a well may not be feasible.
b) They can be less reliable than shallow horizontal construction. There is a history of failures in CU Project and Cahora Bassa where electrode failures were reported because of electro-osmosis and overheating respectively.

If the wells are arranged along a circle, it will be easier to equal current division, assuming equal resistivity conditions for all wells, but taken into account the current distribution in the individual well is unequal, as indicated in Figure 5.16.

The mutual influence among the wells must be considered regardless of the pattern selected. The separation of the wells should be kept larger than well length to avoid this effect.

During the operation of these electrodes gas will be produced due to the electrolysis and heating of water. A system to evacuate the gas inside electrode wells shall be considered and installed if necessary.

Currently there are only a small number of vertical electrodes in operation: The Apollo electrode of Cahora Bassa System in South Africa, Coyote and Sevier electrodes of Intermountain System and Coal Creek and Dickinson electrodes of CU Project in United States, and electrodes of the Rio Madeira HVDC system in Brazil. More details of electrodes already in service can be found in the survey [3].

The required length of the active part of the electrode and the burial depth depend on the geology and distribution of the different stratums of the soil.

5.3.1.4 Electrode Materials

5.3.1.4.1 Inner Conductor

All land electrodes summarized in [3] use an inner conductor, surrounded by coke, to ensure good contact to the soil.

Three materials, which are all suitable for reversible operation, can be used as far as the inner conductor is concerned:

a) Steel or "mild" steel rods or tubes - 30-40 mm or larger in diameter. Mild steel can be either rods or tubes and have the advantage, of being low cost, easy to transport, and robust to handle and install. When using mild steel relatively dry conditions would be preferred, because water saturation in the coke surrounding the conductor would involve increased metal corrosion. For short wells the steel conductor extend over the full length without any gaps or breaks.

b) SiCrFe rods or tubes – High silicon chromium iron elements are commonly between 45 mm and 150 mm in diameter, with a length between 1.25and 2.3 m. The electrode bars normally only partially cover 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 backfill especially where the soil resistivity is low. High silicon chromium iron electrodes are highly resistant to corrosion, but must be handled with care because of the brittleness of the material.

c) Graphite rods – These are commonly 100 mm in diameter, 1.2-2.4 m length. Similar to SiCrFe rods, the graphite rods would only cover part of the length or depth of the coke. This type of electrode material is not commonly used because of its low mechanical strength and tendency to decompose under the action of large currents.

5.3.1.4.2 Backfill

The conductive backfill shall preferably be calcinated petroleum coke. It has a specific gravity of about 1.6 and a bulk density of about 950 kg/m^3. The preferred grain size of coke varies from 5 to 22.5 mm. Coke originating from calcination of bituminous coal is not preferred as it tends to have higher resistivity, a larger proportion of impurities and larger grain size.

The resistivity of coke is very much dependent on compression. Thus it is strongly recommended to compress the coke when used in horizontal arrangements, to at least 1000 kg/m^2 (10 kN/m^2) during 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. In vertical arrangements, there is no need to compress the coke.

An acceptance limit of 0.05 Ω-m at 10 kN/m^2 is suggested. Some qualities of coke, may have a resistivity of 0.02 Ω-m or lower.

Raising the compression to 20 kN/m^2 lowers the resistivity by about 30 per cent. Coke has been shown to be suitable for use to compression values of 200-400 kN/m^2, which would occur in the case of100 m deep electrodes due to natural pressure increase with depth.

For chemical composition EPRI has suggested the following specification for coke breeze:

- Carbon ≥ 92 %
- Sulphur ≤ 1 %
- Volatile ≤ 0.2 %
- Ash ≤ 1 %
- Balance of other minerals 0.5 %

While the user can adjust his specification according to local market possibilities, but it is preferred to have final acceptance values closer to the EPRI.

It is strongly recommended 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. The resistivity might be increased if significant amounts of (insulating) sand mix with the coke. However, the outside of the coke pile will be in direct contact with the surrounding soil. A certain "contamination" of the coke against soil is thus inevitable. If the soil is sandy and includes very fine particles that could cause silting into the coke it may be necessary to cover the top surface of the coke in the trench to avoid excessive infiltration of fine particles.

For horizontal arrangements, a cover of geotechnical cloth or other material will protect the coke, and this construction would also allow easier clean-up of backfill soil, if the coke trench is opened for inspection at some later occasion.

The inclusion of the cloth or other covering would hinder current flow from the from the coke to the soil and an increase in trench dimension may be needed to maintain the current density within acceptable limits. The reduction of current flow upwards might be an advantage as it may reduce step voltages above the electrode.

Geotextile materials 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 worthwhile 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.

In case of vertical arrangements, it might be necessary to have a provisional tube of for instance steel or PVC 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.

5.3.1.5 Longevity Considerations

For any type of electrode, wastage of materials due to electrolytic action will occur over time that will be proportional to the ampere hours of duty in anodic mode. The longevity of the electrode will depend on the amount of corrosion and sufficient material must be installed to withstand.

Inner conductor: The estimated life of the inner conductor is given in the next equation:

$$W = \frac{I \cdot t \cdot C}{f} \qquad (5.3\text{-}22)$$

Where,

W = Total anode weight (kg)
I = Average current discharge (A)
t = design life (years)
C = Consumption rate of the material (kg/A-Year).
f = Utilization factor (numeric value between 0 and 1.0).

The consumption rate of the material depends on the environment in which it is placed, and normally needs to be estimated based on information provided by the manufacturer of the material when tested in similar conditions. The electrode material manufacturer would usually be able to give the electrolytic grams per ampere-hour or some other indication, but frequently cannot give more precise information for each possible type of environmental condition in which the electrode would be installed. As already described, this environment will normally be within a bed of coke backfill. The consumption rate is high when the inner conductor is in direct contact with soil. For example, as Kimbark [2] explains, an anode of iron carrying 1000 A, having a theoretical loss of mass of about 9.0 kg per Ampere year, and if it's surrounded by coke, the loss of mass could be 0.140kg per Ampere year. The reason for this is the type of conduction, from iron to coke is mostly electronic but from iron to soil is primarily electrolytic.

The utilization factor is the percentage of the material that can be used before it fails.

Backfill: The consumption of the backfill could be problematic because the inner conductor might be exposed directly to the soil, resulting in an increase of the consumption rate of the inner conductor.

The life of the backfill could be estimated using the same equation as for the inner conductor, but with an assumed consumption rate of 1 kg/A-Year. The suggested utilization factor is 50%, which is very conservative due to the critical situation of inner conductor exposure as explained above.

As a criterion for electrode design, it could be assumed that the anode would remain useful until it loses 50% of its mass and it should last for at least the useful life of the transmission project.

5.3.1.6 Electrode Resistance

Electrode resistance in Ohms is given by:

$$R_e = \frac{V_e}{Id} \qquad (5.3\text{-}23)$$

Where

V_e is the voltage rise of the electrode, and
Id is the current.

The resistance should be kept low to keep system losses in an acceptable range.

5.3.1.7 Sizing

There are several ways to model electrodes with different levels of complexity. The methods include analogue analysis like EPRI method, image method, and finite elements. Successively more detailed methods could be applied during different stages of project development with the most detailed models being used in the final design.

The electrode sizing consists of finding the dimensions of the electrode such as electrode burial depth, backfill section, radius in case of circular electrodes, number of wells in case of deep electrodes that satisfy the limits of electrode resistance, step and touch potential, current density and temperature. It is also recommended, after the electrode sizing, to check the expected longevity of the electrode as well as the corrosion of the material for an electrode. Probably, the corrosion of the material for an electrode of a bipolar scheme could be negligible. This is more important for electrodes in monopolar schemes that will operate for long periods.

The degree of influence of the different dimension parameters is different in the results. When radius or length of electrode is changed, the dimension parameters will vary more than if depth or backfill cross section is changed [49]. The dimensions of a land electrode can be determined following the design process as shown in Figure 5.1.

5.3.1.8 Future Extension

Having selected a configuration and determined the size, 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 within or completely surrounded by the existing part, the current density of the new parts wold be lower (assuming the same cross-section of trench). If, however, the new parts are extremities to the existing configuration, then the new parts would have increased current density, and the existing parts would see a decline in current density. For example, if a single ring electrode is extended with a new inner ring, then a diameter of about 80 per cent would be preferred to obtain the lowest possible combined resistance to remote earth, but the inner ring will have lower current density than the outer. Making the optimal electrode configuration is often a question of priority and economics. 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

5.3.2 Operation and Maintenance Considerations

For bipolar HVDC operation, the electrode is normally operated constantly, carrying the imbalanced currents between the two poles. During emergency or maintenance operation, when only one pole is in service, the electrode could be operated to its maximum designed current for a short duration. For monopolar HVDC configurations, the electrode can be operated continuously between the minimum and maximum rated current.

Historical statistics of existing electrode stations based on the survey conducted by CIGRE [3] does not provide detailed information on the electrode operation. Most of the answers given conclude that HVDC electrodes are usually very reliable when considering the total HVDC system. However, a number of failures have occurred at some electrodes such as Cahora Bassa and Inga Shaba due to poor site conditions.

When it comes to single sub-electrodes, some failures have been reported. These failures have occurred mainly at the cables branching to each sub-electrode. The cables may be damaged for instance when cut by sharp stones or on edges of concrete. Failures can also occur due to corrosion if there is an insulation failure or water leaks into a joint in the feeder or distribution cables. The electrode would not become disconnected, because in general the electrode would be designed conservatively to allow for 20% to 30% outage of feeder conductors or sub-electrodes and without decreasing the total current carrying capacity.

Broken conductors caused by faulty insulation as well as conductor being stolen have been observed and reported by Manitoba Hydro in Canada and Furnas in Brazil.

In general, the electrode station should be inspected regularly, and also after any period of extended operation in monopolar mode to ensure integrity. Inspection should cover the following:

a) The backfill over the coke beds and cable trenches should be inspected to ensure that there has not been excessive settlement and that the grading of the depressions above the trenches slopes towards the seepage wells if installed. Any soil that has been lost to settling or local erosion due to excessive water flow should be restored.
b) Remove all foreign matter that may impede water flow from the top of the seepage wells. If there has been settlement or erosion around the concrete curbs, they should be restored to the original grade and the backfill restored.
c) Inspect the condition of the disconnectors, cables, clamps, insulators, structures, structure grounds, structure foundations, moisture and temperature measuring tubes/wells, etc. and repair any damaged items as necessary.

d) Schedule a period of monopolar operation, measure the currents in each electrode subsection, and compare it with the current sharing obtained during the initial commissioning tests. Excessive current unbalance compared with the original measurements may be a sign of hidden damage such as a cable joint failure.

5.3.3 Land Electrode Design Example

This section illustrates an example of a land electrode design with a single or double shallow ring configuration.

(a) Design Conditions and Criteria

The specified design conditions, electrode current ratings and design criteria are listed in Table 5.2.

Table 5.2 - Design ConditionS, current RatingS and Design Criteria

Design conditions	
Ambient Air temperatures	
Maximum daily average temperature	35°C
Average annual temperature	30°C
Soil Conditions	
Soil Resistivity (uniform)	70 Ω·m
Soil thermal conductivity	1°C·m/W
Electrode Current Ratings	
Continuous current rating (A)	3000
Continuous overload current rating (110%, A)	3300
30-minute short-time overload rating (120%, A)	3600
10 second short-time overload rating (130%, A)	3900
Current for calculating coke-soil boundary current density, with 30% of sub-electrodes out of service (A)	3600
Design Criteria	
Maximum allowable Step Voltage required suggested by designer, (V/m), which is used as design criteria.	$5+0.03*\rho_s=7.1$
Touch Voltage for grounded metal structures accessible to public, (V)	$7.42 + 0.016*\rho_s=8.54$
Electrode Design Working Life	Lesser of • 60 million Ampere Hours, or • 30 years normal Operation
Operational mode	either cathode or anode
Maximum electrode resistance to remote earth, (Ω)	≤ 0.3
Average Current density at coke-soil boundary with 25% of the sub-electrodes out of service (A/m²)	<1.0
Preferred electrode type	Single or Double Concentric Circular Shallow Ring
Number of sub-electrodes	At least 4
Max temperature at any point of electrode during operation, (°C)	< Water boiling temperature
Continuous operation at 3000 A	Design life of Electrode

(b) Electrode Design Parameters

Table 5.3 shows the electrode design parameters of both a single and double ring design to meeting the design criteria based on the design conditions and current ratings.

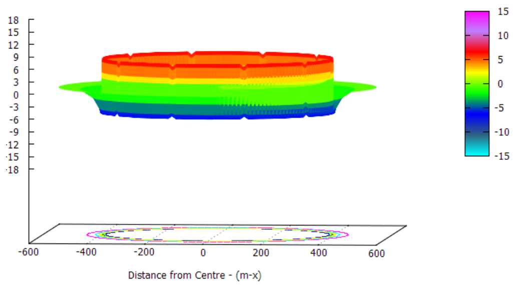
Table 5.3 - Electrode Design Parameters

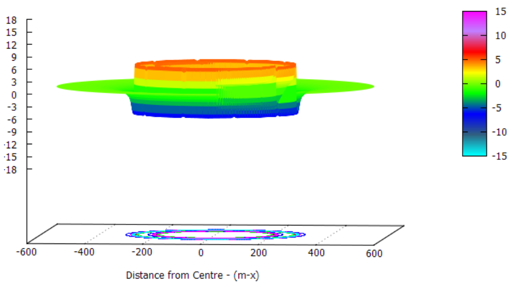
	Single Ring	Double Ring
Diameter (m)	800	Inner ring =420, Outer ring =560
Depth (m)	3	3

Coke cross section size	1.25m x1.25m	1m x 1m

(c) Safety Consideration – Step Voltage, Touch Voltage and Transferred Potential

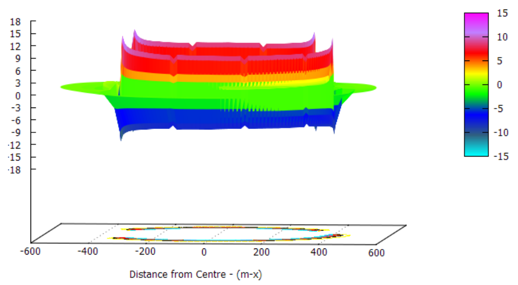
The potential gradient generated by the designed electrode calculated with FEM program is shown in Figure 5.17. Figure 5.17 (a) shows the potential gradient assuming a uniform soil resistivity of 70 Ω·m, the highest step voltage produced by single ring and double ring is 6.69V and 6.68V, respectively. If 30% of the electrode is out of service for maintenance, the maximum step voltage would increase to 15.4V and 14.1V as shown in Figure 5.17 (b).

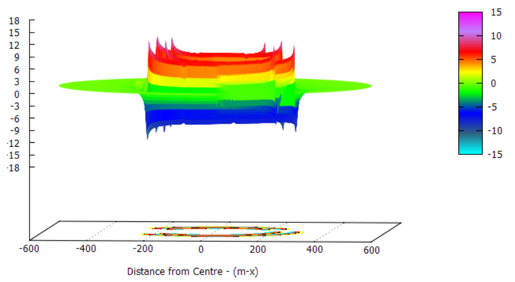




Single Ring Design (E_{SCmax}=6.69V) Double Ring Design (E_{SCmax} x=6.68V)

(a) Uniform Soil Resistivity without Outage (70 Ω·m)

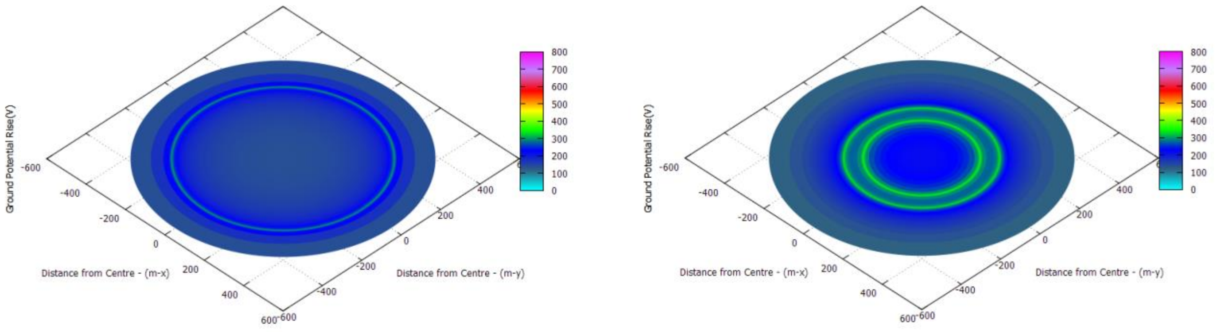




Single Ring Design (E_{SCmax} =15.4V) Double Ring Design (E_{SCmax} =14.1V)

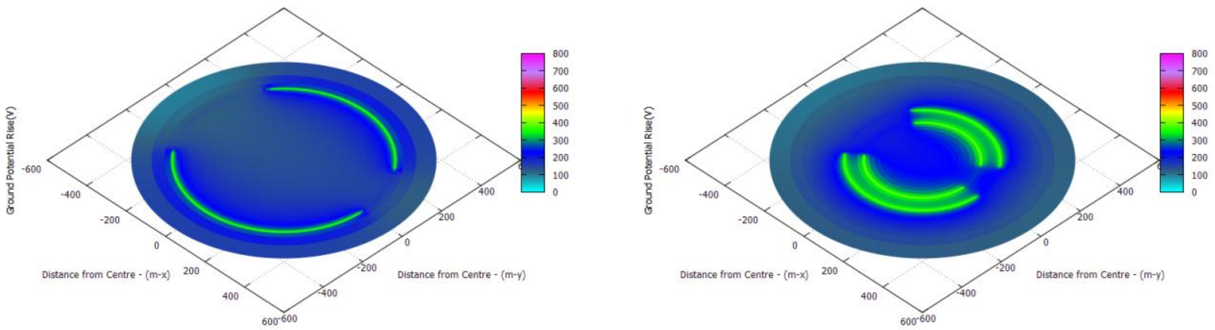
(b) Uniform Soil Resistivity Outage of 30% of Electrode

Figure 5.17 – Simulated Potential gradient



Single Ring Design Double Ring Design

(a) Uniform Soil Resistivity without Outages



Single Ring Design Double Ring Design

(b) Uniform Soil Resistivity with Outages of 30% of Electrode

Figure 5.18 – Ground Potential Rise nearTHE Electrode Site

(d) Thermal stability at specified current ratings

Table 5.4 presents the maximum electrode temperature rise, thermal time constant and the associated soil data used in the calculation. The pre-existing ambient soil temperature at the coke-bed depth is conservatively assumed to be 30°C.

The calculated maximum temperature rise using equation (5.2-2) is about 325°C. With the application of the factor of 5 as per CIGRE 14.21 TF2, the actual temperature rise is expected to be 65°C and the final temperature of the electrode would be 65°C +30°C = 95°C which meets requirement. Given the long time constants in excess of 1 year and the expected temperature rise of about 65°C, in excess of 2 years of continuous overload operation in monopolar mode at 3300 A should be possible for this electrode.

Table 5.4 - Electrode Maximum Temperature Rise

Parameter	Symbol	Unit	Value		
			Single Ring Design	Double Ring Design	
				Inner Ring	Outer Ring
Soil electrical resistivity	ρ	Ω·m	70		
Soil thermal conductivity	λ	W/m-°C	1.0		
Calculated thermal time constant	T	years	2.77		
Electrode current (Rated continuous overload current)	Id	A	3300	1287	2013
Calculated electrode resistance to remote earth	R_e	Ω	0.07	0.12	0.09
Electrode voltage rise with respect to remote earth, (based on uniform soil resistivity)	V_e	Volts	213	154	182
Expected Maximum Electrode temperature rise	θ_e	°C	325/5=65	169/5=34	237/5=48

(e) Current Sharing between Sub-electrodes

The ring electrode is divided into 10 equal sub-electrodes to facilitate inspection, testing and, if necessary, maintenance. If the soil resistivity were completely uniform, the current would be equally distributed to ten sub-electrodes when there are no outages of electrode sections.

However, in the case of outage of some sub-electrodes, more current will flow in the sub-electrodes adjacent to the de-energized sub-electrodes as seen in Table 5.5 which was calculated with 10-second current rating of 4500 A. Also if resistivity is not evenly distributed which is the normal case, the current into these sub-electrodes will vary even under no outage condition. Thus, the current rating of cables has to take into account the uneven current distribution during outage of electrode sections and also for other soil conditions rather than uniform resistivity.

Table 5.5 - current division between sub-Electrodes

Case No	Current flow in Each Sub-electrode(A)											
	1	2	3	4	5	6	7	8	9	10	Max	Avg.
Uniform Soil Resistivity	450	450	450	450	450	450	450	450	450	450	450	450
Uniform Soil Resistivity Outage of 30% Electrode	out	662	611	682	out-	out	680	604	601	659	682	643

(f) Current density

The average current density is calculated as the injected current divided by the surface area of the coke to soil boundary. The current at the 30-minute overload rating and with 30% outage of sub-electrodes is used for the current density calculation. The current density is determined separately for the inner and outer rings for double ring design and the results are given in Table 5.6. The calculated current density meets the specified 0.5-1.0 A/m^2.

Table 5.6 – Calculated Current Density at Coke-Soil Boundary

Parameter	Single Ring Design	Double Ring Design	
		Inner Ring	Outer Ring
Size of coke cross-section (m x m)	1.25 x1.25	1.0 x 1.0	1.0 x 1.0
Diameter of ring (m)	800	420	560
Surface area of coke-soil boundary no outage, m^2	12556	5278	7038
Volume of coke used in the ring (m^3)	3927	1319.5	1759.2
Current Sharing for each ring (%)	100	39	61
Maximum Current in each ring (A)	3600	1404	2196

Current density at Coke-Soil boundary without any outage (A/m²)	0.29	0.27	0.38
Surface area of coke-soil boundary 30% outage (m²)	7037	3694	4926
Average Current density at Coke-Soil boundary with 30% outage (A/m²)	0.41	0.38	0.45

(g) Electrode Resistance to Remote Earth

The electrode resistance to remote earth is required to be less than 0.3Ω under all conditions. Table 5.7 summarizes the estimated electrode resistance to remote earth for both single and double ring design under normal and outage operation conditions. In all cases, the resistance meets the requirement.

Table 5.7 - Electrode Resistance to Remote Earth[1]

Design Cases	Resistance from Injection Point to True Earth (Ω)		
	Single Ring	Double Ring	Criteria
No Outage	0.074	0.078	≤ 0.3
Outage of 30% Electrode	0.092	0.092	
Note 1: Feeder Cable resistance included			

5.4 SEA ELECTRODES

5.4.1 Design Considerations

Sea electrodes would be applied where land or shore electrodes cannot be utilized due to lack of a suitable site or the need to avoid wave action as well as to reduce ground currents in the earth.

Sea electrodes can be located in the sea at any distance from the shore (generally >100 m) and are completely immersed in seawater. Sea electrodes have advantages compared to land electrodes located in soil, such as a better safety because they are usually not easily accessible to human beings. Their environment offers a good cooling system and a surrounding conducting medium which has a higher specific conductivity than soil.

