ELECTRIC POWER RESEARCH INSTITUTE

HVDC Ground Electrode Overview

1020116

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Technical Update, November 2010

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ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

HVDC Ground Electrode Overview. EPRI, Palo Alto, CA: 2010. 1020116.

ABSTRACT

High-voltage direct current (HVDC) transmission has been used to transmit power in bipolar, monopolar, and back-to-back applications for the past sixty years. An electrode is typically required in the case of bipolar and monopolar HVDC. The alternative to an electrode is the use of a dedicated metallic return. HVDC systems utilizing electrodes have been successfully designed and put into commercial operation. Some of the earlier HVDC systems utilizing electrodes have been operated for extended periods using the electrode return with no adverse effects. However, in recent years, operators have raised concerns regarding the operation of electrodes. This report is intended for system planners and HVDC system designers and operators. It reviews the latest techniques in establishing a ground electrode, the environmental constraints and regulations in establishing ground electrodes, challenges and advantages of land and ocean termination, condition assessment, and future research required in the area of HVDC electrodes.

Keywords
HVDC
Converter stations
Ground electrodes
Sea electrodes
Electrode lines
Ground return
Sea return
Metallic return

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OVERVIEW

Introduction

At present, HVDC transmission is a mature technology that has been utilized to transfer bulk power over long distances. HVDC systems can designed to be back to back, monopolar, or bipolar in configuration. Back-to-back HVDC systems are not considered in this report, because ground electrodes are not needed in their application. Typically, HVDC cable transmission systems utilize monopolar configuration, and overhead transmission line systems utilize bipolar configuration—although there are exceptions.

The most cost-effective way of designing a monopolar HVDC system is to construct it with a high-voltage conductor and an earth return or sea return, depending on the application. In such a system, the dc current path is through the high-voltage conductor, and the return path is through the earth or sea. In monopolar HVDC links, an electrode connection is required at each terminal. The electrode either carries dc current into the earth or receives dc current from the earth, so in principle, the earth is utilized as the current return path for the dc current. If earth or sea return is not desired or acceptable, then a metallic conductor dedicated for current return referred to as a "metallic return" is implemented.

Current return through the earth saves the extra cost of the metallic return and reduces the power losses as a result of the smaller ground resistance path when compared to the resistance of the metallic return. The cost of adding an extra conductor for metallic return in the case of an overhead line differs from the cost of adding a dedicated metallic return cable for monopolar cable applications. The cost impact for each case needs to be evaluated during the planning phase of the project.

In the normal operation of a bipolar HVDC transmission system, currents in the positive and negative poles are equal and in opposite directions, therefore current between converter stations is essentially zero and practically limited to the tolerances in the control and measuring systems of the two poles, typically in the range of 10 amperes. During single-pole operation, earth return could be utilized, or the conductor of the out-of-service pole can be utilized as a metallic return for the return current. However, to ensure uninterrupted power transfer in one pole during a sudden block or trip in the other pole, a bipolar system should be equipped with an earth electrode or a dedicated metallic return.

Earth electrodes perform an important function for either monopolar or bipolar HVDC systems. Almost 30 years ago, EPRI produced a detailed design manual [1] for high-voltage direct current (HVDC) earth electrodes. Since then, changes and improvements have been made in earth electrode design and operation. This report provides an overview of HVDC ground electrodes including the following specific topics related to design and operation of ground electrodes.

- Latest ground electrode techniques
- Environmental constraints and applicable regulations for ground electrode operation

- Challenges and advantages of ground electrode land and ocean termination
- Condition assessment of ground electrodes

Converter Configurations

Monopolar HVDC System Configurations

Monopole with Electrode Return

A monopole system with earth electrodes is shown in Figure 1-1. In this configuration, there is only one high-voltage conductor, and the current return path is through the electrodes. However, this configuration may not be acceptable in some situations due to environmental concerns. This configuration has been applied in some older cable systems.

Figure 1-1
Monopolar HVDC with Earth Return

Monopole with a Dedicated Metallic Return

This type of system avoids the concerns raised due to permanent earth electrode current. In this case a second conductor of the same current rating of the main conductor but with a much lower dc voltage rating is needed as shown in Figure 1-2.

Figure 1-2
Monopolar HVDC with Dedicated Metallic Return

Bi-polar HVDC System Configurations

1. In a bipolar HVDC system, there are two poles of opposite polarity, and the typical operation mode is with equal current between the two poles, which means no current will flow in the electrodes, as shown in Figure 1-3.