The sea electrodes transfer the DC current from an electrode line of the HVDC system via one or more feeder cables to the seawater, which is a high conductivity homogeneous medium, and to the sea bottom, which has a lower specific conductivity than seawater but usually, particularly in layers close to seawater, higher than for soil layers far away from the sea. Sea electrodes should be electrically safe, have high operational reliability and sufficiently long service life and should not cause any harmful environmental effects.

The active part (electrode elements) of sea electrodes can be:

a) in direct contact with seawater and should be properly anchored in order to withstand tidal currents, natural ocean currents and storm surges,

b) laid on the sea bed and anchored with proper materials (e.g. rock damping, gravel, etc.) in order to withstand any potential ocean currents,

c) completely buried in the seabed.

Sea electrodes are usually installed in water not deeper than 30 m – 35 m since this is the maximum depth at which divers can work without special precautions. In the case in which the electrode is installed at water depth deeper than 50 m the installation would be supported by remotely operated underwater vehicle (ROV) only or by deep-sea divers (frogmen). However, in such a case the costs of installation and maintenance increase abruptly. Water depths ranging between 35 m and 50 m belong to a "gray zone" and shallow water divers usually need decompression facilities to operate in this range of water depth.

In case of electrodes with active elements in contact with seawater only, special attention should be paid to the structure that supports the active elements above the seabed. Such structure should be able to withstand currents and fishing activities and to the extent possible anchoring. On the other hand, the current passes directly from the active elements to the seawater (or vice versa) with a reduced interface resistance[1]. Consequently, the heat generated by the current due to the presence of the interface resistance is small and easily dispersed in the water.

Electrodes in direct contact with water have a reduced total electrode resistance compared with other types of sea electrodes. For this type of electrode special attention should be paid during the installation of active elements to ensure that the elements are in contact with seawater only, since if they are not placed far enough from the seabed, sand or mud can strongly influence their operation especially at high currents. Therefore this type of electrodes must have the active elements at some height from the seabed usually to avoid burial by silting.

Electrodes with directly buried active elements are better protected against damage caused by fishing activities and anchoring. However, due to higher interface resistance, electrodes require a larger active element surface area compared to electrodes having active elements in contact with water only. Buried elements may also be subjected to more rapid corrosion than exposed elements and thus different element types capable of withstanding such corrosion would need to be selected.

Electrodes with active elements laid on the seabed would be subject to silting and would need to be designed for buried conditions.

As a general rule, it can be stated that sea electrodes should not be subject to overheating, since heating of the seawater will create a vertical convective flow of seawater which would readily remove the heat even where there is no natural current flow.

As far as sea electrodes are concerned, special attention should be given to the installation since it has a significant impact on the total cost of electrode. Laying vessels, marine cranes, diver assistance and equipment for precise navigation generally make sea electrodes more expensive compared to shore electrodes. The cable systems between the shore and the electrode must also be included in the total cost of electrode.

Sea electrodes may be required to be operated as bidirectional electrodes and should be capable of both anodic or cathodic operation without unacceptable reduction of its expected life.

Today there are applications of sea electrodes with both unidirectional and bidirectional electrodes but there is much more experience with unidirectional solutions.

Although there are obvious advantages to have bidirectional electrodes, it is generally the case that the cost of installation and maintenance is higher for bidirectional electrodes. Therefore, in some cases, it may be more cost effective to install two unidirectional electrodes, one for each polarity.

5.4.2 Operation and Maintenance Considerations

There is an important distinction between electrodes operating as anodes and/or as cathodes. Anode electrodes produce oxygen and chlorine while cathode electrodes produce hydrogen. In general, the amount of oxygen, chlorine and hydrogen are not enough to alter the environmental conditions since the natural marine currents help dissipate any ions and thus avoid build-up of critical concentrations in the open sea. Furthermore, measurements or numerical simulations that take into account both the diffusivity of such gases and the effect of marine currents can be performed.

Experience and tests [2] have shown that the electric field generated by cathodic electrodes tends to drive fish away while electric fields above a given threshold at anodic electrodes tends to attract fish.

Cost of maintenance has should be considered when choosing between unidirectional and bidirectional electrodes. Anodic electrodes are subjected to wear out of the active materials while cathode electrodes activate materials tend to foul up. Worn out electrode elements need to be replaced while the fouled elements need to be periodically cleaned. In any case, all the aforementioned considerations are strictly connected with the hours of electrode utilization generally in monopolar operation.

Each utility may have its own biases based on positive experience from years of operation with a particular type of electrode, which has been improved through small adjustments along the road based on studies and/or measurements in field. This background often restrains utilities from adopting new or different electrode solutions and also from coming across uncertainties that can lead to higher

[1] The interface resistance is the resistance that the current encounters to cross the interface between the electrode element and the medium in which the current is dispersed.

installation and maintenance costs. Consequently, it is also understandable that utilities are generally not motivated to change unless there is a change of regulations that requires it.

Sea electrodes are in general very difficult to maintain due to difficulties in working underwater. For this reason, electrode suppliers are encouraged to produce solutions that are "virtually maintenance free". Such solutions are usually based on remote diagnostics able to assess the electrode conditions by electrical measurements made from the converter station or from a shore-based station (if present) where the transition from the land to the sea line is performed. If the measured values are different from those recorded during the commissioning phase, a warning would be generated and a forced maintenance action should be planned. In some cased this kind of measurement can help to predict a fault or the malfunctioning portion of the electrode which can reduce electrode outage for maintenance. The difficulties in the detection of faults or malfunctioning of the electrode increase with the number of active elements on each feeder cable since the current variation on the electrode feeder cable id inversely proportional to the number of elements and consequently probability of detecting a fault is reduced. For this reason, as the number of active elements increase, the number of feeding lines to the electrode should also increase.

Sea electrodes are always designed to ensure safety of fish and divers near the electrode. In the condition in which some fault occurs on the electrode, conditions that are present in normal operation can be strongly altered and consequently special precautions must be taken when operating the electrode in such conditions. Failure mode analysis and the resulting operational restrictions to ensure safety should be performed during the planning/engineering stage of the electrode. Furthermore, the philosophy of transmission system operators is that each part of the grid should be monitored for security and safety reasons, but also inspected whenever it is deemed necessary. In this respect electrodes with active elements in direct contact with water would be preferred since diver personnel and remote operated vehicles can easily approach electrode elements and visually evaluate their condition by eye or by remote camera without requiring equipment for digging or uncovering the elements.

There are no general rules for the sea electrode maintenance since each electrode type would have its own particular requirements. The electrode designer should be asked to provide a detailed maintenance programme and procedure during the tender phase in order to give to the user information to estimate the electrode operational electrode cost during its life-cycle.

5.4.3 Environmental Impact

The regulatory approval process of a sea electrode normally requires evidence of zero or at least minimal negative environmental impacts. To meet this requirement, it is essential to have knowledge, good technological solutions and documented experience as well as good information on the local conditions at and near the electrode site. It may be possible to demonstrate positive impacts for electrode operation such as reduced CO_2 production compared to dedicated metallic return. These should be demonstrated together with any negative impacts.

If there are possible negative environmental effects, suitable mitigation methods should be identified since an exact prediction of the electrode impact may not be possible.

An anode is an electrode with positive polarity, conducting the current into the seawater. Two competing electrolysis reactions take place at an anode in seawater; chlorine and oxygen evolution. Chlorine is unstable in seawater, and reacts with seawater molecules forming hypochlorite. In secondary reactions hypochlorite, chloride, hypobromite, bromide, chloroform and bromoform may be formed.

Chloride and bromide are natural compounds of seawater, and are considered harmless. Existence of hypochlorite and hypobromite can lead to formation of chloroform and bromoform, which intrinsically are toxic. Bromoform is however the dominating organic halogen in natural seawater, being produced by algae [51].

From an environmental viewpoint, it would be desirable to design the electrode to reduce the chlorine selectivity and increase the oxygen evolution. The amount of chlorine can be reduced by:

a) Maintaining a low pH-value at the electrode surface by ensuring sufficient seawater exchange
b) Increasing the electrode size to reduce the current density
c) Use of favourable electrode materials

The environmental concerns expressed relate mainly to marine flora and fauna. Several studies have been done to evaluate the impact from sea anodes, with the major result that electrode designs can be achieved such that no environmental impact should be expected. [52][53][54].

Experience with sea electrodes are different all over the world. Some sea electrode had corrosion problem during the initial operation and was mitigated. To date, no negative effects on either marine flora or fauna have been experienced. Extensive environmental monitoring activities have been undertaken on sea electrodes of different HVDC interties to assess actual environmental impacts. In the case of Norwegian Skagerrak-electrode extensive tests of seabed sediments and mussels have been done to check the environmental impact on the marine surroundings [55]. No negative environmental impact was revealed. Video recordings of the active elements (graphite electrodes) in operation, from the Konti-Skan HVDC showed that bottom dwelling organisms, such as crabs and starfish, lived directly on the electrodes without any apparent disturbance. Fish observed close to the electrodes showed no sign of reaction, even though the electric field was estimated to be as high as 6 V/m.

The generally accepted limit for the voltage 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 would need to be increased in size, at decreasing salinity (increasing resistivity) in order to maintain the gradient at a safe value.

During the first 5–6 years of operation the two monopolar Scandinavian HVDC links, Baltic Cable and around Baltic Cable anode (a titanium mesh) in Sweden, the seabed flora and fauna were thoroughly studied before and after the anode was commissioned. The content of organochlorines including bromoform in blue mussels was analysed, and pH levels at the titanium mesh surface was measured. The re-colonisation of flora and fauna was normal. No organochlorines were detected in the mussels and the pH followed a normal variation in seawater [56].

Around the Kontek anode in Denmark, the concentration of halogen compounds was measured in the sediment and in mussels. No increased levels due to the presence of the anode were found [57].

Although the results here reported represent only a small number of installed sea electrodes, the results of all these investigations indicate that no negative environmental impact effects have been found.

In some cases, concerns over possible environmental issues have led to abandonment of plans for an electrode solution. The Basslink HVDC link is monopolar and was originally planned with sea electrodes. Great environmental concerns for marine life were raised, but these were allayed based on experiences documented in [54].

However, there was continuing concern that the long gas pipelines in Southern Australia between Melbourne and Sydney would be affected by the electric fields and stray dc currents and corrosion mitigation measures were proposed. The authorities accepted monopolar operation with electrodes on the condition that appropriate agreement was reached with the pipeline owners. As the pipeline owners were commercial competitors of the HVDC link it proved impossible to reach agreement. Thus, a metallic return configuration was adopted instead of electrodes.

This illustrates that there should be clarity with respect to rights of various parties and for protecting the interests of existing infrastructure owners while facilitating new development projects.

5.4.4 Chemical Aspects

In electrolytic processes, there will always be a chemical action, because the substances diluted in the ground water or seawater will be decomposed and/or form new chemical substances.

The study of the chemical aspects relates two different processes: anodic and cathodic.

In an anodic process in groundwater of very low or zero salinity, O_2 (oxygen) is evolved, which is generally not seen as a 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 that present in seawater level, a substantial evolution of O_2. The total amount of evolved gases must respect the law, which says that the mass of decomposed material is proportional to the electric charge. The two chemical reactions that describe the process are:

Anodic oxygen production

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

(5.4-1)

Anodic chlorine production

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

(5.4-2)

Immediately after the formation of chlorine gas, a hydrolysis reaction takes place in the water forming hypochlorous acid (HOCl), chloride ions and hydrogen ions which gives hydrochlorous acid.

The amount of chlorine produced is related to the magnitude of current through the electrode and a typical current efficiency plot for available chlorine production in a laboratory cell is shown in Figure 5.19. Here the term "available chlorine" includes all free chlorine, hypochlorite and chlorite. Oxygen evolution can be assumed to consume the balance of the anodic current [59]. This data was taken at slow electrolyte velocity in a simple beaker cell and an extrapolation of these curves back to zero concentration of chlorine can then be used to determine the relative efficiency for chlorine and oxygen evolution in seawater.

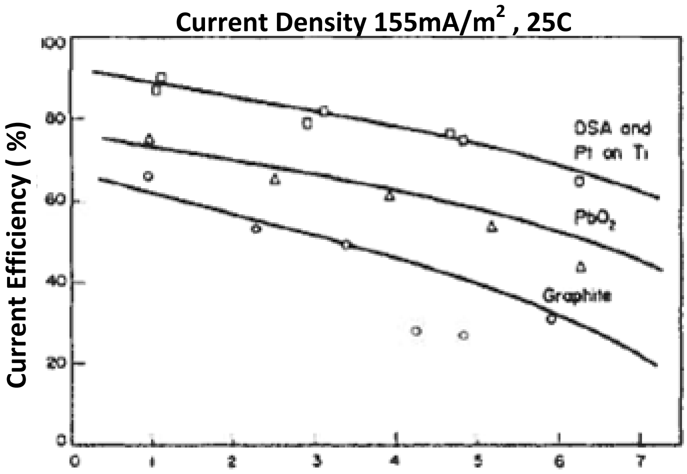
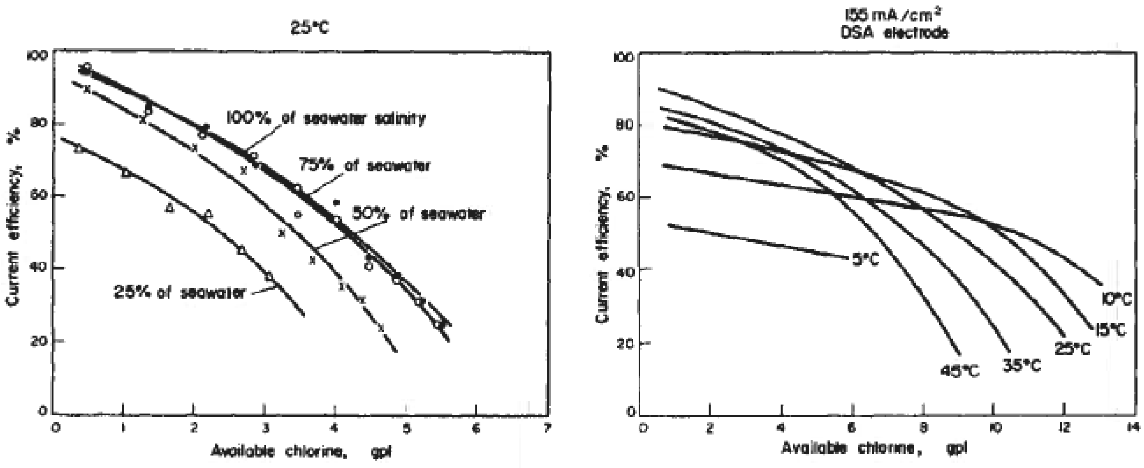


Figure 5.19 - Current Efficiency vs. Available Chorine Concentration in Seawater for Different Electrode MaterialS [59]

The increase of hypochlorite concentration decreases chlorine efficiency due to both the electrochemical oxidation and reduction of the hypochlorite itself. An extrapolation of the curves on Figure 5.19 shows that chlorine current efficiency can vary appreciably for different anode materials., For example for the patented DSA (Diamond Shamrock Corporation) and platinized titanium, when the current efficiency is at 92% lead dioxide is at 76% and graphite is at 66%. The materials used by DSA was the TiO_2/RuO_2 coating normally used for commercial chlorine production.

Comparison of the four curves in Figure 5.20(a) demonstrates the effect of seawater salinity on current efficiency in commercial cells [59]. The more rapid drop in efficiency shown in Figure 5.19 is due to a higher degree of water turbulence than in the laboratory cell. Seawater velocity of 60 cm/s was maintained to minimize deposit formation on the cathode surface. Salinity is an important parameter since seawater in coastal areas is often brackish, having a lower salinity due to the influx of fresh water from continental runoff, while seawater in hot and arid climates may have a much higher than normal salinity. A solution referred to as "100% seawater salinity" contains 18980 mg/l chloride ion, an average value for the oceans. The decrease in chlorine efficiency at low salinity is the evidence that the current density is approaching the diffusion limiting current for chloride oxidation.

The effect of temperature on the relative oxygen/chlorine efficiency is shown by laboratory cell data in Figure 5.20(b). The decrease in chlorine efficiency at high concentration of available chlorine is due to an increase in the rate of reactions of hypochlorite, particularly the cathodic reduction. The variation of current with temperature at zero concentration of available chlorine is a direct result of lower limiting current for chlorine oxidation, increasing oxygen evolution under these conditions.



(a) Effect of Salinity (b) Effect of Temperature

Figure 5.20 - Current Efficiency vs Available Chlorine Concentration using DSA Anodes [59]

As mentioned above, the anodic process leads to the formation of chlorine and oxygen and the fraction of evolved Cl_2 as a ratio to the sum of Cl_2 and O_2 is called the chlorine efficiency (or selectivity) that also corresponds to the percentage of the current that forms chlorine. Chlorine selectivity increases with increase of salinity, water temperature, pH and current density.

A supplier of coated titanium mesh electrodes has given the following information concerning the anode for the Baltic intertie: at the salinity of this site and at the rated current 1364 A, the selectivity ratio of Cl_2/O_2 is 30/70 %. At 50 % of the rated current the selectivity Cl_2/O_2 is about 17/83 %, and at 20 % of the rated current 9/91 %. Thus, 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.

To reduce the chlorine production as much as possible, a low current density should be selected, which means use of large size electrodes. Using small-sized sub electrodes that have direct contact with water to transfer the current to water, may not be feasible to achieve low current densities. However, the use of coke could help to reach low values of current density in a feasible way.

Furthermore, 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 seawater. 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 around the elements is not subject to natural exchange.

The anodic electrode material should ideally be noble, that is, it should not release any significant amount of material into the environment. In this sense, graphite, coke, SiCrFe and titanium are noble materials. If the electrode element is non-noble, as Al, Zn, Mg or Fe, it releases metallic ions which will participate in the anodic chemical process. A steel anode during operation gives rise to oxygen and chlorine which then react with the anode material to form substances like Fe_2O_3 (i.e. common rust), $FeCl_2$ or related chemicals. In this condition, most of the oxygen and chlorine generated are not released as gas. Of course, such an electrode is consumed but still with a rate of "only" 9130 kg/kA•yr. This kind of electrode if limited in operation to a short-time duty would with suitable design last for many years. Natural wear-out due to telluric currents should be taken into account in the design.

An anode coating which selectively evolves oxygen from chloride solutions has been identified [59]. The oxygen-selective coating can be applied to a DSA substrate during the electrolysis of seawater or dilute sodium solution at 150 mA/cm^2. The electrolyte is first doped with 150 mg/l manganese ions and is then acidified below pH 1 with HCl. The acid electrolyte will first cause chlorine to evolve as a gas but the chlorine is quickly replaced by oxygen as electrolysis proceeds. Continued electrolysis for 15-20 min is sufficient to complete application of the coating. An anode prepared in this manner is stable for long-term electrolysis of seawater solution. This type of coating is not degraded anodically in the presence of significant amounts of chlorine ions.

The coating is apparently a porous deposit containing about 100 mg/m^2 manganese. Attempts to characterize the coating with X-ray diffraction show no crystalline pattern, but only a broad amorphous ring, leading to the conclusion that it is essentially a poorly crystallized amorphous form of MnO_2. During coating process, the anode voltage should be kept high enough to permit the anodic deposition of MnO_2. This kind of anode produces oxygen from seawater at 99% efficiency with no significant production of chlorine. Such coatings would be most useful in non-reversible electrodes which only act as anodes. The impact of current reversals on this type of coating has **not** been evaluated.

At the cathode, where the electrons leave the electrode and react with water molecules, H_2 (hydrogen) is released in gaseous form and partly dissolved in water. When H_2 in water reaches a saturated concentration and little or no exchange of electrolyte occurs close to the cathode, the chemical reaction is:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (5.4\text{-}3)$$

If the oxygen quantity is limited, water molecules will be reduced to form hydroxyl ions and hydrogen gas, according to the following reaction

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \qquad ((5.4\text{-}4)$$

The hydrogen that is not dissolved in seawater is released to the atmosphere. If a little exchange of water occurs, a strong base NaOH (sodium hydroxide) builds up around the cathode. Cathodic sea electrodes are subject to chalk-like substances being deposited on the electrode surface. These deposits are not harmful to the electrode surface, but may increase resistance and then heating. If this heating is too accentuated, the deposit may be blasted off due to steam expansions inside the deposit itself.

Current reversals, or changes between anodic and cathodic operation may be a problem for some 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. For either polarity of operation, the electrode elements will adopt the characteristic polarization. In case of current reversal, the local chemical environment is forced to change, switching from acid to basic and vice versa. Both coke and graphite are able to withstand basic environments well and thus they tolerate current reversals well. Silicon iron does not easily tolerate current reversals as the SiO_2 layer "bursts" under basic environments causing localized pitting. However, the pitting is limited and will stop after some time once the electrode adapts to the basic environment. Thus, if sufficient material is installed to withstand limited pitting at current reversal, SiCrFe can be successfully used in electrodes where current reversal is required.

Titanium and coated titanium, which withstand the harsh anodic conditions extremely well, will not withstand cathodic conditions and are easily damaged in current reversals. Even very low current densities and the combination of ripple and low current density can be detrimental to the coating. Recently, titanium electrodes coated with special oxides have been proposed which have been formulated to withstand cathodic operation. This has been used in FennoSkan.

5.4.5 Structure and Features

Geometry of sea electrodes can be a simple linear and ring shape similarly to land electrodes, or more complex structures as n-armed stars, sort of tree shape in which the trunk represents the feeding cable line and the branches are the arms where the active elements are connected.

More complex structures are usually used for anodic electrodes but simple linear and ring shapes have also been used for anodic electrodes. Anodic electrodes are usually realized with three main parts: the feeder or distribution cable line, active elements and jumper cable lines that interconnect the feeding cable lines to the active electrode elements.

Linear and ring structures are typically applied for cathodic electrodes in which a conductor (usually stranded) with a suitable cross section is used as active element. Cathodic electrodes mainly consist of a feeding cable line and active elements

The geometric layout of reversible sea electrodes has the same possibilities as described for land electrodes. Near the coast a semicircular arrangement may be suitable but at a fairly large distance from the coast the circular arrangement would be preferable as the symmetry would help promote equal current sharing.

5.4.6 Electrode active element materials

Materials used for electrode elements are related to the type of operation, i.e. anodic, cathodic or bidirectional (both as anode and as cathode). The selection depends on the required duty and chemical reactions as described in Section 5.4.4.

5.4.6.1 Anodic and Bidirectional electrodes

Anodic electrodes and bidirectional electrodes are considered together since bidirectional electrodes are in fact anodic electrodes engineered to work continuously without time restriction also in cathodic operation.

The electrode active materials used for sea electrodes can be different from those used in land electrodes and their base formulation is sometimes based on active patents. A list of the electrode commonly applied element materials is given below:

Graphite – Graphite/coke elements - Electrodes constructed with this kind of element have shown capability to work without any restriction both as anode and cathode with very low active part wear-out in anode operation. On the other hand chlorine production can be very high in comparison with other types of electrode that use different kind of active materials. In environments where water circulation is limited this should be carefully considered since it can give rise to severe corrosion or deterioration of other electrode components.

Graphite elements shaped as cylindrical rods will perform well when used for direct transfer of current to the water both as anode and as cathode, and the material can withstand reversals between these two conditions. Typically, graphite rods 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. The rods should not be buried in or even be covered with sea-bed deposits unintentionally such as by silting, because the electrodes would rapidly corrode.

Another possible configuration, which has not been tried, is to construct large flat graphite electrodes, for instance, 1.2 × 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 Ω•m), but if the graphite electrodes are functioning in an environment open to free water but closed to entry of marine fauna, the current density could be raised to values of about 40-50 A/m^2 if the resulting increase in chlorine production can be tolerated.

Titanium rods/Titanium mesh shaped elements - These types of electrode elements are developed to prevent the corrosion during chlorine production by coating the titanium rods or mesh with special mixed metal oxides (coating thickness in the range of 5 – 20 µm) that can rise up. Reversibility (cathodic operation) can only be with special kinds of coatings and with reduced current density. For electrode elements to be able to work also as cathode, it is recommended to reduce the current density to very low values with the result that such kind of electrodes need large areas, especially if the active elements are comprised of expanded mesh.

Silicon-Chromium-Iron (SiCrFe) rod elements - This kind of elements, initially used as anode type elements only, have shown that they can be operated also as cathodic elements without excessive deterioration of the active parts. The utilization for long periods (for example in HVDC systems operated continuously in monopolar) can result in rapid element consumption unless very low values of current density are selected. In respect of other types of electrode elements, SiCrFe rods give rise to higher values of chlorine production. A great advantage of this kind of electrode element is the reduced area is needed which means lower likelihood to external damages by anchors, trawlers, etc.

For SiCrFe electrode rods or tubular anodes, similar limits on current density of ~5A to 6A/m^2 would be applied in order to satisfy the voltage gradient constraint of 1.25 V/m close to the electrodes. If higher current densities 40 to 50 A/m^2 such as are required, the SiCrFe electrodes must be enclosed to prevent marine fauna and divers from getting too close. As the material is better able to withstand burial than graphite electrodes, it could be covered with a layer of coarse stone (75-100mm) to provide the required separation.

However, it should not be covered too deeply as some maintenance to remove deposits may be needed following extended periods of operation in cathodic mode. Given the significant possibility of such maintenance to remove deposits being needed, it is likely more economical over the life of the project to install additional electrodes initially to reduce the current density so that covering would not be required. Uncovered elements are also easier to inspect by divers or ROV cameras.

Magnetite rod elements - This type of electrode element is classified as reversible but when operating as a cathode, the current density must be limited to very low current values and short durations. In anodic operation, compared to other types of electrode elements, they have the great advantage of being capable of operation with very high current density and consequently reduced area as long as access is restricted to ensure safety. A disadvantage is that the material of the elements is brittle and not easy to manufacture.

5.4.6.2 Cathodic electrodes

Cathode electrodes are for unidirectional operation only. Usually cathodic electrodes are designed with a small margin to withstand anodic operation for some hours per years in order to cope with specific contingency. Different kinds of conductors can be used for this type of electrode, but copper is always preferred over other types of materials since it is readily available and reliable welded and compression joints are easy to achieve.

Stranded conductors would be installed to achieve the desired shape: line, star, circle, etc. Unfortunately, bare copper conductors cannot be operated as anode electrodes continuously since the copper is quickly consumed. However, a few hours per year is usually permitted and additional copper is included in the design, to meet a necessary reliability for HVDC bipolar systems and to ensure adequate life before maintenance is needed. Depending on the current, and the surface area of the copper, this kind electrode may require lengths of conductor in the order of some hundreds or sometimes thousands of meters. Due to simple construction and laying, the total cost is usually in the order of 1/4 or 1/5 compared with anodic electrodes.

5.4.7 Sea Electrode Designs

The resistance of electrodes in general is required to be low, usually well below 1 Ohm. In particular, electric field in the seawater in the vicinity of the sea electrode, should be less than a desired level, often specified as 2.5 V/m [51], to avoid a harmful influence on the environment and affect fish and possibly also other sea organisms near the sea electrode.

A conventional sea electrode comprises:

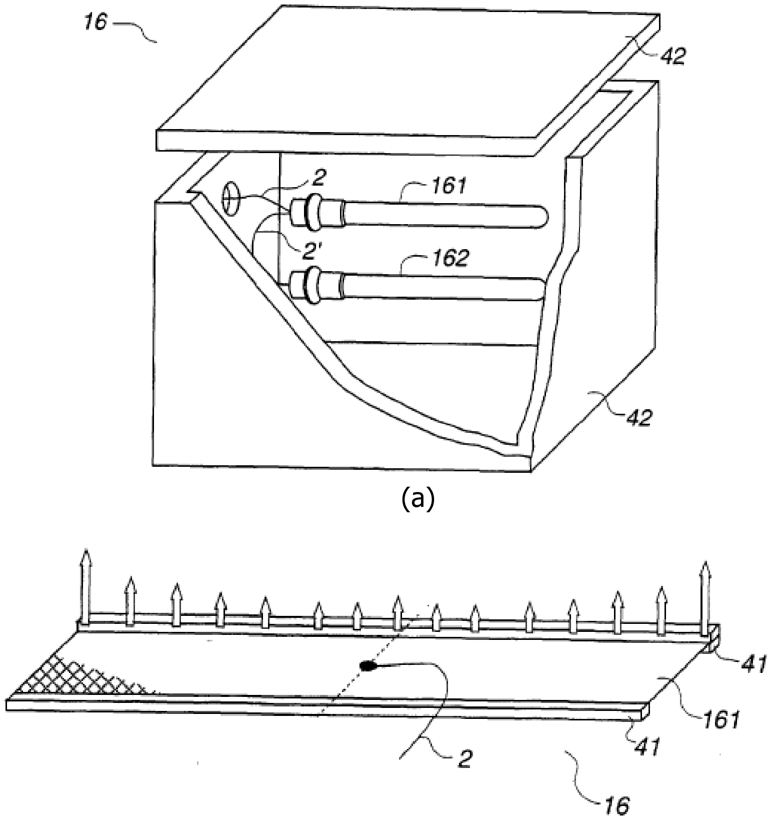
- an active part, called the electrode body which is in electrical contact with the seawater and possibly the sea bottom through which the current is transferred,
- interconnection cables for internal connection of parts of the electrode body and additional parts performing purely mechanical functions, such as for instance electrode holders, supports and mechanical protection parts.

In order to reach a sufficiently low resistance, a sea electrode usually comprises a large number of sub-electrodes with each sub-electrode being fed from a separate feeder cable. The surface of each sub-electrode element comprises an active part which is in electrical contact with the seawater and/or seawater impregnated matter at the sea bottom. In cases where the sub-electrode comprises more than one sub-electrode element, these elements are connected to each other by interconnection cables. The sub-electrodes are usually arranged in sections. Each sub-electrode usually also comprises additional elements such as sub-electrode element holders.

Typically, the sub-electrode elements are manufactured in the form of rods, tubular elements, plates or meshes, which makes them easy to manufacture and to mount. Usually, sea electrodes are protected and kept in place by ballast, either in the form of a separate solid cover or box, or a layer of stone or gravel.

There are various forms of sub-electrodes, some of which are shown in Figure 5.21 [60]. Figure 5.21(a) shows embodiment of a sub-electrode, comprising two cylinder-shaped sub-electrode elements (#161and #162), connected in parallel by an interconnection cable (#2’) and fed from a common feeder cable (#2). The sub-electrode elements are mounted in a concrete box (#42) for mechanical protection.

The box is provided with venting slots or holes (not indicated in the figure) to allow continuous exchange of fresh seawater with the sub-electrode elements.



(a)

(b)

Figure 5.21 - Two Different Types of SEA Sub-electrode [60]

Figure 5.21(b) shows another known embodiment of a sub-electrode (#16), with its active part, a sub-electrode element (#161), executed as a flat, elongated mesh, made of a metal with a low dissolution rate, for instance coated titanium, and supported at its long sides by concrete slabs (#41). Such a sub-electrode might also be provided with interconnection cables, connecting the feeder cables to other parts of the electrode. Here, the whole surface of the sub-electrode element constitutes the active part of the surface.

Another example of a sea electrode is shown in Figure 5.22. It shows schematically a cross section in a side view of sea electrode with a mesh-type sub-electrode element (#161) as active part, and a ballast (#4) in the form of a gravel layer. The sub-electrode element is located at the sea bottom (#31), has a length 2L in the plane of the drawing and is fed at its midpoint using a feeder cable (#2). The specific conductivity of the seawater and of the sea bottom is usually several orders of magnitude below the specific conductivity of the material of the electrode body. It should be noted that the equivalent specific conductivity of a gravel layer above the electrode, although lower than the conductivity of the seawater, is high enough to allow for currents to penetrate the layer and reach the seawater. This is the case also for a massive ballast made of concrete, which becomes electrically conducting after being immersed into seawater for some time. Thus, in a configuration according to Figure 5.22, the electrode current will also flow from the sub-electrode element upwards to the sea surface.

The current density distribution on the electrode body depends on the current distribution between the sub-electrodes as well as on the current distribution within each sub-electrode.

It can be assumed that the current density and the electric field strength in seawater and sea bottom surrounding the electrode body are proportional to each other. Thus, also the localization of areas with high local electric field strength will depend on the current distribution within and between the sub-electrodes.

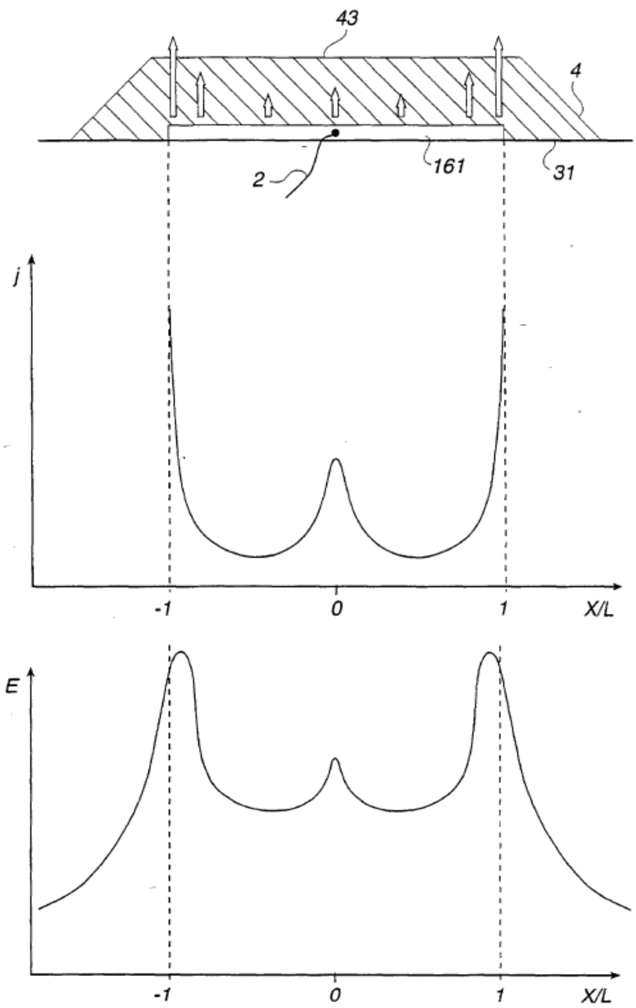
The current distribution between the sub-electrodes depends mainly on their relative location to each other and on the distances between them. Usually, the currents are highest at the outermost located sub-electrode of the electrode. The current distribution within the sub-electrodes depends mainly on the shape of the sub-electrode elements and the locations of their feeding points.

The highest current density will occur at the peripheral parts of the outermost sub-electrodes and this is illustrated in Figure 5.22 with arrows indicating the direction and magnitude of the current along the surface of the sub-electrode element.

Figure 5.22(b) shows relative distance x/L along the sub-electrode element on its horizontal axis according to Figure 5.22(a) as measured from its mid-point and on the vertical axis the current density J at the surface of the sub-electrode element. The diagram illustrates that the principal shape of current density distribution is such that it has maxima at the ends of the sub-electrode element and a local maximum at its feeding point.

Consequently, as the ballast separating, the electrode body from the seawater in this context can be regarded as a thin conducting layer, the maximum electric field strength on the surface of the ballast will occur at locations in the vicinity of the surfaces of the sub-electrodes and sub-electrode elements having the highest current density.

Figure 5.22(c) shows on its horizontal axis the relative distance x/L along the sub-electrode element according to Figure 5.22(a) as measured from its mid-point and on the vertical axis the electric field strength E along the upper surface of the ballast above the sub-electrode element. The diagram illustrates that the principal shape of the electric field strength distribution is such that it has maxima close to locations above the ends of the sub-electrode element and a local maximum above the feeding point of the element, corresponding to the current density distribution maxima illustrated in Figure 5.22(b).



a) Side view of a sea electrode with a mesh type sub-electrode element and gravel layer ballast.

b) current distribution at the surface of the sub-electrode element

c) electric field strength distribution at the upper surface of the ballast for a sea electrode

Figure 5.22 – Possible Configuration of Sea Elctrode Mesh Covered with Gravel Ballast [60]

Another embodiment of a sea electrode is illustrated in Figure 5.23. It comprises an electrode body (#15 arranged in two closed concentric rings #151 and #152). The rings may be divided into sub-electrodes as mentioned above (not shown). The ballast is in the form of a number of sector-shaped cover plates (#4), one of which in the figure being removed to show the electrode body. The plates are made of a solid material such as concrete. The plates, which cover the electrode rings, are coated with an electrically non-conducting layer (#5) at their surfaces facing the electrode bodies. The electrode rings are connected to feeder cables (#2), which are electrically insulated against the surrounding seawater.

The sub-electrode elements (not shown) are in the form of cylinders joined to each other to form sub-electrodes, and the sub-electrodes are then connected to form the rings of the electrode body.

The massive plates placed above the electrode body constitute a good mechanical protection of the electrode body and will prevent damage from for instance fishing nets, anchors or large waves. The size of the plates is chosen to facilitate the mounting of the electrode on the sea bottom.

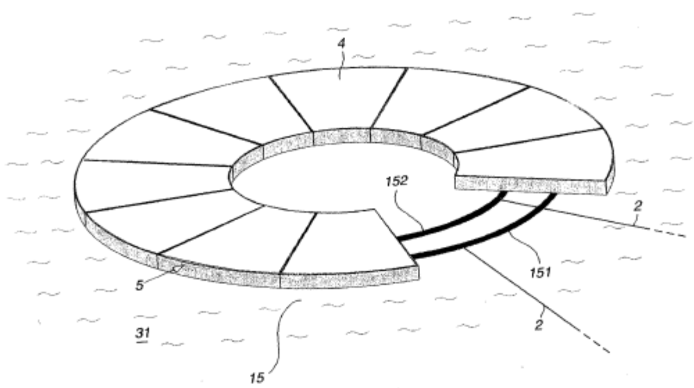


Figure 5.23 - Sea Electrode with Two Concentric Rings as Electrode Body and Ballast [60]

In the arrangement shown in Figure 5.23, the non-conducting layer is located between the electrode body and the ballast. This will direct the current transferred by the electrode body along the non-conducting layer and downwards to the sea bottom and prevent the current from penetrating the ballast and the seawater immediately above the electrode elements.

The electric field strength in the seawater in the vicinity of electrode, and in particular outside a zone located below the non-conducting layer and in a vertical direction limited by the edge of the non-conducting layer, can always be influenced to be below a desired level by choosing the dimensions of the non-conducting layer according to the above-mentioned principles. This makes it possible to reduce the electric field strength outside a given zone to levels where negative effects on the environment can be avoided.

Alternatively, with reference to Figure 5.23, the sub-electrode elements can be of flat shape and located immediately below the non-conducting layer. Another alternative is to locate the sub-electrode elements in cavities of the ballast plates, and then install the non-conducting layer as a coating surrounding the sub-electrode elements in three directions to direct the current towards the sea bottom only.

The non-conducting layer can also be executed in the form of a separate sheet, for instance made of a polymer foil, arranged above the electrode body, either between the electrode body and the ballast or above the ballast. In both cases it will influence the electric field strength in the vicinity of the electrode body as described above although in this later case it would not be mechanically protected by the ballast. A non-conducting layer can be covered or embedded in a ballast consisting of a covering of gravel.

A suitable material for such a non-conducting layer can be glass fiber reinforced polyethylene, typically of a thickness in the order of 12 to15mm.

The ballast can also be implemented as a container made of a non-conducting material, filled with sand or gravel and located above the electrode body, at least a part, typically the bottom wall, of the container constituting the non-conducting layer.

For plates made of steel reinforced concrete, the concrete becomes electrically conducting after immersion in seawater for some time. In this case, all surfaces of the plates should be coated with non-conducting material, to avoid corrosion of the steel reinforcing caused by currents flowing in the concrete and thus entering and leaving the reinforcing rods. Corrosion would occur at the points where the current leaves the rods and the resultant swelling would eventually break the concrete. A better solution would be to use non-conducting reinforcing material such as fibreglass epoxy rods.

Massive plates with an electrically non-conducting covering or containers made of non-conducting material can be mounted together with sub-electrode elements, constituting prefabricated units, for example sub-electrodes, for easy assembly on the sea bottom.

The sea electrodes described above are comprised of an electrode body to be placed at the sea bottom and held in place by a ballast in the form of a heavy covering, and in addition, a non-conducting layer located above and extending over the electrode body.

For sub-electrode elements of an elongated shape, such as cylinders and flat meshes, substantially increased electric field strengths will occur locally, typically at the ends of the sub-electrode elements due to higher current densities at the ends of the sub-electrode elements than the average value for the electrode body.

To improve current distribution of sea electrodes when the sub-electrode has an elongated linear form, it is possible to introduce electrically non-conducting barriers, spaced apart along the sub-electrode element and especially at the ends of the sub-electrodes. The barriers should have a substantial extension outwards from the active part of the surface of the sub-electrode element into the seawater and/or seawater impregnated matter at the sea bottom. The effect of the barriers is to equalize the current distribution along the active part of the sub-electrode element surface by preventing current flow out the ends of the electrode.

This effect is illustrated in Figure 5.24 where on the horizontal axis there is the relative distance x/L and on the vertical axis there is the ratio $J(x) / J_{avg}$, where J(x) is the actual current density at a relative distance x/L along the sub-electrode element and J_{avg} is the average value of the current density along the sub-electrode element.

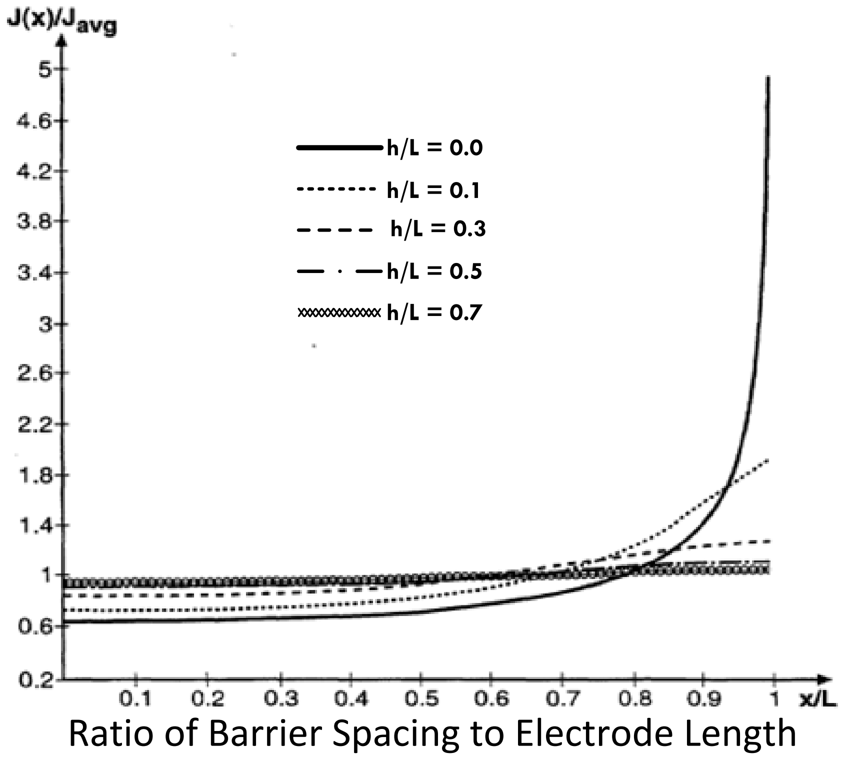


Figure 5.24 - The effect of Non-conducting Barriers according to Figure 5.25 on the Current Distribution Along a Cylinder-shaped Sub-electrode Element [60]

For comparison, the same ratio is plotted as a solid line for a similar sub-electrode element without barriers (h/L=0.0). The ratio is calculated for specific polarization resistivity ba = 0.02 W·m^2 which is representative for silicon iron. As can be seen in the figure, for a ratio h/L = 0.5, the maximum current density, at any point at the surface of the sub-electrode element, will be only about 12 % higher than the average current density, which for most practical purposes can be considered as a sufficiently uniform current distribution.

Figure 5.25 (#161) shows a sub-electrode being operated to transfer current to seawater. The sub-electrode element is equipped with two barriers (#8), one at each end. The barriers are made of a non-conducting material which is chosen to maintain its non-conducting properties during the service lifetime of the electrode, for instance polyethylene or polypropylene. The barriers have the shape of circular discs, and are arranged in a plane perpendicular to the sub-electrode element.

In certain cases, especially for long sub-electrode elements, a number of barriers, spaced apart along the length of the sub-electrode element, can be used to achieve the desired equalization of current density. The same effect could also be achieved with barriers and sub-electrode elements with different geometries, other than circular barriers.

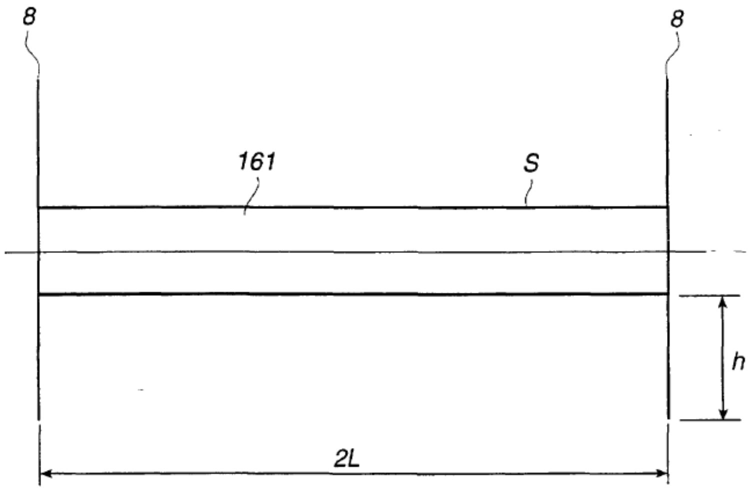


Figure 5.25 - Cylinder Shaped Sub-electrode Element Provided with Non-conducting Barriers [60]

Figure 5.26 shows an arrangement having a rectangular shape with rounded corners on the bottom in which two sub-electrode elements (#161 and #162) have been mounted with three barriers (#8) of a non-conducting material, such as polyethylene or polypropylene which also serves to mechanically support the elements. All barriers are common for both sub-electrode elements. Two barriers are located at the ends of the sub-electrode elements and one is located at the middle of the sub-electrode elements.