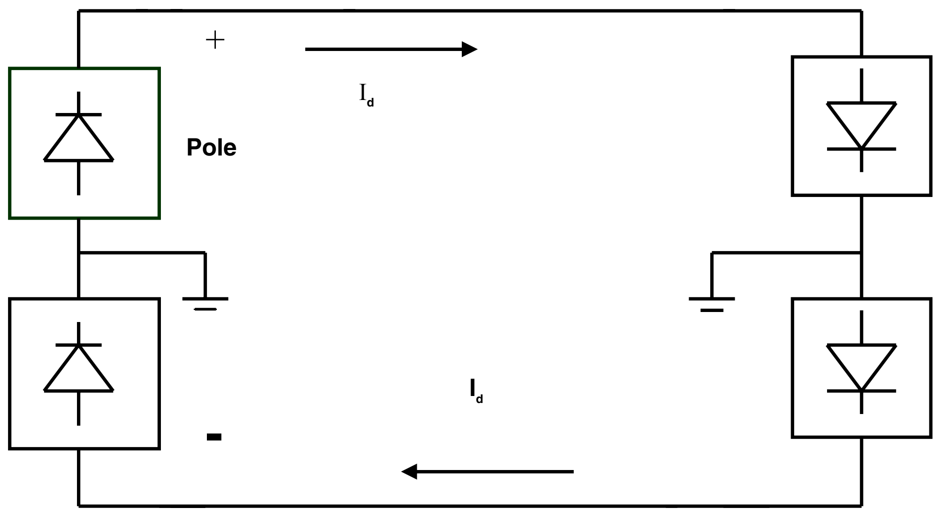

Figure 1-3
Bipolar HVDC System with Ground Electrodes

2. In the event that one pole is out of service, the operation of the second pole can continue either using the electrode as a return current path, or by using the metallic conductor of the out-of-service pole as a return path, which is referred to as metallic return operation. The metallic return operation is the preferred mode of monopolar operation, because no current will then be carried by the earth electrode.
3. Shown in Figure 1-4 is the starting point of a bipolar system with balanced current operation. Any current in the electrodes would be due to a very small amount of unbalance between the two poles. Note that the circuit breakers shown in red are closed.

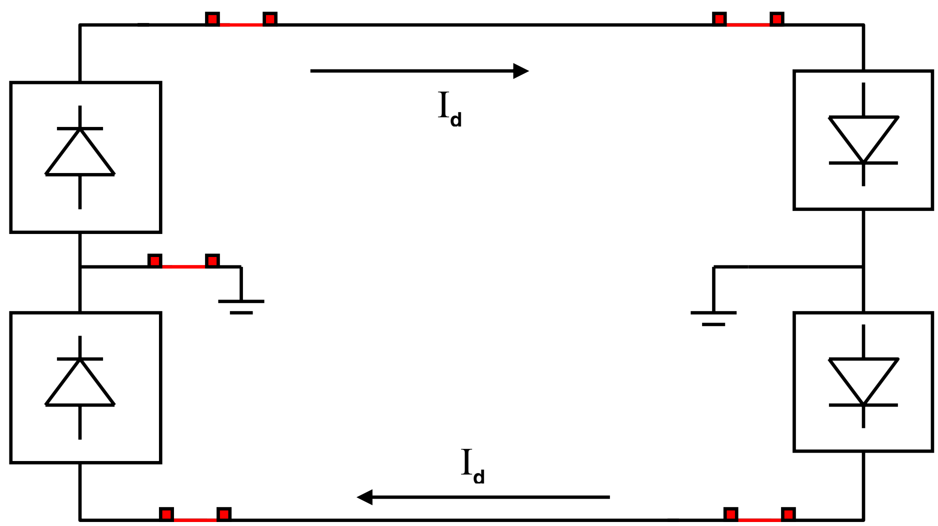

Figure 1-4
Bipolar System with Balanced Current Operation

Figure 1-5 shows the same system with one pole taken out of service, while the remaining pole continues its operation with the full dc current flowing in the electrodes.