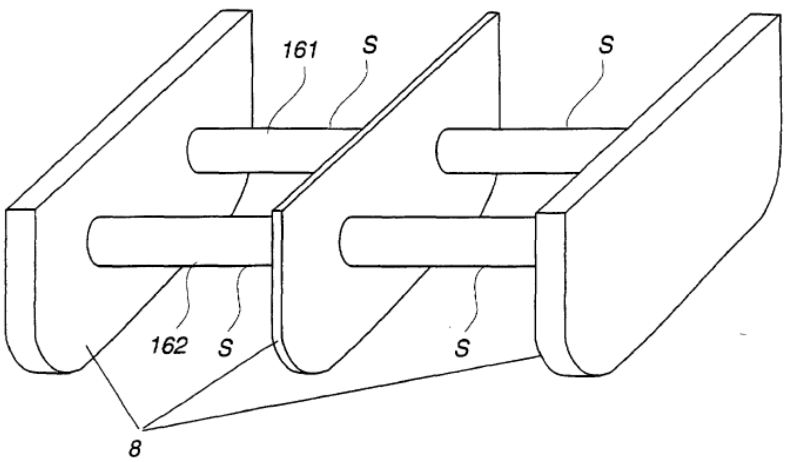
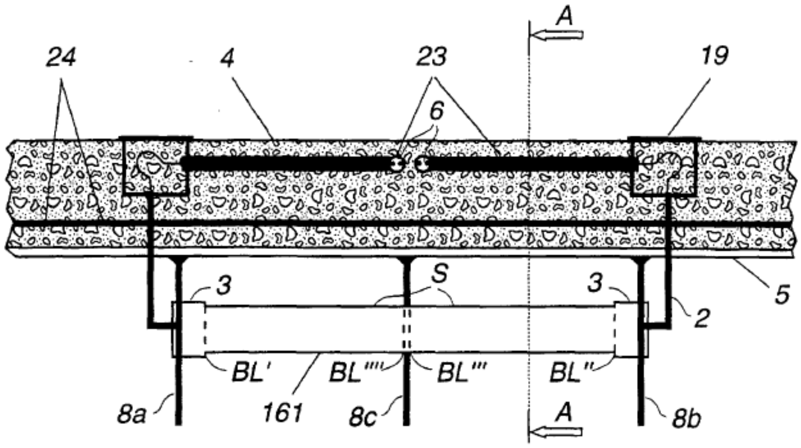
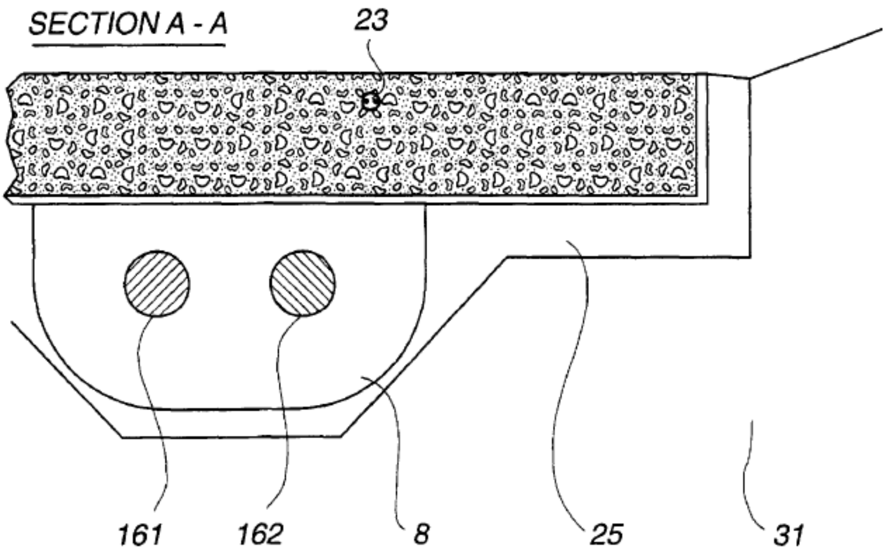


Figure 5.26 - A Pair of Cylinder-shaped Sub-electrode Elements with Non-conducting Barriers, also Serving as Mechanical Supports [60]

Figure 5.27 shows a side view of an arrangement where sub-electrode elements ((#160 and #161 in Figure 5.27(b)) as described in connection with Figure 5.26 are joined to a concrete ballast (#4 in Figure 5.27(a)) to form a sub-electrode. The ballasts are made of reinforced concrete, and are coated with a non-conducting material (#5 in Figure 5.27) on the bottom and side walls. The feeder cables (#2) to the sub-electrodes are connected to a main feeder cable (#6) via connection boxes (#19) in the plates. The main feeder cables are placed in tubes (#23) embedded in the concrete.



(a) Side view of a part of an electrode with sub-electrode elements according to Figure 5.26 arranged at an armored concrete plate



(b) A section along the line A-A

Figure 5.27 - Electrode Sub-element Combined with Barriers and Concret Ballast [60]

Each sub-electrode element is equipped with three barriers (#8a, #8b and #8c). The barriers #8a and #8b are each provided with a cap (#3) of a non-conducting material of the same kind as the material for the barriers, which sleeve may be an integral part of the respective barrier and serves to block the flow of current to the outside of the barriers away from the active elements. The active part (S) of the surface of the sub-electrode element is surface of the sub-electrode element minus the areas covered by the two sleeves (#3) and by barrier (#8c). The border lines of the active part (S) are the lines along which the surface of the sub-electrode element adjoins the respective sleeves (BL' and BL''), and the lines along which the envelope surface of the sub-electrode element adjoins the barrier (#8c) at points BL''' and BL''''.

Another possible configuration for a sea electrode is shown in Figure 5.28. A ballast (#4) made of reinforced concrete is placed on a gravel bed (#24) on the sea bottom (#31) which has a cavity (#4a) at its downward facing side where there are a number of flat sub-electrodes, in the form of meshes.

Mechanical protection shields (#26), made of a non-conducting material or coated with non-conducting material, arranged as a number of parallel oriented tubes, are located below the sub-electrodes. A coating (#5) of non-conducting material constitutes a non-conducting layer to block current flow though the concrete ballast.

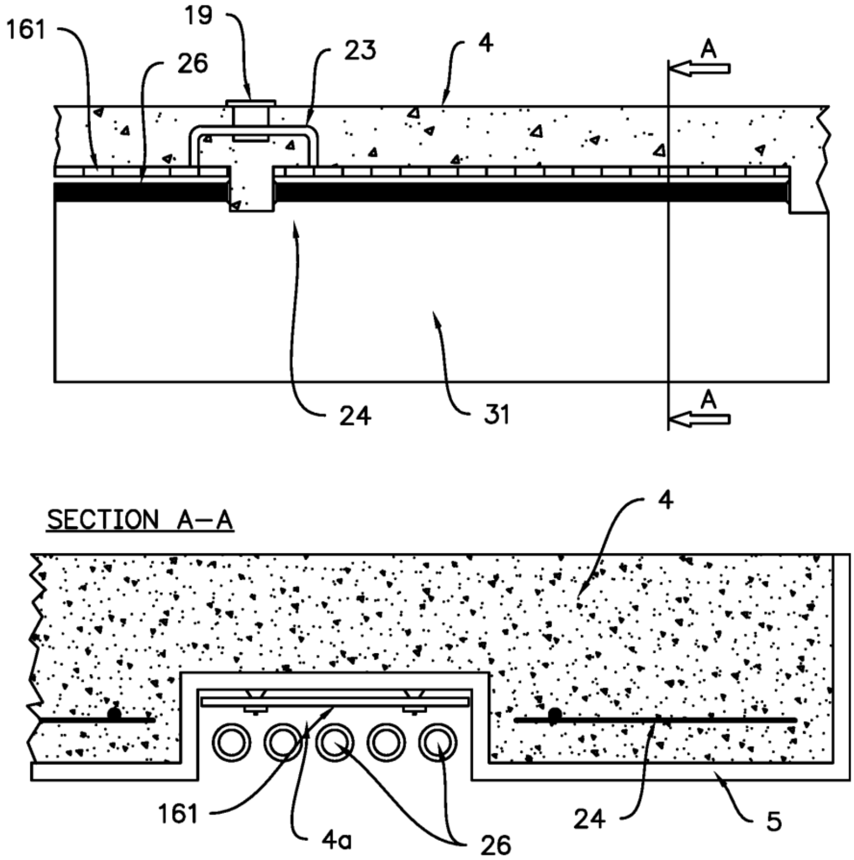


Figure 5.28 - Side View of a Part of an Electrode with Flat sub-electrode Elements Located within Cavities in a Concrete Plate and A section View along the Line A-A [60]

Figure 5.29 shows a section of a ring-shaped electrode body, which comprises a sector-shaped cover plate (#4) and sections of the two concentric rings (#151and #152). The section of the outer ring (#151) comprises sub-electrode elements labeled (#161, #162, and #163), interconnected with interconnection cables in a series connection. The inner ring (#152) is of similar kind. The sub-electrode elements are provided with barriers (#8). The plate (#4) is coated with a non-conducting material (#5) on the surface facing the rings and on side walls (#27) of the plate. The side walls serve as both mechanical protection and mechanical support for the plate, reducing or eliminating the load on the sub-electrodes and the sub-electrode element supports.

In design similar to the one described in connection with Figure 5.29, the electrode body can comprise at least one ring or several rings.

An electrode as described in Figure 5.29, designed for a current in the order of 1400 A, would typically have a diameter of the outer ring (#151) of about 16 m. In order to not to exceed the maximum electric field strength of 1 V/m in the seawater in the vicinity of the electrode the diameter of the non-conducting layer would be about 19 m.

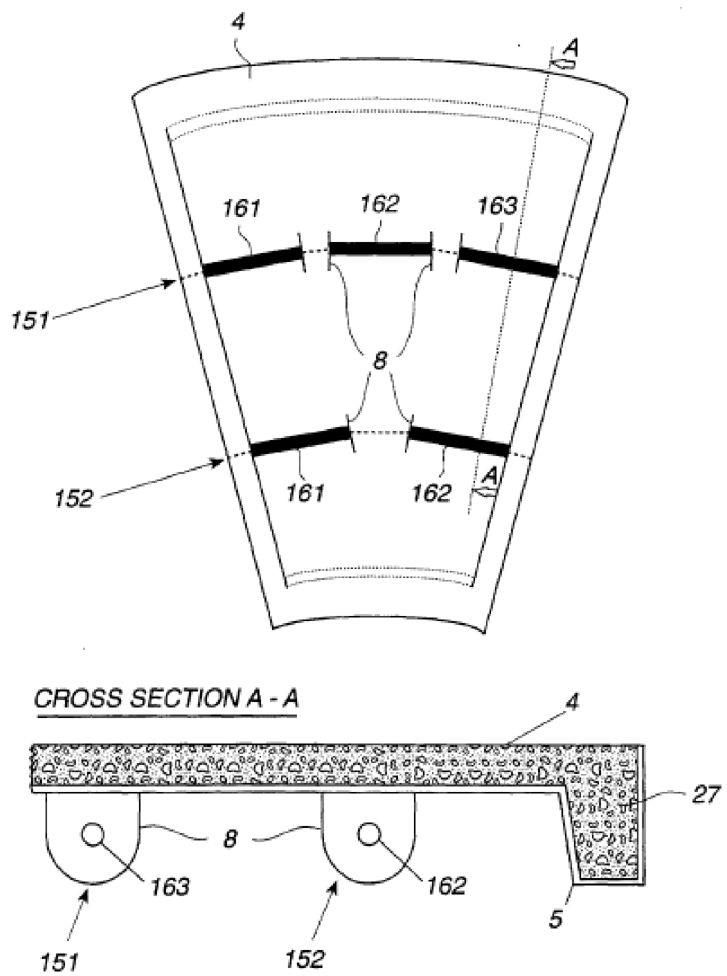


Figure 5.29 - Section Of An Electrode, Seen from Below, With A Ballast in the Form of Concrete Plate with Coated Side Walls and A Section along The Line A-A [60]

The arrangements shown in Figure 5.27 to Figure 5.29 can also be implemented with ballasts filled with gravel, concrete or sand. As an example, in Figure 5.29 cross-section A-A, the layer (#5) can thus illustrate a container wall and the item (#27) indicates for example gravel of stone filling the container.

In arrangements where the electrodes are comprised of massive plates or gravel filled containers, the plates or containers can be equipped with electrically insulated channels for release of gases produced by electrolysis on the electrode body in order to avoid gas accumulation beneath the plates or containers.

The non-conducting barriers are applicable to sub-electrodes and to sub-electrode elements of various shapes which can substantially equalize the current density at the electrode surface.

Another implementation of non-conducting barriers is shown in Figure 5.30. The figure shows a perspective and cut-out view of a part of a sub-electrode element (#161) similar to the one described in connection with Figure 5.21(feeding points are not shown). The sub-electrode element is provided with two barriers (#8a and #8b in Figure 5.30(, manufactured from an electrically non-conducting material formed by four beams (#8aa, #8ab, #8ba and #8bb), each having an L-profile and running along the sub-electrode element.

The beams are located between concrete slabs (#41a, #41b, #41c and #41d), in such a way that one leg (#8aa') of the L-profile of the beam (#8aa) and one leg (#8ab'') of the L-profile of the beam (#8ab) are located between the slabs #41a and #41b, and one leg (#8ba'') of the L-profile of the beam (#8ba) and one leg (#8bb) of the L-profile of the beam (#8bb) are located between the slabs (#41c and #41d). The other legs (#8aa', #8ab', #8ba' and #8bb) of the L-profiles are thereby arranged so that the legs (#8aa' and #8ab') together form one side barrier (#8a) and the legs (#8ba' and #8bb') together form another side barrier (#8b), facing the first mentioned side barrier. Parts of the sub-electrode element are extending in between the legs (#8aa'' and #8ab'') and in between the legs (#8ba'' and #8bb''), respectively, and these legs are formed so that those extending parts of the sub-electrode element become electrically insulated from the conducting medium (not shown in detail in this figure). The active part of the sub-electrode element is located between the two barriers so that it has a border line BL' located at the edge of the beams (#8aa'' and #8ab''), facing the beams (#8ba'' and #8bb''), and a border line BL'' at the edge of the beams (#8ba'' and #8bb'') facing the beams (#8aa'' and #8ab'').

The active part of the surface of the sub-electrode element is embedded between an upper layer (#25b) and a lower layer (#25a), constituting a backfill for the electrode element. The layers comprise an electronically conductive material, such as coke. The upper layer (#25b) is covered by a thin layer of gravel (#24) to keep the layer (#25b) in place.

The advantages achieved with this design of sea electrode are that the maximum electrical field strength in the seawater outside a zone below the non-conducting layer can be limited below a specified level and harmful environmental effects can be avoided. In addition, the intensity of electro-chemical reactions between the material of the electrode element and the seawater will be decreased and the amounts of reaction products would be reduced.

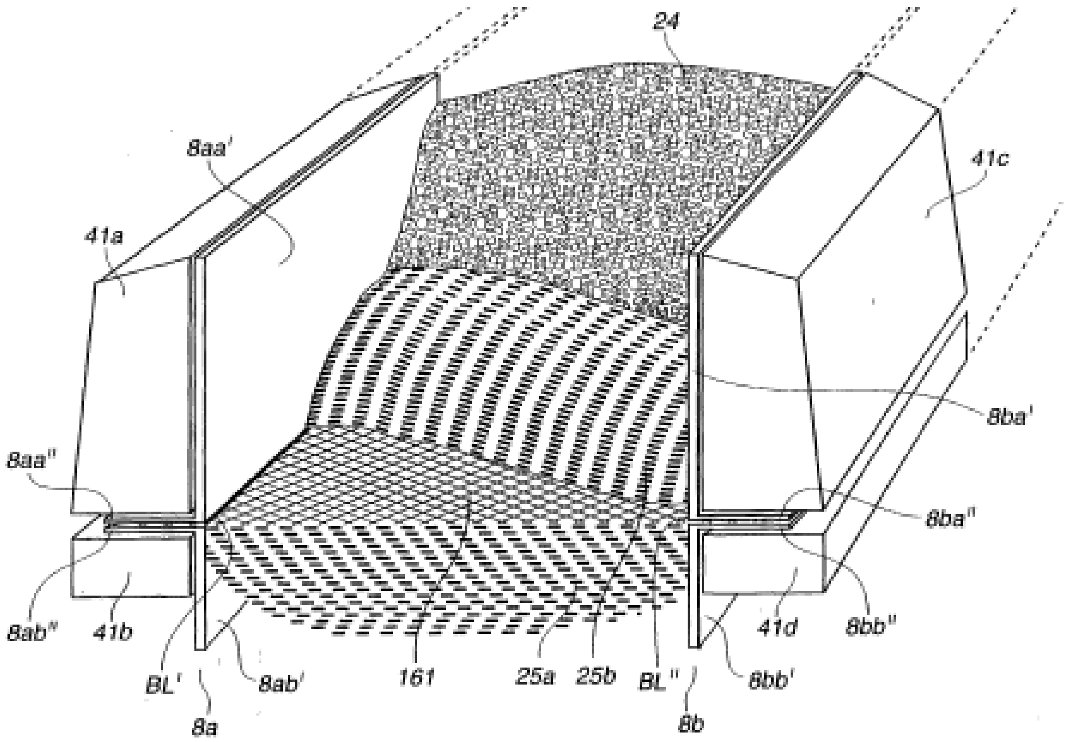


Figure 5.30 - A Sub-electrode Element Embedded in a Backfill [60]

Typically, sea electrodes can be assembled from prefabricated and standardized parts, such as plates or ballasts, sub-electrode elements and barriers, thereby significantly reducing the costs for installing the electrode.

5.4.8 Sea Electrodes in Operation

At the moment, the summary of existing sea electrode stations includes three kinds of constructional modes:

a) Titanium as their active part (for anodic operation only)

b) Bare copper conductors as active part (for cathodic operation only) Brief periods of anodic operation would possible as sufficient material is allowed in the initial design.

c) Coke and SiCrFe-rods as their active part (for reversible operation)

5.4.8.1 Examples of Sea Electrodes for Anodic Operation

An interesting solution for anodic operation is the one consisting of titanium as active part. As of this writing, there are three electrodes of this kind:

- Fenno-Skan anode Dannebo;
- Baltic cable anode Smyge;
- Kontek anode Bøgeskov.

The material consists of 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 covered by a special thin (5-20 µm) layer of metals, resistant to anodic corrosion.

The expanded mesh net is delivered in sub-electrodes each covering 1.22 m × 16.5 m = 20 m^2. On both sides of the net there is a system of polyethylene tubes for mechanical support and protection, which are placed with interspaces, leaving 33 % open area for the current. For transportation and handling purposes, one sub-electrode 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 area for the Baltic cable electrode is mechanically protected by a layer of natural stones as backfill. For the Kontek anode, the protected area is 2000 m^2 and no backfill material is described. An underlying construction of fibre reinforced concrete against the seabed is included.

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 sub-electrodes so that current density is not increased in any of the sub-electrodes to minimize the production of Cl_2. The depth of the seawater is 8 m or more.

5.4.8.2 Examples of Electrodes for Cathodic Operation Only

The following sea electrodes are installed for cathodic operation only.

- Baltic Kathode1 electrode, German end of Baltic cable;
- Pampriniemi electrode, Finnish end of Fenno-Skan (Titanium net);
- Graal-Müritz electrode, German end of Kontek;
- La Torraccia electrode, Italian mainland end of SACOI (Sardinia Continental Italy) intertie;
- Otranto electrode, Italian mainland end of Italy - Greece intertie;
- Nettuno electrode, Italian mainland of the SAPEI (Sardinia Peninsula Italy) intertie.

The material chosen as active part for these electrodes is bare copper, although other less costly metals may be able to act as cathodes. 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 seawater. For installation and maintenance purposes, this type of electrodes is normally installed in water depths not deeper than 35 m.

As for the geometric arrangement, the Baltic cable and Kontek both use rings of 1 km in diameter. Some chords (cross-connections) are added to ensure equal potential all along the total conductor. The Finnish electrode forms an oval net while the Italian electrodes consist of two linear electrodes each 300 in length.

Diver inspection is usually performed yearly. Maintenance actions are performed to remove the layers of deposit growths. The deposit is made of a very hard white substance mainly composed of magnesium hydroxide ($Mg(OH)_2$) and other substances as Na_2O, CaO, MgO, Fe_2O_3 and SiO_2. This stratum is removed by divers usually once a year with high pressure nozzles.

The very large experience with this kind of electrodes (some of these electrodes have been in service since the 1960's) highlights that no negative influence on marine life has ever been recorded and furthermore due to the economical construction they are all within safe limits to avoid any danger to curious divers.

Danish research work, including video taping of marine creatures around a test electrode, has confirmed that up to 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.

In the case of the SAPEI intertie (bipolar HVDC system) the electrode is allowed to operate in reverse direction (as anode) for 5 events of 2 continuous hours at full current (1000 A) each per year as studies performed in laboratory had confirmed this kind of emergency operation would not cause unacceptable levels of copper wasting due to anodic operation. The capability to reverse current is particularly useful in bipolar systems in case of short-time faults of one of the two HVDC converters or one of the two HVDC overhead/cable lines.

5.4.8.3 Examples of Sea Electrodes for Reversible Operation

Sea electrodes using Graphite or SiFeCr-rods as their active part (for reversible operation) have been used in the past. As of this writing, there are only three electrodes of this constructional type in the world:

- Risö electrode (Swedish end of Konti-Skan);
- Santa Monica electrode (Los Angeles end of the Pacific Intertie);
- Grosøysøyla (Norwegian end of Skagerrak).

The design and construction of these three electrodes are quite different. Risö electrode has horizontal graphite/coke sub-electrodes laid at the seabed and covered by concrete (originally sacs filled with ready-mixture, stacked over the internal sub-electrode). Santa Monica electrode consists of sub-electrodes with each built as a concrete box containing two SiCrFe rods to transmit current directly to the water and finally the Norwegian Grosøysøyla electrode consists of sub-electrodes containing graphite and coke in a wooden container placed vertically at the seabed.

5.5 SHORELINE POND ELECTRODES

An electrode located on a sea shoreline in a natural lagoon or man-made pond with active elements submerged below the chart datum and isolated from the marine environment by a permeable breakwater, is classified as a shoreline pond electrode.

The chart datum is generally taken to be the lowest astronomical tide (LAT) or the lower low water large tide (LLWLT) (the lowest normal tide at the location). The permeable breakwater provides continuous water exchange between the pond and adjacent seawater mainly due to tide action. This exchange of water is essential for maintaining salinity in the pond similar to the seawater, removing heat from the pond and protecting the electrode installation from wave action and, in polar and temperate regions, from pack ice.

A shoreline pond electrode offers the advantage of low resistance to remote earth similar to a sea electrode. However, it is isolated from marine environment, provides easy access for inspection and maintenance, and with adequate water exchange would not be prone to overheating. The zone of influence from a shoreline pond electrode is smaller compared to land and beach electrodes because the bulk of the ground current flow is through the seawater which has resistivity of 0.2 Ω•m to 0.5 Ω•m. Generally, a lower resistance to remote earth can be achieved and the ground potential rise is lower in the vicinity of the electrode compared with land or beach electrodes.

A typical shoreline pond electrode installation would include

a) Electrode line termination dead end structure(s),
b) Equipment to facilitate detection of electrode line faults, which could include filter(s) on the main electrode circuit for high frequency line impedance (HFLI) measurement scheme or current transducers for end-to-end differential (ETED) and high frequency current differential (HFCD) schemes,
c) Surge protection at the electrode line/cable transition, (only required in the case of long feeder cables)
d) Electrode line isolation disconnect switches,
e) Electrode element sectionalizing disconnect switches,
f) Distribution cables,
g) Distribution and splitter boxes,

h) Active electrode elements immersed in seawater with jumper leads for connections to splitter boxes,
i) Station services to support the infrastructure and facility operation and maintenance,
j) Permeable breakwater to isolate the active elements from marine environment and protect the installation against waves and wind complete with element pedestal if applicable. The breakwater, topped with a fence is also useful for preventing entry by the public into the electrode area.
k) Pond directly linked to seawater via the breakwater for active current elements,
l) Fence to restrict public access,
m) Road for access to the site and various installation within the fenced facility, and
n) Miscellaneous infrastructure (e.g. wooden bridge for suspending electrode elements).

The following subsections provide an overview of design considerations and typical design approaches.

5.5.1 Design Consideration

5.5.1.1 General Overview

The location of a pond electrode site is normally selected to take advantage of a natural cove that is protected from large wave action, and which has wide exposure to the adjacent seawater. The site should have a rapid slope to deep water to ensure low resistance to remote earth, and should be located away from large population centers and large infrastructure, and should ideally be located where land cost is low and access for construction is easy so as to offer a low-cost solution.

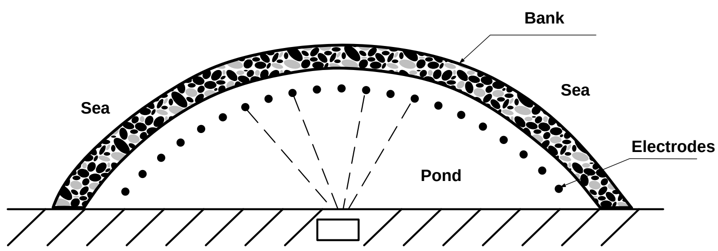
The selection of the electrode site and electrode/breakwater materials is a complex process which requires expertise of diverse disciplines (electrical engineering, geotechnical and structural engineering, marine engineering, chemistry, environmental science, and oceanography) to ensure that the pros and cons of various operating conditions and materials selected are understood, and the design would meet applicable safety and local environmental regulations. An environmental impact assessment (EIA) process would be pursued in parallel with the site selection to identify and quantify the potential impact of the electrical and magnetic fields, chemical emissions and physical emissions on the marine environment if any.

Active elements would typically suspended in the pond or installed on the pond side of the breakwater as illustrated in Figure 5.31, and Figure 5.32. The electrode elements for both arrangements are in contact with seawater. However suspended elements provide better exposure to water, are less prone to silting or binding in the even to deposits and are easier to access and maintain. As the elements are fully in contact with seawater the heat would be dissipated into the water and would be dispersed away from immediate area of the electrode elements by convection. Heat would be removed from the surface of the pond by radiation and by water exchange with the sea though the breakwater by tidal water level fluctuation.

The main factors that determine the electrode resistance to remote earth are the sea bed slope near the shoreline and adequate water depth at the breakwater to ensure an adequate area of exposure of the electrode pond the adjacent seawater.

The type of electrode elements, number of elements, electrode element surface current density, breakwater void ratio and pond volume determine the dynamics of the electrolysis in the pond. The selection of materials and the design parameters should be such that it would result in low chlorine selectivity at the anode, in low concentration of electrolysis products and by-products in the pond, and in efficient dilution and dispersal of any chemical emissions.

Breakwater void ratio is the ratio of free space to the total volume of material in the breakwater. The breakwater will generally be constructed using a blend of large and medium stone with the outer sea facing side being large stone to resist wave action. The stone will have a large resistivity, up to 4 orders of magnitude higher than the seawater. Hence it is essential that adequate void spaces exist in the rock to ensure that water and current can readily pass through the breakwater. Given the high resistivity of the rock, a void ratio of 30% would mean that the apparent resistivity of the breakwater would be about 3 times higher than higher than seawater even when fully immersed in water.



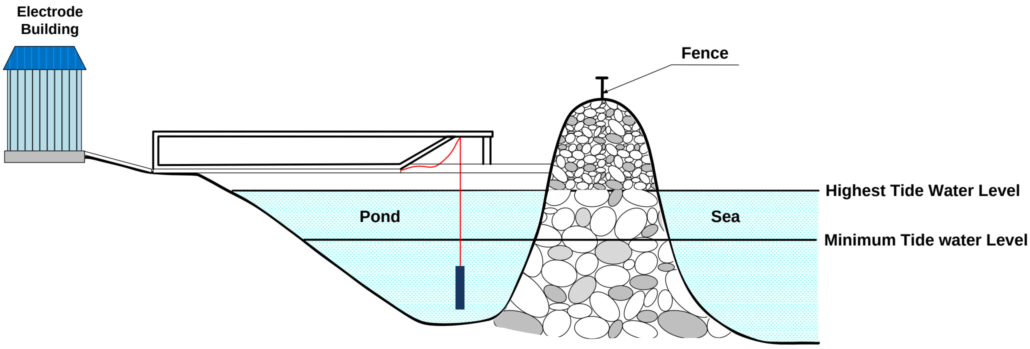


Figure 5.31 - Shoreline Pond Electrode-Suspended Electrode Element

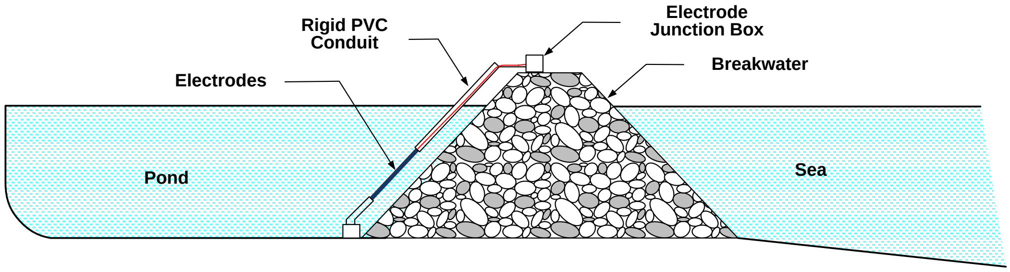


Figure 5.32 - Shoreline Pond Electrode-Elements on Inside Face oF Breakwater

Electrical safety of the humans and the marine life on the sea side of the breakwater is a function of area of breakwater in contact with the sea and the maximum HVDC system current. The outside of the breakwater must be large enough to ensure safety. The designer should take note that the current density and hence gradients at the outer surface of the breakwater would be increased at low tide. Safety in the pond near the elements is normally very difficult to achieve and measures must be taken to restrict access by people and marine life.

A small footprint of the electrode installation is desirable from a cost point of view. Therefore, the electrode element current surface density would be selected at the highest level resulting in acceptable chlorine selectivity or loss electrode element material. As the breakwater will ensure that marine life would not be able to approach the high gradient area near the elements, the number of elements would be reduced to the extent possible and the elements arranged in array with the smallest practical inter-element spacing.

5.5.1.2 Polarity, Type of Active Elements and Current Density

The operation of an electrode as an anode or a cathode is governed by the operating configurations of the HVDC system as described in Chapter 1.

During monopolar operation of a bipolar scheme, the pole that is in operation and its polarity determine the mode of operation of the electrodes. Suspension of elements in the pond and installation through a conduit require a rod or pipe type construction of the electrode elements. The need for fewer electrode elements to optimize the footprint requires larger diameter and longer elements which provide larger surface area. Therefore, a mesh type elements or smaller diameter rod elements are not the candidate electrode elements.

Electrode elements for shoreline pond application may include magnetite, impregnated graphite (carbon), high-silicon chromium iron (SiCrFe), platinised titanium and mixed-metal oxide type.

High-Silicon Chromium Iron (HSCI)

High–silicon iron alloy conforming to ASTM A518 Grade 3 is generally selected for pond electrode applications as it has very good resistance to corrosion and low loss of material in anodic operation and can tolerate current reversals. In addition to silicon, chromium and iron, the material may include low levels of different impurities. Table 5.8 shows the composition of elements manufactured to ASTM A518 Grade 3.

Table 5.8 - High-Silicon Chromium Iron Composition

Elements	Content	
	Minimum %	Maximum %
Silicon	14.2	14.75
Chromium	3.25	5
Carbon	0.7	1.10
Manganese		1.5
Copper		0.5
Molybdenum		0.2
Iron		Balance

The most common shapes available are solid rod and hollow tubular shapes in 1.5 m and 2.1 m lengths and 56 mm to 122 mm diameters. Hollow tubular shapes are generally preferred because they provide larger surface area for a given amount of material. Different manufacturing processes have been developed which include sand cast, spin cast and chill cast. According to a leading supplier, chill cast elements have better mechanical and electrical characteristics and have lower consumptions rates in anodic operation.

Typical consumption rate reported while operating as an anode is in the range of 0.23 kg/A•yr to 0.32 kg/A•yr [62]. The consumption increases with increase in discharge current density. The low consumption rate of the material is due to a thin barrier film of hydrated oxides of silicon which forms on the surface. The hydrated oxides can reach a thickness of 3 to 6 mm. The hydrated oxide layer is not detrimental in moist electrolytes (e.g. sea or pond application). However, the hydrated silicon oxides can substantially increase the resistance in soil where the oxide layer may dry out.

The corrosion by-products from HSCI anodes are considered innocuous. The laboratory tests suggest that a trivalent chromium which readily precipitates out is formed while hexavalent chromium which is a carcinogen is generally not released as the surface potential gradient is not high enough to form hexavalent chromium.

HSCI electrode elements are noble elements which are suitable for reversible anodic and cathodic operation. Although some of publications suggest that high silicon chromium iron [63] can suffer surface pitting during reversals other research work [64] and operating experience has proven that HSCI is suitable for reversible operation.

Vendors have tested HSCI elements in sodium chloride solution for discharge current densities between 40 A/m^2 and up to 160 A/m^2 [62] as anodes. However, the current density selected for design in a pond electrode would generally be selected so that it does not exceed proven in field experience.

Graphite Elements

Graphite anodes consist of graphite rods impregnated with wax, linseed oil or resin to increase the anode life. Impregnation hinders penetration of water and oxygen into the pores and reduces oxidation in the pores.

Graphite electrodes are available in solid rod form with 76 mm and 100 mm diameters and 1500 mm and 2000 mm lengths.

The evolution of oxygen at high rate while operating as anode will result in formation of carbon dioxide and disintegration of the element structure. The element is bi-directional. Hydrogen production while operating as a cathode does not cause deterioration of the carbon elements.

Consumption of graphite electrodes ranges from 0.1 to 1 kg/ A•yr. Recommended current densities range from 10 A/m^2 to 20 A/m^2. However, higher current densities may be used for pond electrode applications. Therefore, at Sansum Narrows the graphite elements have been replaced with HSCI elements which allow higher current density.

Magnetite Elements

Chemically magnetite material is Fe_xO_4 where x is either 2 or 3.

Magnetite displays a strong anisotropic wear rate and the conductivity depends on the shape of the electrode element and casting procedure. Magnetite is fairly brittle and is prone to crack when subjected to temperature variation. The electrode is usually cast as hollow tubular element, coated internally with copper and filled with polystyrene.

Elements are available with diameter of 60 mm and length of 760 mm [65]. The maximum current density recommended by the vendor for anodic operation exceeds 100 A/m^2 [65].

Magnetite can withstand current reversal if the cathodic current is less than 10 A/m^2. The material is not stable in reducing environment which occurs at high cathodic current densities above 10 A/m^2 [63].

Platinum Coated Titanium Elements

This material consists of a thin platinum layer that is coextruded with or plated onto a titanium substrate. The most widely available shapes are wires, meshes and rods.

The degradation mechanism of platinum-coated anodes is consumption of the platinum. The consumption rate in a chlorine-evolution (anodic) environment is 8 mg/A•yr at very high current densities up to 5400 A/m^2.

The consumption rate in an oxygen-evolution (cathodic) environment at current densities less than 110 A/m^2 is 16mg/A•yr. Thus, platinum coated elements are not suitable for reversible operation. Platinum electrodes should not even be operated at low currents where there is a possibility that ripple currents may force excursions into the cathodic mode where the platinum may be easily dissolved in saline solutions.

Mixed-Metal Oxide Elements

Mixed-metal oxide (MMO) elements consist of commercially pure titanium, tantalum or niobium substrate with applied activation coating.

Titanium, tantalum and niobium are "valve metals" (film forming metals). Under exposed anodic operation where oxygen is available, each of these metal forms a thin, protective and self-healing and tightly adherent surface oxide film. This oxide film resists the passage of current in the anodic direction until sufficient voltage is applied to cause film failure. MMO film has the same protective quality as substrate oxide, but unlike the substrate oxide, the MMO film provides conductive current path in the anodic direction.

MMO usually comprises a mixture of oxides of Group IV and Group VIII metals and other non-precious metal-oxides. Titanium substrate anodes are the most widely used; substrate conforms to ASTM B338 Grade 1 or 2.

MMO elements are available in a variety of shapes including tubular, wire, rod, strip, disk and mesh. Rod-type or tubular-type can be operated as anode at 600 A/m^2 [66]. MMO consumption is extremely low in anodic operation and not a significant factor in determining the element operational life. MMO anode design is not suited for cathodic operation or applications requiring current reversals. The maximum cathodic current density should not exceed the value at which an excess of hydrogen atoms will be present in the coating and the total change in reverse direction should not be capable of reducing a significant amount of the oxides [63].

5.5.1.3 Electrode Site, Breakwater and Active Element Arrangements

The key parameters that determine the electrode site layout and the arrangement of elements include the safety in the water on the sea facing side of the breakwater, rating of HVDC scheme and need to balance the current sharing among the elements, type of elements, site spatial constraints, and the acceptable concentrations of the chemical emissions in the pond.

Number of Elements and Spacing

The HVDC scheme current rating and mode of operation dictate the type of elements and number of elements required. Each element type would have recommended maximum impressed current limits for reliable anodic and cathodic operations. The number of elements should be selected large enough to meet the HVDC system current rating and to have lower gradient around the elements to ensure reduced chlorine selectivity at anode.

The elements are in contact with the conductive water and the coupling is not a dominant factor affecting the overall performance. However, an optimal space between the elements in the range of 1 m to 2.5 m is typical to ensure adequate space for constructability and maintenance. An array of uniformly spaced elements in a straight line or a semicircle would result in higher current density for the end elements. Therefore, the end elements should be arranged with smaller spacing to increase coupling and provide more equal current sharing among the elements.

The current sharing should be studied to balance the current sharing.

Breakwater and Element Pedestals

The available real estate, bathymetry of the pond, available construction materials in the area, wave action, tidal water level fluctuation and the safety requirements dictate the breakwater design, breakwater layout and the arrangement of elements inside the pond.

A shoreline pond electrode breakwater is comprised of a permeable bank of regular size rocks for water exchange between the pond and the adjacent seawater, random size rock zone above the permeable zone, armour stones on the sea side of the breakwater and host of other filter layers. Constructability aspects of breakwater (e.g. straight sections of breakwater are easier to construct) and available construction materials in the area (e.g. size of the regular size permeable zone rock and armour rocks on the seaside for breaking waves) determine the type of breakwater structure. The majority of shoreline pond electrode in operation are straight sections except the Gotland scheme pond electrode. Figure 5.33 shows elements are arranged on the breakwater while Figure 5.34 shows elements are suspended and attached to a Bridge. The electrode elements are arranged such that the top of electrode elements would be lower than chart datum at that location.

The length of the breakwater and the slope on the sea side should be sufficient to ensure a maximum voltage gradient of 1.25 V/m [2] on the sea side of the breakwater to ensure the safety of human and fish. A voltage gradient of 2.5 V/m [2] causes discomfort for humans and large size fish; smaller fish species of length 0.3 m or so can tolerate higher gradients up to 7 V/m [61]. The sloped breakwater on the sea side results in asymmetrical current dissipation at the interface of the breakwater and sea. The current density near the water surface is expected to be higher and the design should be conservative to address this aspect particularly at low tide.

The height of the breakwater is dictated by the highest astronomical tide, wave height, wave overtopping, and acceptable damage coefficient after the worst design basis storm (e.g. 100 year or 50-year storm). Element installation on the land side of pond is possible if shoreline excavation is planned for developing the pond. This provides better and safe personnel access even under wind and wave conditions.

If the site is exposed to significant wave action or pack ice, it requires larger and more robust breakwater with potentially higher maintenance over the life of the project. A robust breakwater requires larger size armour rock. Armour rock of the required size should preferably be available locally and transportation to the site and handling at site should be viable. The armour can be either hard natural rock or concrete tetrapods. As concrete tetrapods can be mixed and poured at site, it would simplify transportation and avoid constraints due to non-availability of suitable rocks locally.

Figure 5.33 - Electrode Elements Arranged on Inside of Breakwater

Figure 5.34 - Elements Suspended and Attached to a Bridge

A wind and wave study would be undertaken to establish the wave fetch area and expected wave height and the worst-case wind to establish the worst-case wave height. The wave height would be reviewed with acceptable wave overtopping discharge and damage factor to establish the graduation for the breakwater core, breakwater seaward armour, breakwater rear side armour and breakwater toe rocks.

Detailed design of breakwater should take into account factors such as the void ratio which dictates the breakwater resistivity. This is critical for electrical performance and other operational aspects (e.g. potential clogging of the permeable zone). The height of breakwater above chart datum and size of armour rocks becomes significant if the structure is exposed to waves of 6 to 7 m height (e.g. on the east cost of Canada and USA exposed to the Atlantic Ocean). Locations which are protected from the large waves require minor breakwater structures (e.g. Sansum Narrows-Vancouver Island).

Concrete pedestals with cable run section in the top, and element conduits below are required. The element conduits are arranged such that the elements can be install or removed from the conduit while standing on the breakwater. In the event that, individual element pedestals are not viable, multiple pedestals can be poured as single structure. The rebar should be of fibre type to avoid corrosion.

If a support bridge is used to suspend the electrodes, the bridge design should be such that it accommodates the full range of tidal fluctuation. Either a floating bridge or the bridge above the higher high water larger tide (HHWLT) should be designed.

5.5.1.4 Heat Dissipation from Pond Electrodes

The energy dissipated at the electrode is directly proportional to the current flowing into or out of the electrode and the resistivity of the seawater surrounding the electrode elements plus the energy loss due to the polarization voltage at the surface of the electrodes as described above.

Heat dissipation densities through the breakwater of a pond-type electrode can be estimated, which may be useful for predicting the extent of temperature rise as a result of electrode operation. Also, the worst-case heat dissipation through the seawater can be calculated at the seaside interface of the breakwater.

The minimum area of breakwater required to achieve a safe voltage gradient is the prime consideration of the analysis. The voltage gradient across the breakwater can be established by multiplying the equivalent resistivity of the breakwater by the current density at the interface of the breakwater.

The heat volumetric dissipation in the sea away from the breakwater will be insignificant because of the large volume of water. The heat dissipation in the breakwater and in the pond results in heat gain in the pond water and this heat gain tends to increase the pond water temperature. The pond water temperature rise can be estimated using a conservative approach assuming:

- All of the heat is assumed to be dissipated in the pond water and the breakwater. The amount of heat dissipate in the open sea is negligible
- Half of the heat dissipated in the breakwater is gained by the pond and the other half by the adjacent seawater.
- Conductive, radiation and evaporation losses of the heat from the pond water to the air are assumed to be zero.
- Heat is exchanged between the pond and the adjacent seawater as a result of tidal flushing only. Half of the water in the pond is assumed to be replaced with new water every 12 hours.

The heat dissipated into the adjacent seawater is small and the temperature rise of the water adjacent to the breakwater will not be noticeable. An efficient mixing due to wave action is expected.

5.5.1.5 Disconnect Switches, Filter Equipment and Surge Protection

Disconnect switches should be rated for maximum dc current. The voltage class of the switches should be selected to withstand the maximum converter neutral bus voltage and surge associated with transition from bipolar to monopolar operation.

Surge arresters may be provided to protect the terminal equipment and electrode feeder cables from lightning surges transmitted over the electrode line. The surge arrester should be selected to coordinate with the equipment or cable insulation withstands levels and should have the capability to discharge the worst-case lightning surge. The surge arrester should not discharge for a bipolar to mono-polar transition surge. Station class surge arresters are preferred.

5.5.1.6 Raceways, Cables, Lead and Junction Boxes

The main distribution cable for the subsection from the main structures to the elements should be rated for the subsection current and should have voltage class higher than the expected electrode GPR.

The cable raceway includes direct buried run to the edge of element pedestals for elements on the breakwater and to the bridge for elements attached to the bridge.

The raceways between the element pedestal runs above grade between the element pedestal and junction boxes are either in the pedestal or attached to the pedestal.

The raceways on the bridge should be arranged in the access corridor and the junction boxes are arranged in the access corridor as well.

The junction boxes should be preferably non-metallic water tight to avoid touch potential hazard if a conductor comes in touch with the junction boxes. In case metallic junction boxes are provided, the tolerable touch potential should be evaluated for safety.

Leads from the junction boxes to the elements can be exposed to chlorine and leads should preferably be high molecular weight polyethylene (HMWPE).

5.5.1.7 Grounding and Bonding within the Electrode Site

The grounding and bonding should be arranged to avoid local loops that will result in dc stray current from between different grounded points. Preferably the ac stations service equipment and other infrastructure structure should be arranged in close proximity and single ground loop should bond and ground all the equipment.

5.5.2 Operation and Maintenance Considerations

Typical operation and maintenance associated with a shoreline pond electrode include the following tasks.

a) The monitoring of electrode elements currents and current sharing
b) Inspection to assess the condition of elements and replacement as needed
c) Inspection of other structural infrastructure
d) Inspection of breakwater armour stones and reposition if movement has occurred
e) Inspection and switching of electrical disconnect at the site to ensure contacts have not degraded.

Elements suspended on a bridge offer the most flexible option to inspect and replace the elements as shown in Figure 5–33.

The elements arranged on the face of the breakwater are typically guided through a heavy-duty HDPE or PVC conduit as shown in Figure 5.32. The slope of the conduit should be preferable such that elements are slide down under their own weight without requiring to be pushed. The conduit and elements support infrastructure at the toe of breakwater arranged for easy retrieval of the elements for inspection.

Access is required along the whole length of the breakwater allow inspection and maintenance of all elements and to observe any evidence of movement or dislodging of armour rocks on the face. Adequate space and is needed to allow heavy equipment access to adjust dislodged rocks on the seaward side. This may not be a requirement if the breakwater is located at a location where wave action is limited.

The electrical switches should be located such that these are accessible during all ambient and wind conditions, and interlocks or protocols are in place to avoid operation of isolation switches for breaking current. As a minimum, switches should be padlocked with key held by the converter station operating staff. Safety and electrical clearances are arranged in accordance with regulating authorities. The equipment maintenance and operation aspect are reviewed and factored in the design.

5.5.3 GPR, Potential Gradient and Resistance to Remote Earth

The performance of a shoreline electrode is a function of the exposure to the adjacent seawater, the slope of sea bed, and design of the electrode site. A larger site with lower current densities of elements with good exposure to the sea body of water and steep sloping sea bed provides better performance.

The performance can be gauged using simplified analytical tools during planning stage and detailed analysis is required during the design stage.