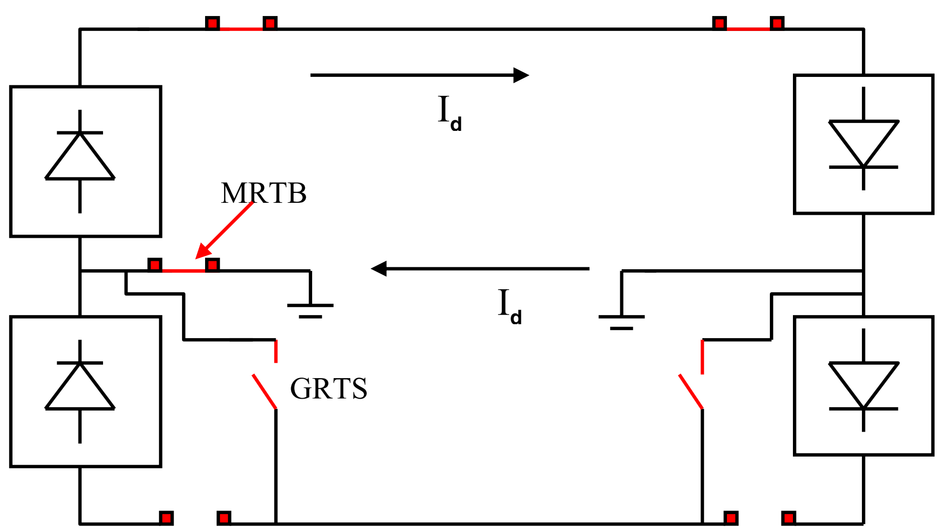

Figure 1-5
Monopolar Operation Using Ground Return

4. The Ground Return Transfer Switch (GRTS) is then closed; this then connects the metallic return in parallel with the electrode path, as shown in Figure 1-6..

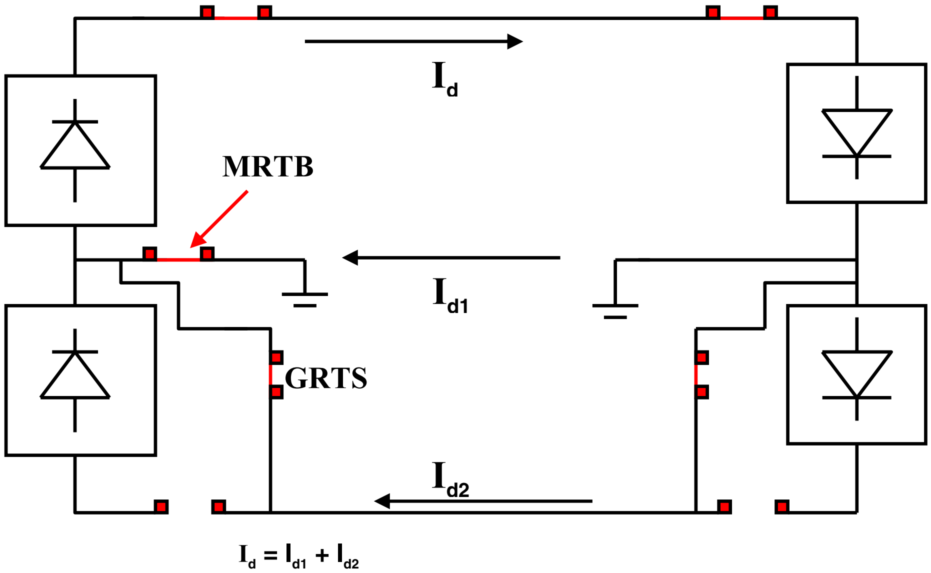

Figure 1-6
Monopolar Operation Using Ground Return and Metallic Return

5. The next step is to open the Metallic Return Transfer Breaker (MRTB) and complete the transfer of current from the electrodes to the metallic path, completing the process as shown in Figure 1-7.