5.5.3.1 Simplified Analytical Approach During Planning Stage

A shoreline electrode can be assumed to be a spherical electrode centered at edge of sea shore and sea bed can be assumed to be a slope at an angle to the horizontal. Figure 5.35 shows the simplified representation of the shoreline electrode and the conductive bodies surrounding the electrode. At a distance "r" from the electrode centre the space surrounding the electrode can be viewed as sphere. Soil body forms the hemisphere, water body is a portion of the sphere, and the rest is insulated medium of air.

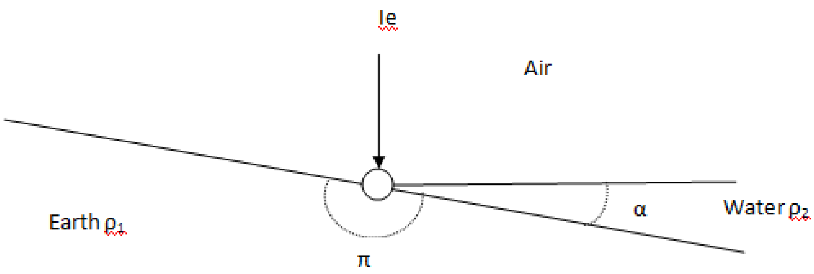


Figure 5.35 - Shoreline Pond Electrode Simplified Model

The surface area of the soil body and the water body at a distance "r" on the spherical shell are,

Surface area of soil body $A_1 = 2\pi r^2$ (5.5-1)

Surface Area of the water body $A_2 = 2\alpha r^2$ (5.5-2)

The total current passes through the water and soil body since air is insulated medium of high resistivity. For uniform resistivities of soil and water bodies, the total current passing through the soil and water bodies is,

Total Current $Ie = I_1+I_2$ (5.5-3)

$= J_1A_1+J_2A_2$ (5.5-4)

$= 2r^2 (J_1\pi+J_2\alpha)$ (5.5-5)

The radial voltage gradients parallel to the interface of seawater and the soil body are equal.

Voltage gradient $E_1=E_2=\rho_1J_1=\rho_2J_2$ (5.5-6)

$J_1=(\rho_2/\rho_1)\, J_2$ (5.5-7)

Substituting Equation 5.4-7 in Equation 5.4-5 gives,

Total Current $Ie = 2r^2 J_2((\rho_1/\rho_2)\pi+\alpha)$ (5.5-8)

Current Density in soil body $J_1=\frac{Ie}{2r^2\,(\alpha+\frac{\pi\rho 2}{\rho 1})}$ (5.5-9)

Current Density in water body $J_2=\frac{Ie}{2r^2\,(\pi+\frac{\alpha\rho 1}{\rho 2})}$ (5.5-10)

The voltage gradients in water and soil bodies are,

Gradient $Ew=Eg=\frac{Ie}{2r^2\,(\frac{\alpha}{\rho 1}+\frac{\pi}{\rho 2})}$ (5.5-11)

The voltage at a location r distance from the center of electrode is, Voltage $$V = \frac{Ie}{2r^2\left(\frac{\alpha}{\rho 1}+\frac{\pi}{\rho 2}\right)} \qquad (5.5\text{-}12)$$

The resistance to remote earth by integrating voltage from remote earth to a distance "a" at the edge of electrode for a current of one (1) ampere is,

Resistance to remote earth $$Re = \frac{1}{2a^2\left(\frac{\alpha}{\rho 1}+\frac{\pi}{\rho 2}\right)} \qquad (5.5\text{-}13)$$

The above approach is simplistic and would predict optimistic performance for the electrode. The following assumptions which were made in deriving the above equations do not hold true for actual installations:

a) An infinite straight shoreline: The electrodes are normally located at protected location in a cove or bay and full exposure to the sea is not available. The straight section of the shoreline is limited in length.

b) A uniform slope: The actual slope varies in both radial and axial directions.

c) Uniform seawater and soil resistivity: The resistivity will vary and the equipotential contours will not form circular rings as suggested in the above equation. With varying resistivity of different soil bodies, the equipotential contours form complex shapes especially near the electrode site and extend farther into sea.

d) Hemisphere of soil and wedge formed by body of water: The water does not form a uniform wedge and its profile varies in different directions. The profile along the shoreline will be flat. Only a section (less than 180 degree) of spherical shell will form a wedge and for some instances is limited to a few degrees if the electrode is located in a narrow bay.

The analysis can be improved by considering seawater sections of different seabed slopes possibly including flat sea bed at a distance from the electrode as shown Figure 5.36.

The exposure to the sea needs be reviewed and appropriate multiplying factor to be applied (e.g. if the exposure to sea is limited to 15 degrees a multiplying factor of 180/15=12 should be applied to the calculated resistance to remote earth).

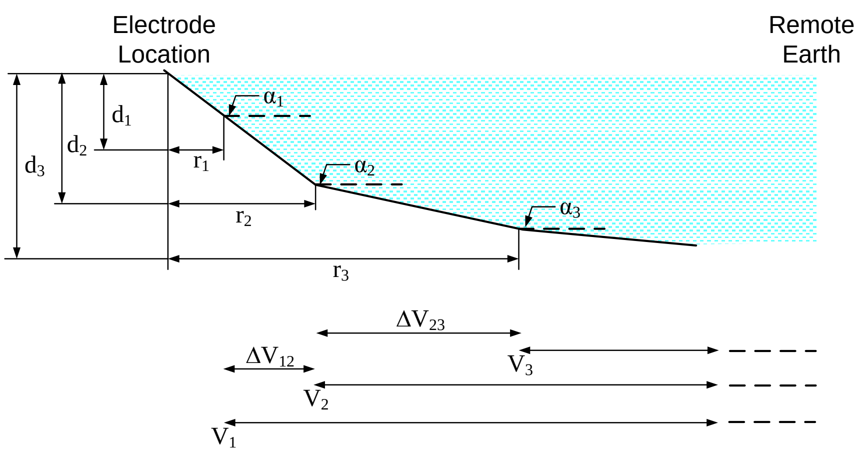


Figure 5.36 - Model Representation with Varying Sea bed Slopes

5.5.3.2 Detailed Analysis during Design Stage

A detailed analysis using a suitable software package is required to quantify the GPR at the electrode and different locations of interest for qualifying the design and location of the electrode. The GPR values and gradients are used for analyzing the safety, and electrical interference and corrosion impact associated with electrode operation.

The software packages normally subdivide the volume of the conductive body to be analyzed into smaller finite volumes and use either network techniques or finite element analysis method.

The critical aspects to be evaluated for the analysis include:

a) Volume of the conductive bodies to be modelled for reasonable accuracy (e.g. deep soil is not critical for shoreline electrode)
b) Soil model assumptions especially where only ranges of probable resistivity of conductive bodies are known. The approach is to have conservative analysis.

5.5.4 Pond Electrode Examples

Table 5.9 shows the design and operating parameters of shoreline pond electrodes that are in operation.

Table 5.9 - Shoreline Ponds electrodes in Operation and Design Parameters

Description	Eknö	Massänge	Haenam	Cheju	Punta Tramontana
Scheme	Gotland	Gotland	Haenam-Cheju	Haenam-Cheju	Sacoi
Current rating of the electrode Station (A)	915	915	850	850	1000
Electrode Operation	Reversible	Reversible	Reversible	Reversible	Anode
Element Installation	Suspended	Suspended	Suspended	Suspended	Suspended
Element Type & Size (Radius x Length)	Magnetite Fe_3O_4 (0.06mx0.72m)	Magnetite Fe_3O_4 (0.06mx0.72m)	Graphite or HSCI (0.12mx2.13m)	Graphite or HSCI (0.12mx2.13m)	Platinized Titanium (0.0325mx0.6m)
No. of Sub-electrodes	2x48	48	20	20	30

5.6 SHORELINE BEACH ELECTRODES

Many HVDC links involve water crossings and it is therefore natural to consider electrodes in marine and shoreline environments. Seawater has very low resistivity and offers an optimal path for ground current. Where conditions permit, electrodes built on a beach exposed to salt water are a viable option. Beach electrodes are a sub-category of shore electrodes.

5.6.1 Design considerations

The design of beach electrodes presents a set of conditions and requirements different from those in the design of land electrodes. For efficient removal of heat and to avoid undesirable build up chemical concentrations leading to corrosive conditions at the elements, it is essential that the electrode elements always be in contact with water and the water be exchanged on a continuous basis or via the tidal cycle. This can be achieved either by locating the electrode elements below the low-tide level or by means of a pumping system where the natural supply or replenishment rate of water is inadequate. A constant exchange of water with a flow rate as low as 0.2 l/s has been found to be adequate for removal of chlorine for an anode carrying 50 A continuously [67]. Without adequate water flow, the water will become more acidic, corrosion of the electrode elements and electrical contacts will accelerate and the temperature will increase greatly. In most cases, natural tidal actions are sufficient to achieve the required water exchange although it may be necessary to replace some of the natural beach material with material of greater permeability to achieve this objective.

In addition to water supply, the conducting elements in a beach electrode require support and physical protection of a different sort from that found in land electrodes. A typical method is to suspend elongated cylindrical elements in well casings installed on the beach. Hard polyvinyl chloride (PVC) pipe, 10" OD and 3/8" wall thickness, installed in clay and sand, was used at Konti-Skan [67]. Very dense hard concrete tubes, installed in a bed of large rocks set in an area of smaller stones, were used in New Zealand [69]. The protective encasement must be perforated with sufficient holes or openings to allow for adequate water circulation and for current to pass through the walls of the tube.

The materials used in beach electrodes – carbon/graphite or other cylindrical units and encasing materials - as well as the depth of the well in which the materials are placed are limited in length and hence cannot be easily extended as in the case with land electrodes. Therefore, the general procedure is to design an electrode element and protection arrangement suitable for the site conditions and then determine how many of these modular elements are required to provide the desired electrode properties including safety, duration between maintenance and resistance to remote earth.

Potential gradients in the water which could affect people, fish and other marine species are handled somewhat differently in shore-type electrodes than those on land. Because beach electrodes rely on the water body to conduct the majority of the current, the potential gradients in the water, especially in close proximity to the elements, can become quite high. Controlling these gradients to within safe limits is achieved through design aspects (e.g., limiting current densities or providing adequate material to create separation between the water environment and the electrode elements), or by restricting access to the water in the near vicinity of the electrode by means of nets or other barriers. Step potentials on the earth are usually not significant because the current density in the earth is relatively low and resistivity is much higher on land than in the water.

Beach electrodes designed for anode use have different design requirements from those used only as cathodes. Cathode elements do not lose mass, but rather accumulate deposits on their surface. As these deposits are conductive, they do not seriously affect performance. Cathodes also do not attract fish, but rather repel them, so that barrier installations are not necessary. Conversely, an anode electrode will lose material at a rate proportional to the current, therefore material loss in an anode is an important factor in the design. Anode elements do not accumulate deposits and as they may attract fish must be provided with barrier installations to keep fish out of the high field region.

Replacement of the anode material will be required from time to time in shore electrodes and should be considered in the physical design. Each element in a shore electrode array should be provided with a disconnecting switch so that each element can be isolated for maintenance or replacement. It is also advisable to provide means for measuring the current through each element in order to monitor the sharing of current among the elements.

A diagrammatic section through a generalized beach electrode is given in Figure 5.37, from which it can be seen that the electrode environment contains two materials, water and stone, typically of widely different resistivities. Seawater, designated by ρ_1, normally has a resistivity of about 0.2 Ω•m. Fresh water could have a resistivity between 2 and 300 Ω•m depending on the dissolved chemical content. Suspended matter, even of high conductivity, has little effect on the resistivity of fresh water. The land resistivity could be anywhere in the range of 10 to 1000 Ω•m or more.

The basic equation [70] for the resistance of a vertical electrode is a function of the earth resistivity ρ, and the length l and diameter D of the electrode. The approximate equation for the resistance of one single element, which is valid when the length of the conductor is much greater than its diameter, is given by:

$$R_1 = \frac{\rho}{2\pi l}\left(ln\frac{4l}{D} - 1\right) Ohms, when\ l \gg D \qquad (5.6\text{-}1)$$

Equation 6-1 gives the resistance of one vertical electrode to remote earth, which is applicable to electrode design. In practice, an electrode will be made up of more than one vertical element. If several vertical electrode elements are arranged in a straight line with equal spacing which is equal to or greater than the length of the electrode element, the combined resistance [70] of the array can be found by Equation 5.6-2:

$$R_n = [R_1 + \frac{\rho}{\pi s}\left(\frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots + \frac{1}{n}\right)] Ohms \qquad (5.6\text{-}2)$$

where

R_1 is the resistance of one element found by Equation 5.6-1,
n is the number of all elements that have the same diameter D and length l.

For a large number of elements, the expression $\left(\frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots + \frac{1}{n}\right)$ approaches $ln\frac{\gamma n}{e}$

and Equation 5.6-2 can be written as (6):

$$R_n = \frac{1}{n}\frac{\rho}{2\pi l}\left(ln\frac{4l}{D} - 1 + \frac{2l}{s} + ln\frac{\gamma n}{e}\right) Ohms \qquad (5.6\text{-}3)$$

Where

γ =0.57721 (Euler's constant) and
e is the base of the natural logarithms, 2.718

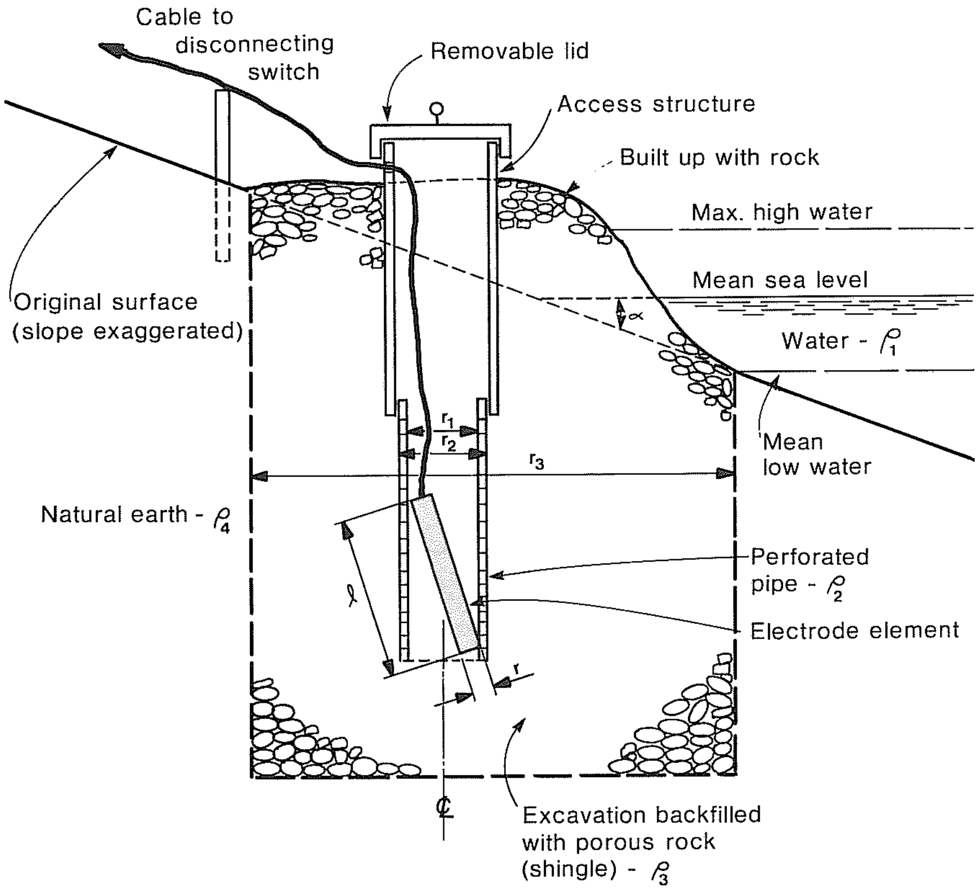


Figure 5.37 - Cross-section of typical beach electrode arrangement [1]

The angle α (expressed in radians) is formed between the plane of the water surface and the plane of the land surface, which can be assumed without risk of gross error to be constant. Since the current densities in water and earth are inversely proportional to their respective resistivities, it can be shown that the potential at any distance r from the electrode, either in earth or water is

$$V = \frac{1}{2r(\frac{\alpha}{\rho_1}+\frac{\pi}{\rho_2})} Volts \qquad (5.6\text{-}4)$$

and the expression for resistance to remote earth is

$$R_e = \frac{1}{2D(\frac{\alpha}{\rho_1}+\frac{\pi}{\rho_2})}\ Ohms \qquad (5.6\text{-}5)$$

The superiority of a shore (beach or pond) over an electrode entirely in land is demonstrated by examining the ratio of their corresponding resistances to remote earth, which is known as the efficiency (l/η) of a shore electrode in comparison with a land electrode [2]. The calculation of η, which is used in design formulas for shore electrodes, is given by:

$$\eta = \frac{R_{es}}{R_{ee}} = \left[\left(\frac{\alpha}{\pi}\right)\left(\frac{\rho_2}{\rho_1}\right) + 1\right]^{-1} \qquad (5.6\text{-}6)$$

Under average conditions of land resistivity ρ_2=100 Ω•m, sea resistivity ρ_1=0.2 Ω•m and slope α=5.7deg, a shore electrode is many times more efficient than a land electrode. It is evident that the higher the earth resistivity is with respect to the water resistivity, the more efficient a shore electrode becomes. It is also demonstrable that the efficiency of a shore electrode increases with increase in α, which is with a steeper slope into the water. However, physical conditions place a limit on the slope.

Where the path of ground current is between two points on opposite shores, it is possible to regard the sea bed as insulating and to assume that all current flows in the water [40].

Calculation of the resistance of an individual vertical element of a shore electrode which is simply suspended in water can be found by Equation 5.6-1, considering only the resistivity of the water. However, for an element installed inside a pipe, the resistivity of the various surrounding media must be considered. In a typical case when a cylindrical electrode unit is installed inside a perforated concrete pipe, which is located in a porous bed of large gravel (shingle), with free flow of seawater, the expression for electrode resistance is a function of the resistivity and dimensions of all the surrounding materials. Equation 6-7 [69] covers the above hypothetical case, but would not necessarily be valid for a different set of conditions.

$$R_e = \frac{1}{2\pi l}\left(\rho_1 ln\frac{r_1}{r} + \rho_2 ln\frac{r_2}{r_1} + \eta_1\rho_3 ln\frac{r_3}{r_2}\right) + \frac{\eta_2\rho_4}{2\pi r_3} Ohms \qquad (5.6\text{-}7)$$

Where

l = length of electrode element (cylinder)
r = radius of electrode element
r_1 = inner radius of enclosing pipe (concrete)
r_2 = outer radius of enclosing pipe
r_3 = radius of excavation backfilled with large rock
ρ_1 = resistivity of water
ρ_2 = resistivity of perforated wall of concrete pipe
ρ_3 = resistivity of backfill saturated with water
ρ_4 = resistivity of earth below electrode and water
η_1 = ratio between equivalent resistance of backfilled section and water as a function of slope of earth (α)
η_2 = ratio between equivalent resistance of underlying earth and water as a function of slope of earth (α) - refer to Equation 5.6-6

5.6.2 Beach Electrode Example

Figure 5.38, Figure 5.39, Figure 5.40 and Figure 5.41 are pictures of the beach electrode at Te Hikowhenua, associated with the Haywards converter station on the North Island of New Zealand. This beach electrode has operated as a cathode for extended periods of continuously monopolar operation. It comprises 25 wells arranged in a linear array along the beach, spaced at 25 feet, except for the outer elements which have spacings of 20 feet and 15 feet to reduce the effect of current imbalance at the ends of the array.

The features of the Te Hikowhenua beach electrode are summarized below:

a) On the beach a maximum step voltage requirement of 5+0.03*ρs is met at the maximum dc system current. (ρs=top soil resistivity) e.g. Max step voltage on dry sand Es=5+0.03x1000 =35 V/m.
b) The electrode consists of 42 buried electrode cells (4.8 meter deep concrete cylinders with single electrode element in each cell or well) set into the beach with the top of the well above mean high water level.
c) Electrodes submerged in seawater within the buried concrete cylinders.
d) The electrodes are made from high silicon-chromium iron to resist corrosion when operating as an anode.
e) When operating as anode, metallic ions travel into the seawater and the electrode elements loses mass. Chlorine gas is also produced. For maintenance purposes, the end of electrode life corresponds to 60% loss of material.
f) When operating as cathode, magnesium hydroxide and calcium hydroxide accumulate on the surfaces of the electrodes due to reaction of hydroxide ions with the calcium and magnesium ions of the seawater.
g) These deposits increase the resistance of the electrode element but as the resistance increase is concentrated within a few millimetres or tens of millimeters from the electrode elements the step/touch/marine voltages in the vicinity are not affected. The power loss within the cell increases in proportion to the resistance highlighting the need to be conservative in designing the amount of water exchange required to achieve efficient and adequate heat removal to avoid the possibility of excessive heating in the cells.

h) The condition of the electrode elements is monitored by measuring the weight of one indicative pilot electrode every 6 months to assess condition. If electrodes are too heavy due to build up from cathodic operation, they must be cleaned or replaced. If electrodes are too light due to wasting from anodic operation, they must be replaced.

Figure 5.38 – OVerview of electrode station and ELectrode wells Arranged on beach

Figure 5.39 - Electrode element with deposit build-up, typical for cathodic Operation

Figure 5.40 - Electrode element and encasement well

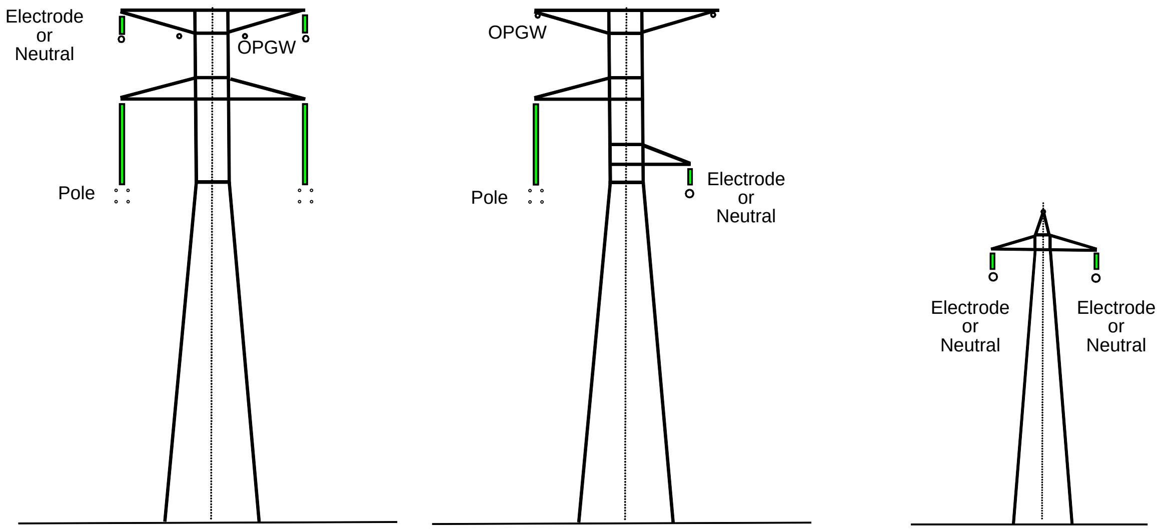
Figure 5.41 - New electrode elements (high silicon-chromium iron)

6. CONNECTION FROM CONVERTER STATION TO ELECTRODE STATION

The electrode line or neutral line system carries the current between the neutral bus of the converter station and the earth electrode. It can be built as an overhead line or as a cable or a combination of the two.

6.1 OVERHEAD ELECTRODE LINES

The electrode line or neutral line may be implemented using combined structures as shown in Figure 6.1a) and Figure 6.1b), or dedicated structures as shown in Figure 6.1c). Often the neutral or electrode lines can conveniently be positioned on the same tower as the pole conductors. Electrode lines are frequently carried for a short distance on the HVDC line towers before branching off on to a separate electrode line. The decision on the line arrangement would be based on technical and economical considerations as well as the location of the electrode site relative to the HVDC line route.



a) Bipolar Tower with Electrode/neutral Line

b) Monopolar Tower with Electrode/neutral Line

c) Separate Tower with Electrode/Neutral line

Figure 6.1 - Conceptual electrode line configurations

The rated current capacity of the electrode line or neutral line will be dependent on operation mode of the converter station and the pole ratings (e.g. bipolar, monopolar earth return, monopolar metallic return, with converter overload, parallel operation of two converters in the same pole). For a monopole scheme without a metallic return conductor, the electrode line would carry current continuously. For a monopolar scheme with metallic return, a bipolar scheme, or a multipolar scheme, the current will depend on the mode of operation as described in Chapter 1.

Generally, the electrode line can be equipped with the conductors of the same current rating as the HVDC systems or a lower conductor cross section. On the Itaipu system, the conductor cross section was optimized for minimum cost of losses and investment which results in pole conductor bundles of 4x1272MCM. In case of a line pole outage, the converter poles can be paralleled on one line. One line pole can carry two times the rated current of one converter under emergency condition based on which the maximum conductor temperature of the conductor was designed. However, the electrode line conductor was selected as 2x1272 MCM which is half of the cross section of the pole conductors and thus it is not capable of transmitting the combined output of the two poles, nor is the electrode designed to accept such a large current. Therefore, if one converter pole is lost while the line poles are in parallel the remaining converter pole would need to reduce current to the rating of a single converter pole.

To avoid the bipolar outages due to failures of electrode line conductors, the electrode line conductors can be split in two conductors or bundles, to be attached on two independent crossarms normally on the opposite sides of the tower. In this case, each conductor or bundle should have sufficient current rating to operate in monopolar up to the inherent continuous overload rating of the DC system.

Due to high currents flowing in the conductors, the voltages at the ungrounded end can reach values in the kilovolt range for typical line lengths and up to tens of kilovolts for extremely long lines, depending on the length of the electrode line and the resistance the line conductors and the electrode. The insulators optimized for the HVDC line would typically also be used for the electrode line insulators to simplify spare equipment requirements. In some cases, the insulator strings have been equipped with special arcing devices to avoid sustained arcing near the insulator strings which could damage or destroy the insulators. The need for arcing devices and the placement on the electrode line arranged on the structures should be reviewed in detail by the designer.

Due to the ground potential rise at the electrode site, the connection of electrode monitoring system (if installed) to Converter Station Control should be based on Fibre Optic or wireless transmission. Although the fibre could be included in one of the electrode line current-carrying conductors it is usually more convenient to provide a separate conductor OPGW. The OPGW would need to be insulated near the electrode to avoid the issues of transferred potential or corrosion of the tower bases due to the stray currents resulting from the surface potential rise of the electrode.

The electrode line routing depends on the final selection of the electrode and would be performed in detail after selection of the electrode site location. However, a preliminary assessment as to the possibility to route the line to the site would be performed during the electrode site selection process.

More information can be found in References [72] [73] and [74].

6.2 CABLE ELECTRODE LINE

Overhead connections for electrode lines are preferred from cost and maintenance perspectives. However, depending on the application and circumstances, cables may be used for some portions or all of the electrode line between the converter station and the electrode station.

For sea electrodes, submarine cables are at a minimum required between the offshore electrode location and the shore. Submarine cables may also be used when long water crossings cannot be avoided. Land cables may be used for line sections where overhead lines are not feasible (e.g., right-of-way for overhead line is not easily attainable).

Cables designed for medium dc voltage often meet the application. Generally, extruded dc cables would be preferred because they are generally lighter and factory made slip-on joints and sealing ends are available which greatly simplifies installation and maintenance. The insulation level of the cable must be selected in coordination with the overall insulation levels of the electrode line. Arresters should be installed at cable transition points to protect the cable from overvoltage surges from either lighting strikes or system overvoltages.

Standard techniques would be applied when calculating the cable ampacity, including thermal resistivity of the surrounding soil or water, temperature of surrounding medium, and separation from other cables in the vicinity (if applicable).

The surge impedance of a cable is lower than an overhead line, therefore electrode line monitoring and protection schemes employing high-impedance supervision techniques, which inject high-frequency signal on the electrode line and calculate the impedance from the response, may not be viable.

6.3 DESIGN FACTORS FOR OVERHEAD ELECTRODE LINES

6.3.1 Factors which affect the overhead electrode line

The main factors which affect the design of the overhead electrode line are current to be transferred, wind, air pressure, temperature, solar radiation, lightning incidence, pollution, seismic disturbances, and reliability requirements of the HVDC system.

These factors should be individually analysed based on available data, previous projects and applicable Standards as well as local Norms and Laws.

Lightning incidence may be evaluated using multiannual average values for the number of thunderstorm days per year (keraunic level) and, if available, multiannual average values of the lightning flash density (GFD-Ground Flash Density). The lightning performance of line expressed as the annual number of lightning flashovers per 100 km of line and per year should be assessed using data from area of the line.

The performance against back flashovers and direct strikes is poor because the electrode line generally has a low BIL insulation level (~400kVmax). Flashovers may also occur due to lightning hits to the ground close to the line (induction effect). The design of the electrode line should be such that an arc should self-extinguish.

If arcing horns are used to control arcing, the following characteristics should be applied:

a) Flashover strength lower than that of the insulator
b) Horizontal gap with expanding distance at top
c) Capable of self-extinguishing with maximum expected arcing current and voltage
d) Designed for frequent operation with minimal maintenance
e) Designed to avoid flashover directly adjacent to the string or quickly guiding the arc away from the insulators to avoid damage to the insulators

Lightning flashovers of the electrode line generally do not affect the reliability of the HVDC transmission since the flashover would be designed to clear without interrupting the HVDC transmission.

In bipolar operation, there would be insufficient voltage and current following the lightning stroke to maintain a dc arc and the arc flashover would clear immediately when the lightning stroke current stops.

In monopolar operation, it is likely that a dc current arc would be initiated if a flashover occurs due to switching surges or lightning. Depending on the voltage and dc current that can be diverted into the arc at the fault location, the dc current arc is likely to persist for some time and may require protection action to clear. To avoid possible damage to the insulators, line hardware and even the structure self-clearing arc gaps are recommended. [73]

Clearances sufficient to allow live line working and in close proximity to live conductors can be provided but the requirement to do such live-line work on electrode lines should be carefully reviewed in view of the risks to personnel from sustained arcing [74]. This hazard can be avoided by separating the electrode line into two separate conductors each of which is separately switchable and capable of sustaining operation of the dc system during outage of one side as earlier discussed.

As portions of the electrode line would be subject to significant dc voltage for long period of time, the creepage distance of the dc line insulators needs to be considered in the line design. The pollution data should be based on data from line area, ESDD and NSDD values may be similar to those applied for the HVDC line design.

6.3.2 Environmental Impact of Overhead Electrode Lines

The possible influences on the environment caused by HVDC electrode line or neutral line include:

a) The effects of magnetic fields,
b) The use of land for transmission line

The environmental criteria related to magnetic field would be selected in accordance with permissible local limits and legislation. The requirements for DC magnetic field are generally much less stringent than for ac lines, but local legislation would take precedence. The magnetic field may be a condition for ground clearance design. Since the electrode line would be required to carry the full pole current, the magnetic field should be checked as the line clearance to ground may be low.

Due to the low design voltage level, the electric field from the electrode line would not be an issue although it could be calculated for completeness when making the environmental application.

The use of land and clearance requirements for the electrode line is similar to the other MV lines as discussed in CIGRE TB 388 [75] and shown in Figure 6.2.

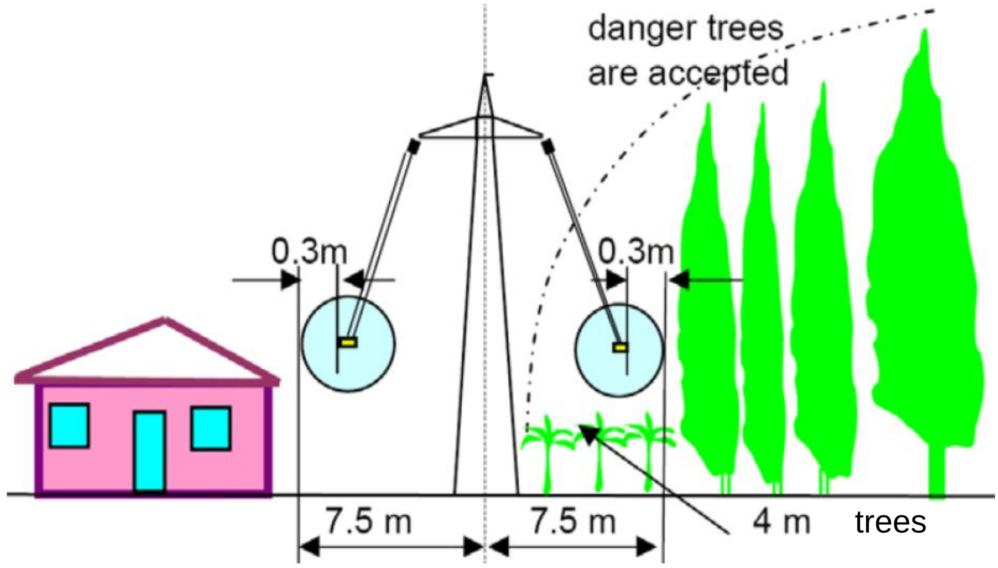


Figure 6.2 – Typical Electrode line Corridor clearance considerations

6.4 ELECTRODE LINE MONITORING AND PROTECTION

Electrode lines are normally designed to ensure self-extinguishing for insulator flashover events. Other faults such as solid faults without arcing should preferably be detected by an electrode line monitoring scheme to ensure safety and reliable operation.

The configuration of the protection and monitoring scheme to be implemented should consider the risks to personnel and property and HVDC reliability requirements. The designer of the protection system should seek inputs from the electrode line designer and converter supplier. The designer should also consider the cost and difficulties in establishing and maintaining the infrastructure especially if auxiliary power is not easily available at or near the electrode sites.

The requirements for lines to land, beach and pond electrode would be similar but sea electrodes may require special considerations due to the cable connection.

Electrode line faults can be grouped into the following types of faults:

a) Insulator flashover to grounded tower
b) Conductor drop making direct contact with ground or tower
c) Conductor drop without touching ground or with high impedance to ground (trees)
d) Open conductor with or without touching the ground

An open conductor fault is relatively easy to detect due to the large voltage rise caused at the converter station neutral bus. Ground faults with intact conductor are more complicated to detect for the following reasons:

a) As the electrodes are grounded, a ground fault along the line will give only minor difference in the voltage and current measurable at the converter. The voltage in normal operation corresponds to the voltage drop in the electrode line, which is of very small magnitude.

b) An LCC converter acts as a current source and there will not be any difference in the current in the electrode line even with a ground fault along the line.

c) Bipolar operation causes a very small current in the electrode line, typically 0.5% to 1% of the rated DC current, which is in the same magnitude as the accuracy of the measurement systems.

A number of different methods for fault detection have been applied in HVDC installations or tested in laboratory environment. The methods listed below are discussed further in the following sections.

a) Conductor Unbalance Current Fault Detection (CUC)
b) End-to-end Differential Protection (ETED)
c) High Frequency Current Injection Method (HFCI)

d) High Frequency Line Impedance Measuring Method (HFLI)
e) High Frequency Current Differential System (HFCD)
f) Neutral Bus Voltage Measurement (NBV)
g) Pulse-Echo Method (PE)

The ETED, HFLI, HFCD schemes require installation of current transducers and blocking filter at the electrode site together with associated auxiliaries and communication infrastructure. Some of the schemes in use are proprietary to specific HVDC OEM Suppliers.

Protective actions to clear a persistent arcing fault that does not clear on its own via the self-clearing arcing gaps would involve one of the two following techniques:

a) closing a high-speed grounding switch at the converter station to quench the arc by removing its driving voltage and then re-opening the grounding switch to avoid sustained ground current at the converter station.

b) temporary reduction of the dc electrode line current to zero using the HVDC control system and then re-establishing the current after the arc path has had time to deionize.

If a temporary reduction of the dc power transfer is not acceptable then the high-speed ground switch method would be preferred. The grounding point for this switch would normally be the ground grid inside the converter station but, in the event that the short time ground current causes unacceptable effects such as saturation of transformers, a separate temporary ground point could be established outside the converter station for this purpose.

Details of possible protection and monitoring schemes and their operating principles are described in [73].

6.5 MAINTENANCE OF ELECTRODE LINES AND CABLES

The maintenance of the electrode line generally consists of patrolling the line to detect visual signs of damage to insulators arcing horns or towers with repair or replacement as required. The electrode line should be patrolled regularly to ensure its integrity.

Although the steady voltage from the electrode/neutral conductor to the tower is not high, significant voltage can be induced on the electrode/neutral conductor by faults, fault clearing actions or simply rapid current changes in the pole conductors. Such events can cause flashover of the arcing gap. The arc will tend to travel upwards and will generally extinguish within less than a second. During this time, the arc would represent startle, shock and burn hazards for personnel working on the tower. Therefore, bare-hand or hot-stick work would be possible on the neutral line insulators but is not recommended due to the possibility of initiating an arcing event.

If the electrode line is designed consisting of two parallel conductors with each capable of carrying the maximum monopolar current, if it is necessary to perform live-line maintenance on the insulators or arcing-horn hardware, one of the conductors can be isolated at both ends. The isolated conductor must still be considered as a live conductor and working grounds or portable earths can be placed immediately on either side of the insulator where the work is being conducted.

Live line safety procedures must always be followed during any work being conducted on the electrode line.

7. AUXILIARY SYSTEMS FOR ELECTRODE STATIONS

7.1 INTRODUCTION

The requirements of an electrode site monitoring, station ac and dc services and communication link(s) to the HVDC station or any central supervisory facility are dictated mainly by the type of electrode, the number and type of monitoring systems required at the site for facilitating HVDC scheme operation, electrode line monitoring scheme, and the utility or owners operational and maintenance practices. Typically, non-availability of the auxiliary systems should not negatively impact the performance of the grounding electrode, and the system should be able to operate in a degraded mode reliably without the auxiliary systems available with little or no operator intervention.

Installation of auxiliary systems should be in compliance to the local regulations and codes. Certain aspects of an electrode facility (e.g. fence grounding and station service grounding) may need to be reviewed and agreed upon in advance of final design with the approving authorities.

General descriptions of typical auxiliary systems are included in the subsections following this introduction and are intended as representative guides for the basis of design.

7.2 STATION SERVICE SUPPLY

Station ac power service may be required to supply the lighting and auxiliary loads (e.g. receptacles and heating) required for operation and regular maintenance, dc service for the grounding site and electrode line monitoring systems, and equipment enclosure space and anti-condensation controlled heaters.

A MV or LV distribution network in the area would be the preferred source for the electrode site station services. An electrode site is located intentionally remote from the populated areas or areas with significant transmission and distribution infrastructure to limit the electrical interference and corrosion of structures from dc stray currents. The availability of the supply in the area should be considered in planning the facility, and equipment/system should be suitable for operation without auxiliary supply if the distribution system supply is not available. Supply to dc auxiliaries from solar panels with back-up diesel generator has been considered in the past, however this configuration has not been implemented in existing systems at this time.

With supply from area distribution network, a back-up diesel generator should be considered if the site is remote, and battery system for monitoring systems or installed equipment cannot operate for extended periods of time during the estimated durations of the worst-case distribution system outage. This backup power supply system may be justified if site security measures such as surveillance systems (e.g. video surveillance and intrusion alarming) are employed at the remote site location.

System voltage selection is a function of the facility load and expanse of the facility. Typically, a lower voltage (LV) of the order of 120/208V is sufficient for distribution within the facility with demand lower than 15 kVA, and a higher distribution voltage (600 V in Canada, 480 V in USA and 380 V in EU countries) is normally required for a higher demand load especially if a significant building is foreseen for the site. The off-site service is typically a medium voltage (MV) feeder. Figure 7.1 shows a typical single line diagram for station service of a site with a building and back-up diesel generator.

The station dc service is required for the monitoring and communication systems. The batteries should be suitable for extreme ambient conditions and should be designed with minimum maintenance requirements. In climates that experience long term low temperatures below 0 °C, appropriate deep discharge and low temperature batteries should be specified.

The grounding and bonding of auxiliary system should be such to avoid local loops of the dc stray currents (e.g. different structure within the facility) and flow of dc current from the facility to remote location via the distribution feeder multi-grounded neutral. The multi-grounded neutral is normally isolated from the facility and gap is provided for sparking over in case of a transformer terminal fault, see the Figure 7.2 for typical detail for single phase transformer.

The distribution within the facility should utilize single point grounding at the service entrance panel and the use of metallic structures should be avoided for installation remote from the service entrance panel.

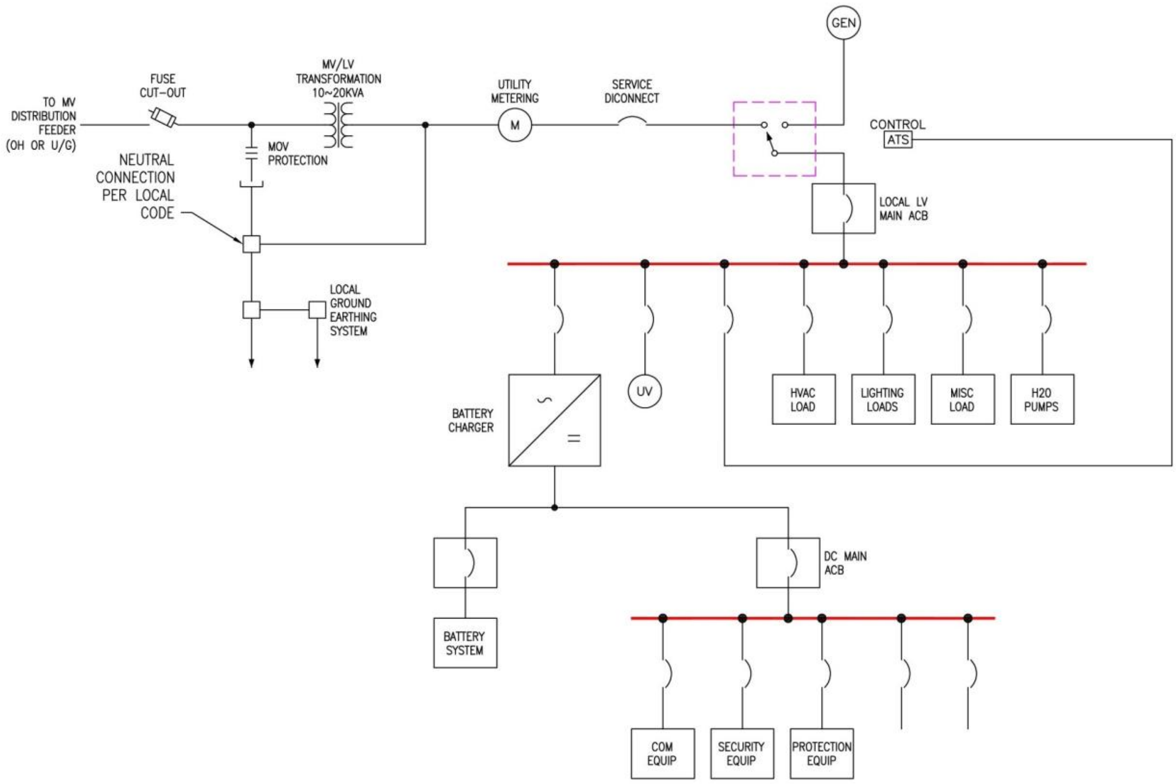


Figure 7.1 - Typical Single line Diagram

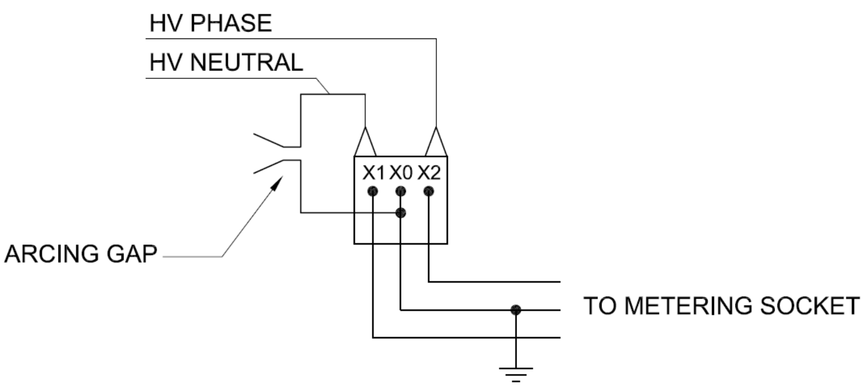


Figure 7.2 - Isolation of Distribution System Multi-grounded Neutral at Grounding Site

7.3 ELECTRODE SITE MONITORING SYSTEM

A monitoring system (e.g. current of individual electrode subsections or elements, monitoring of temperature and moisture surrounding the land electrode elements) associated with an electrode site is mainly for trending the long-term deterioration or slow evolving issues and is not meant for automated corrective actions. The status of electrode line switching equipment is also monitored.

The monitoring systems can vary widely in complexity depending on operational needs. The degree of monitoring can range from no monitoring to extensive local data logging with cellular or dial-in interrogation over a public service network (PSN) with real time data transfer over a dedicated communication link over an OPGW or ADSS fiber optic (F/O) Link. Several low powered data communication technologies can be adapted for this purpose.

Historically, the approach was to build a robust design with provision of periodic manual on-site monitoring by maintenance personnel and monitoring possible overvoltage conditions on the neutral/ground bus at the HVDC terminals without monitoring the electrode site directly. At least two

Canadian HVDC Systems, Nelson River Bipole 1/Bipole 2 electrodes and Vancouver Island Link electrodes, do not have any monitoring in place. These utilities rely on regular inspection by maintenance crews for spotting issues.

Figure 7.3 - Electrode Site without any Control Building or Monitoring System

With complex electrode design such as Caprivi link deep vertical electrode, monitoring is considered as part and parcel of the overall HVDC scheme which helps operators to spot evolving issues, and plan corrective actions and maintenance for reliable operation. Caprivi link electrode monitoring system includes the monitoring of soil temperature at the electrode segments, dc currents through the current distribution cables to the electrode segments, dc currents through the electrode lines, and status of auxiliary power supply.

The need for continuous monitoring is greatest for the electrodes which are not designed for continuous operation at the maximum dc current and may be subject to thermal runaway (e.g. vertical and horizontal land electrodes). Continuous monitoring would allow greatest possible use of the inherent capability of such electrodes.

The monitoring infrastructure for land, beach and shore electrodes would be installed at the electrode sites.

Monitoring infrastructure for sea electrodes, if any, would be located at the submarine feeder cable landing sites. However, very little on line monitoring of the sea electrode condition may be possible especially if there is only a single submarine feeder cable. Thus, sea electrodes typically would not have any on-site monitoring.

7.4 FENCES, EQUIPMENT AND CONTROL BUILDINGS

Physical security perimeter and public safety dictate the need for access controls, site surveillance and other intrusion detection systems. Historically some of the electrode sites have been constructed without security fence and the equipment are installed at elevated heights or on poles similar to the pole mounted distribution switches with no active monitoring systems. The switch manual operators are locked and are operated under the supervision of an HVDC converter operator. Figure 7.4 shows the arrangement of electrode line termination on distribution poles.

A building or electrical equipment shelter (walk-in buildings) is required if the installation includes monitoring and supporting infrastructure that require protection from the elements, or when outdoor installation does not meet the utility operation and maintenance or security criteria. A typical building is shown in Figure 7.5. A building may require larger station service to support the building HVAC, lighting and auxiliary loads.

Figure 7.4 - Electrode Site without Fence and Electrode Switches Mounted on Distribution poles

Figure 7.5 - Electrode Site with Switches in a small fenced building (Itaipu land electrode)

The Utility operation and maintenance practices mainly dictate the installation for access to the facility, and isolation limits for outages and maintenance to align with corporate safety standards.

In some systems underground vaults were utilized for monitoring electronics with variable success due to environmental factors and very damp conditions associated with underground installations. In the USA, vault mounted electronics associated with the telecommunications (common carrier suppliers) have created environmental underground vaults (CEV) with HVAC control, and could be considered for this type of application as shown in Figure 7.6.

Figure 7.6 – Enclosure for vault-Mounted Electronics

8. TESTING AND COMMISSIONING

After the installation of the electrode commissioning tests should be performed to verify the electrode has been constructed in accordance with the design, and to evaluate the electrode performance and ensure it meets the specified criteria and requirements. The electrode station should also be inspected regularly, and after any extended operation in monopolar mode to ensure integrity as described in Section 5.3.2.

8.1 LAND ELECTRODE

The following measurements should be performed during the commissioning of land electrode to ensure that electrode can be successfully put into service.

a) Resistance to remote earth

b) Step and touch potentials

c) Current distribution between sub-electrodes

d) Check of any installed electrode line protections, and electrode monitoring and data acquisition system (temperature, moisture etc.)

e) Measurements of Interference with respect to outside facilities, e.g. transformer neutral currents, pipeline cathodic protection systems

8.1.1 Soil Temperature

The temperature of soil should be measured before and after the electrode is energized.

The soil temperature should be measured at different depths with respect to the location of the electrode. Figure 8.1 shows an example measurement at three depths, 0.5 m, 1.5 m and 2.5 m assuming electrode is located at 2.5m.

It is also recommended to measure the soil temperature over a long period equal to at least one thermal time constant or, if this is unreasonably long, for at least a week so that a measurable temperature rise can be documented and the thermal time constant benchmarked against the design. The measurements can be continuously over the entire period or several measurements can be taken at intervals until a trend can be established. If several measurements are going to be made, each measurement time shall be a day long with temperature sampled and recorded at every hour or two. The maximum and average temperate for each measurement period shall be documented and recorded.

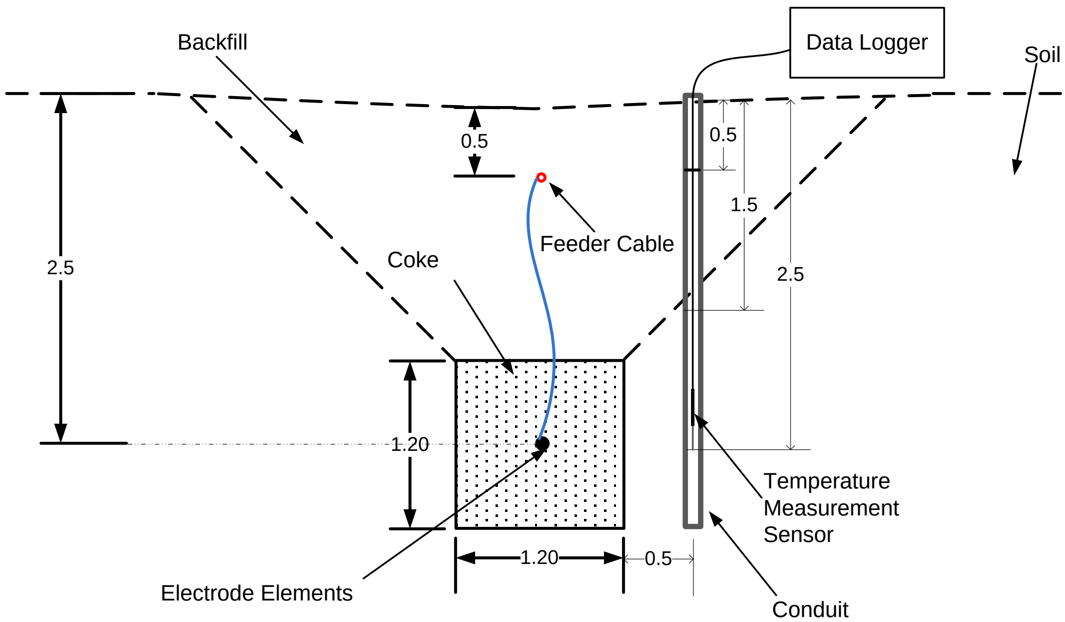


Figure 8.1 - Soil Temperature Measurement Diagram

Measurements should be taken from all of the temperature measurement locations that have been provided at the different locations on the electrode sites.

8.1.2 Soil Moisture

It is suggested to perform soil moisture measurements which shall include the measurement of depth of water level (table) and gravimetric moisture of soil as defined below during commissioning.

Water Level (Table):

The depth to the top of the saturated soil layer should be established for at least one point on the site,

Gravimetric Moisture: (the % of water present in a sample by weight)

$$\theta_{grav(dr)} = \frac{mass_{H_2O}}{mass_{dr}} \cdot 100 \tag{8.1-1}$$

Where:

$\theta_{grav(dr)}$ *is gravimetric moisture on a dry mass*
$mass_{H_2O}$ *is mass of water present in the soil sample*
$mass_{dr}$ *is mass of the dry soil sample*

$$\theta_{grav(wet)} = \frac{mass_{H_2O}}{mass_{wet}} \cdot 100 \tag{8.1-2}$$

Where:

$\theta_{grav(wet)}$ *is gravimetric moisture on a wet mass*
$mass_{H_2O}$ *is mass of water present in the soil sample*
$mass_{wet}$ *is wet mass of the soil sample*

Direct gravimetric measurement of free soil moisture requires removing, drying, and weighting of a sample and lab work which is not easy to incorporate in any measuring programme. It is suggested to use portable soil moisture sensors to measure the volumetric water content. Safety precaution should be taken since the GRP is higher near the electrode.

The soil moisture should be measured at the same depth and locations as for the soil temperature measurement, before and after the electrode is energized.

The decrease of the humidity may take weeks or months when the electrode is in continuous operation. The measuring should be done at regular intervals, in the beginning once a week and later on with longer intervals, depending on the tendency of the moisture content. The data log sheet should record the date/time of the measurement, measured soil moisture and the electrode loading (current) and measurement location.

8.1.3 Resistance Measurements

The resistance to remote earth can be measured without the electrode being in service as follows in accordance with IEEE 81[78], the fall of potential method:

a) Inject a current of maximum 100A to electrode A (Electrode being tested) as show in Figure 8.2 and to a remote current electrode B. Electrode B should be placed far away from the tested object
b) Measure the current between A and B.
c) Measure the potential between the electrode being tested A and the remote potential electrode C.

Move the potential electrode C away from the ground electrode in steps of minimum 50m.

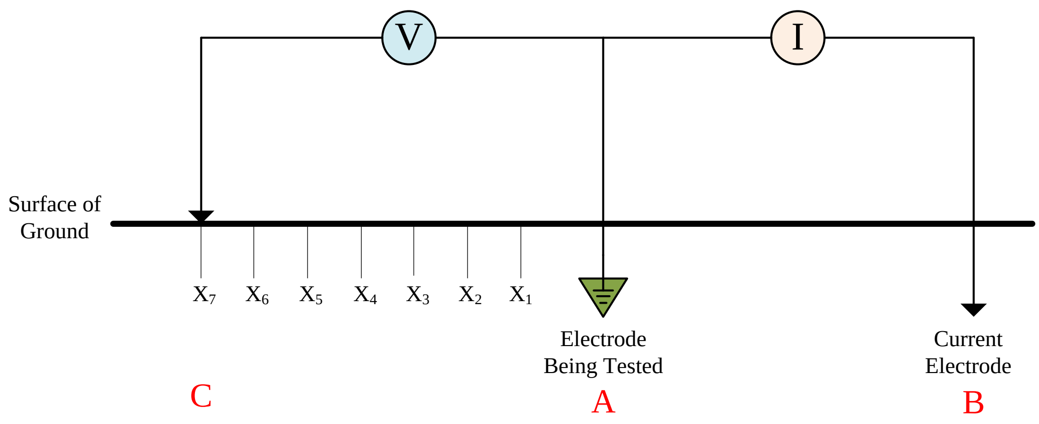


Figure 8.2 - Measurement of resistance to remote earth

A value of impedance is obtained at each step. This impedance is plotted as a function of distance, and the value in ohms at which this plotted curve appears to level out is taken as impedance value of the ground electrode. See Figure 8.3.

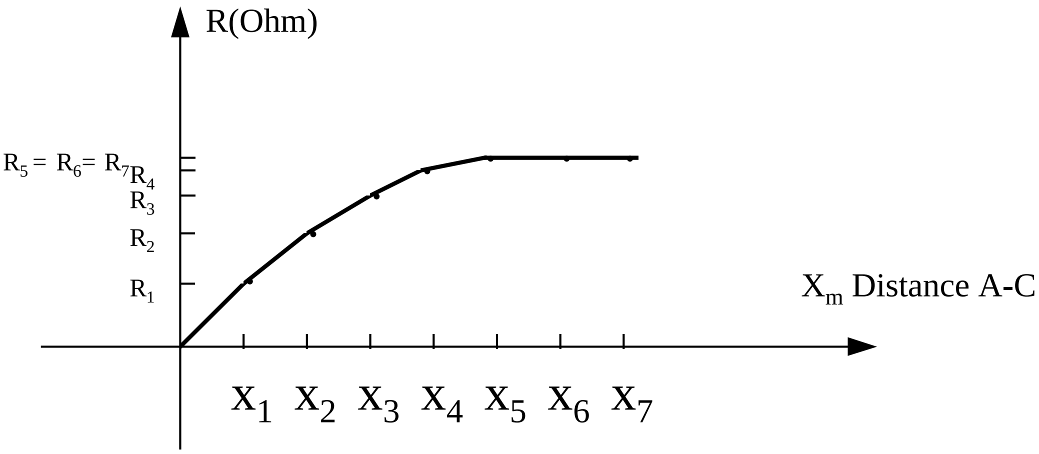


Figure 8.3 - Impedance as a function of distance

To get a good result without any influence between the potentials from the current electrodes, the angle between the current injection line and the potential conductor should be 90-180 degrees as shown in Figure 8.4.

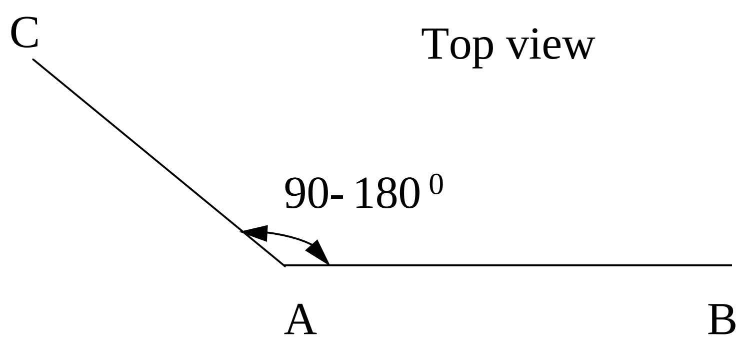


Figure 8.4 - Angle between current line and potential conductor

To avoid the polarization effects of the soil and spontaneous potentials in the ground, the current must be reversed during the measurement in the following steps. The duration of the reversed current should be a few minutes as indicated in Figure 8.5.

Step 1) Read the potential (U_1) when 100A current is switched on,

Step 2) Switched off the current and read potential (U_2) within 10 seconds from current is switched off or as fast as the potential has stabilized

Step 3) Calculate the real potential using U_1-U_2.

Step 4) Repeat this measurement with shifted polarity.

If no current reversal equipment is available, then a test with manually reversed current should be performed.

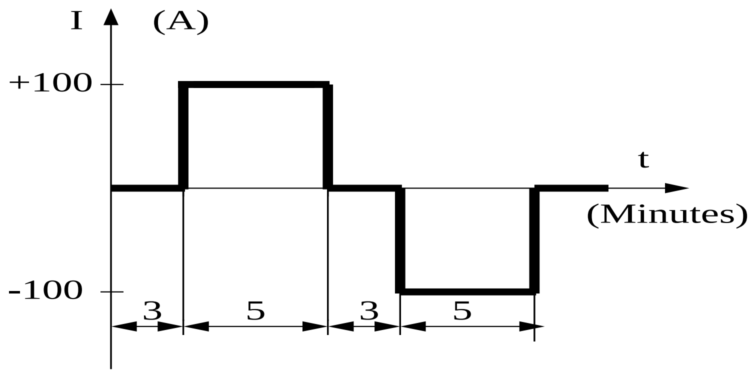


Figure 8.5

8.1.4 Sub Electrode Resistance

Resistance of sub-electrode can be measured similarly to the electrode as described in Section 8.1.3 except that the current source is connected to only one of the sub electrodes and to the remote current electrode. The current should be reduced to approximate 20A. The measurements are to be done without the electrode being in service.

8.1.5 Current Distribution Measurements

8.1.5.1 Temporary Arrangements

To complete the test circuit a remote electrode and a suitable dc current supply capable of substantial output current needs to be arranged.

The remote electrode should be placed at a distance of at least 6.5 times the extent (diameter or length) of the HVDC electrode.

The electrode line or transmission line should be used as remote electrode line if possible. At the end of the line or at distance of 6.5 times the electrode length, the line should be grounded to a tower or to a ground rod.

An appropriate site for the remote ground and the cable raceway for electrode line must be considered in an early stage.

8.1.5.2 Current Distribution

The current distribution in the sub electrodes should be measured to verify that unbalance is within acceptable limits. The measurement should be performed both for low current and high current.

a) Low current

For the first measurement, a current of maximum 100A should be induced between the electrode and the remote ground. If a station ground grid is used as remote ground, the maximum current should be 20A.

Measured currents shall include:

i) The total current in the electrode.

ii) The current in each sub-electrode.

b) High current

The measurement should later be performed with a higher current from the converter. Measure the current through each sub-electrode.

It may be difficult to judge whether a certain degree of unbalance is acceptable or not. In general, if all sub electrodes are equally sized, are in similar soil and are arranged in a geometrically symmetrical fashion the degree of unbalance (I_{max}/I_{avg} or I_{min}/I_{avg}) should not exceed about 20%.

However, if the sub-electrodes are not substantially identical and arranged in a symmetrical configuration or the conditions under which sub-electrodes are installed are not equal larger variations may exist and may be considered normal. Current unbalance may vary with time as soil moisture levels change due seasonal variations.

The ultimate test to determine whether a sub-electrode is carrying too much current would be to monitor it during a long period of high current operation. The current level is too high and steps should be taken to reduce the current by adding an external resistance if any of the following are true:

a) The safety criteria are being violated near the sub-electrode.
b) The temperature is rising faster than other sub electrodes.
c) The moisture levels near the sub electrode are declining consistent with electro-osmosis.

8.1.6 Potential and Gradient Measurements

Test should be carried out for the step potentials and touch potentials.

8.1.6.1 Step Voltage

Step voltage should be measured as follows:

a) Connect a current of maximum 100A to the electrode being tested and to a remote current electrode. The remote electrode should be placed away from the tested electrode. A switched current like in Figure 8.5 should be used. The cycle period can however be shorter.

b) Place two electrodes copper plates or copper-copper sulfate on the surface of earth 1m apart. Two rods driven down 200mm deep in the ground can also be used. Make sure that the probes/rods are in contact with the earth by wetting the earth where the probes/rods should be placed.

c) Measure the potential between the two electrodes/rods with and without a resistor of 1kΩ in parallel. The measurement should be carried out in one-meter interval from the center of the buried electrode area in several radial directions.

The measurement should be made to a distance from the center of the electrode area equal to at least the periphery of the electrode (r) plus twice the buried depth (h) of the electrode (r + 2h). The maximum voltage gradient will occur at a distance from the periphery of the electrode equal to the depth divided by $\sqrt{2}$ of the electrode burial depth.

8.1.6.2 Touch Potentials

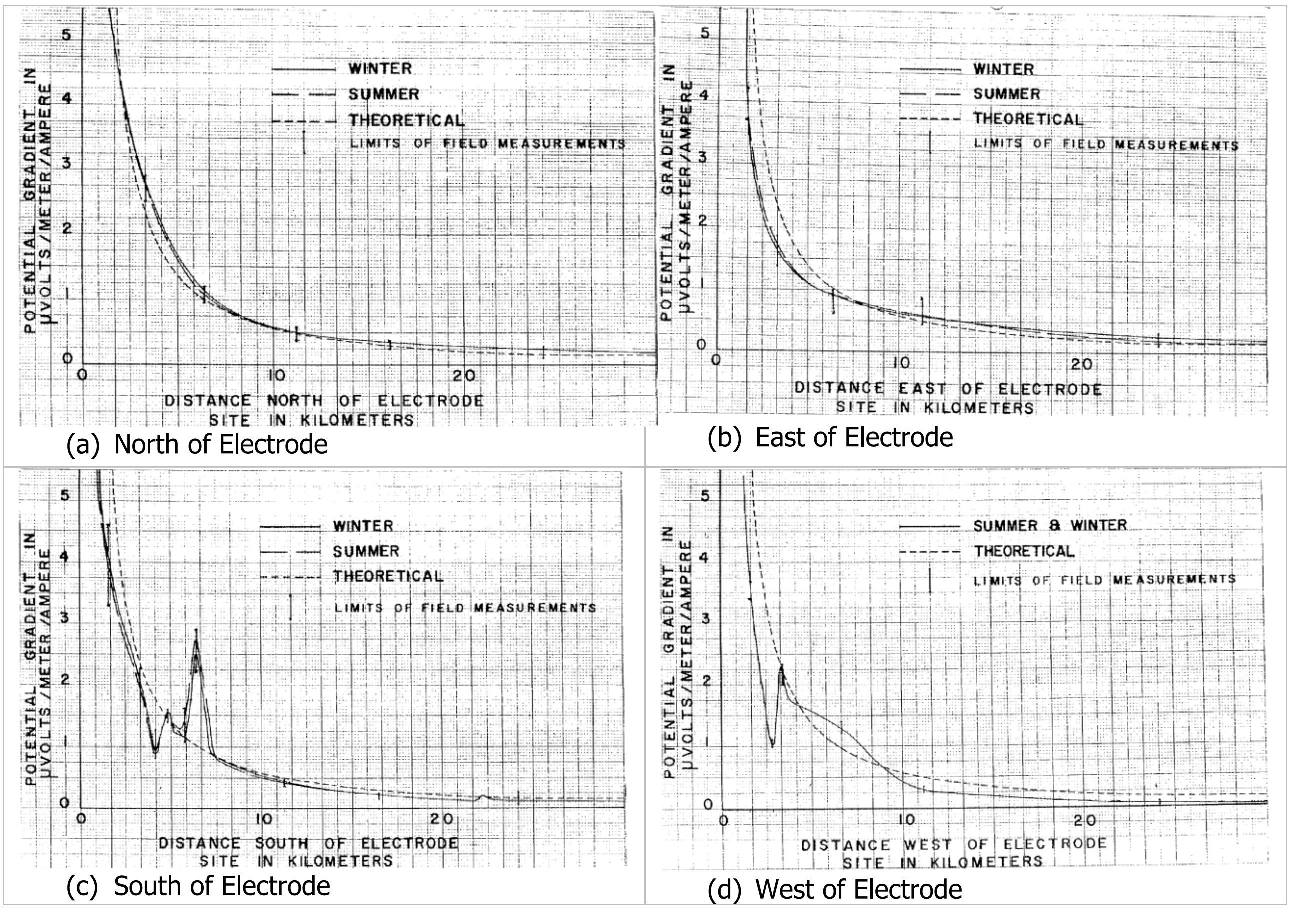
The touch potential measurement in this instruction covers only the touch potential around the electrode without grounding grid. Touch potential shall be measured as follows:

a) Connect a current of maximum 100A between the electrode being tested and a remote current electrode. The remote electrode should be placed away from the electrode. Measure the current.

b) Measure the potential between the metal plates and the peak electrode, which is in contact with the test object, with and without 1kΩ resistor. The horizontal distance between the peak electrode and the metal plates should be 1m. The plates should rest on the ground and with a minimum force of 500 N. The peak electrode imitates the hand, and electrode is a sharp pin that penetrates through layers of paint and rust.

The touch voltage should be carried out on metallic structures, fences, towers etc. close to the electrode, long objects such as pipes, and cables in contact with the ground some kilometers from the electrode.

Figure 8.6 shows the results of field measurements of potential gradient associated with one of Manitob Hydro's Nelson river HVDC electrodes.



(a) North of Electrode

(b) East of Electrode

(c) South of Electrode

(d) West of Electrode

Figure 8.6 – Potential Gradient Measurement (Manitoba Nelson River HVDC Electrode) [79]

8.1.7 Test of Data Acquisition System

If the electrode is equipped with a data acquisition system, the system should be tested for proper operation.

8.1.8 DC Current in Converter or Power Transformer Neutrals

Measure the dc-current in the transformer neutral. This will be performed during the commissioning after detailed design and calculation of the electric field.

8.2 SEA ELECTRODES

For sea electrodes, the following design verification measurements should be carried out:

a) Electrode resistance to remote earth
b) Electrode potential rise
c) Current distribution in sub-electrodes
d) Potential gradients in water

8.3 SHORELINE POND ELECTRODES

For pond electrodes, the following design verification measurements should be carried out:

a) Electrode resistance to remote earth
b) Electrode potential rise
c) Current distribution in sub-electrodes
d) Step and touch potentials on land

e) Potential gradients in water outside the breakwater
f) Observations of gas evolution near the elements
g) Observations of water temperature in the pond

8.4 SHORELINE BEACH ELECTRODES

For beach electrodes, the following electrode design verification measurements should be carried out:

a) Electrode resistance to remote earth
b) Electrode potential rise
c) Current distribution in sub-electrodes
d) Step and touch potentials on land near the wells
e) Potential gradients in water near the wells especially near wells carrying the most current.

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