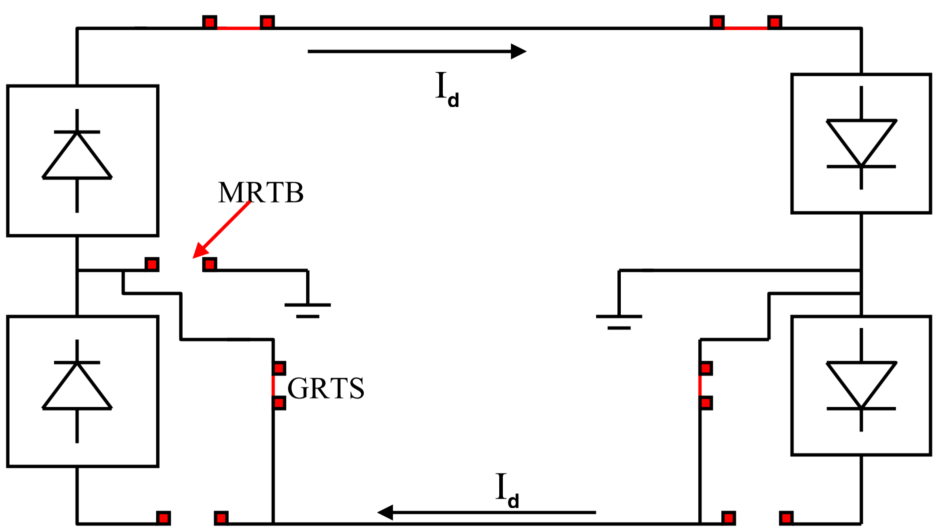

Figure 1-7
Monopolar Operation Using Only Metallic Return

The MRTB is a special commutating breaker that can force the current from the electrodes to the metallic return (see Figure 1-8).

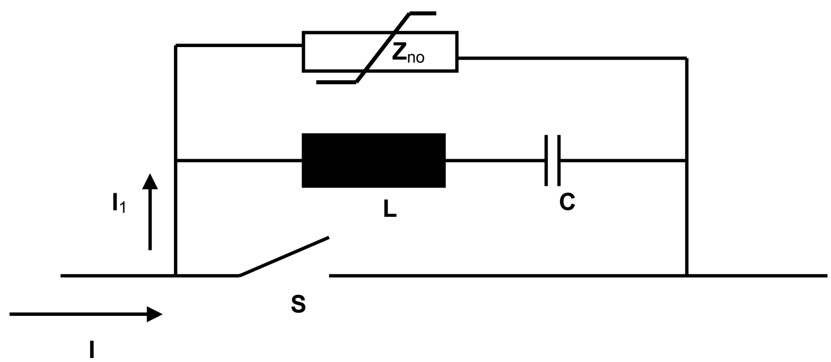

Figure 1-8
Components of MRTB

Operation of the MRTB is as follows:

1. As the contact S opens, and develops an arc voltage, it generates an oscillation in the circuit L, C, and S at the natural frequency of the loop, which is known and is part of the design.
2. As the current in S decreases by being shunted to the L and C branch, the arc voltage of S increases due to its negative current voltage characteristic.
3. A current oscillation is set in L and C, which grows in magnitude with time until its magnitude equals the current to be interrupted, creating a current zero in S, and allowing it to extinguish and recover.

Electrode Rating

Existing electrodes in various parts of the world are rated between 800 A and 4000 A [2, 3]. However, there is no definition available for the current rating of the electrode. Depending on the requirements, the electrode rating could either be:

- the maximum current that the electrode could handle under various operating scenarios, or
- the continuous rating of the electrode, so that maximum current for temporary overload could be higher than the rating.

Reversible Electrodes

Current transfer in a monopolar system is generally in one direction. Therefore, the electrode that injects current into the earth (anode electrode) and the electrode that collects current from earth (cathode electrode) are fixed.

Current transfer in a bipolar system is also in one direction. However, when a bipolar system operates in monopolar mode, the electrode that injects current into the earth and the electrode that collects current from the earth depend on whether the positive pole or the negative pole is in-service. Electrodes connected to bipolar systems should be able perform as an anode as well as a cathode depending on the polarity of the out-of-service pole. Electrodes that could perform as an anode or cathode are referred to as reversible electrodes.

Electrode Line and Reliability Consideration

A survey on existing earth electrodes shows that the length of electrode lines varies from 8 km to 85 km [3]. The lower limit of the length of electrode line is dictated by the influence of the electrode electric field on the ac grid at the converter station and the upper limit of the length of the electrode line is influenced by many factors, including finding a suitable area with low resistivity, proximity to infrastructure such as the ac grid and other metallic structures, and the availability of suitable land sites. Figure 1-9 shows a bipolar system in steady-state operation with equal dc currents in the two poles. The current flow into the electrode line at steady state is essentially zero and practically limited to the tolerances in the control and measuring systems of the two poles, typically in the range of 10 amperes. Upon the failure of the electrode line (open circuit) during bipolar operation, the system can continue operating with the converter station high-speed neutral bus ground switch (NBGS) closed. Operation with the station ground mat is shown in Figure 1-10. This mode of operation can continue until any event that leads to the loss of a pole takes place. Under this condition, the healthy pole must be removed from service to avoid any dc currents in the station ground mat. Electrode lines are generally reliable and designed with two separate conductors in order to avoid this situation.

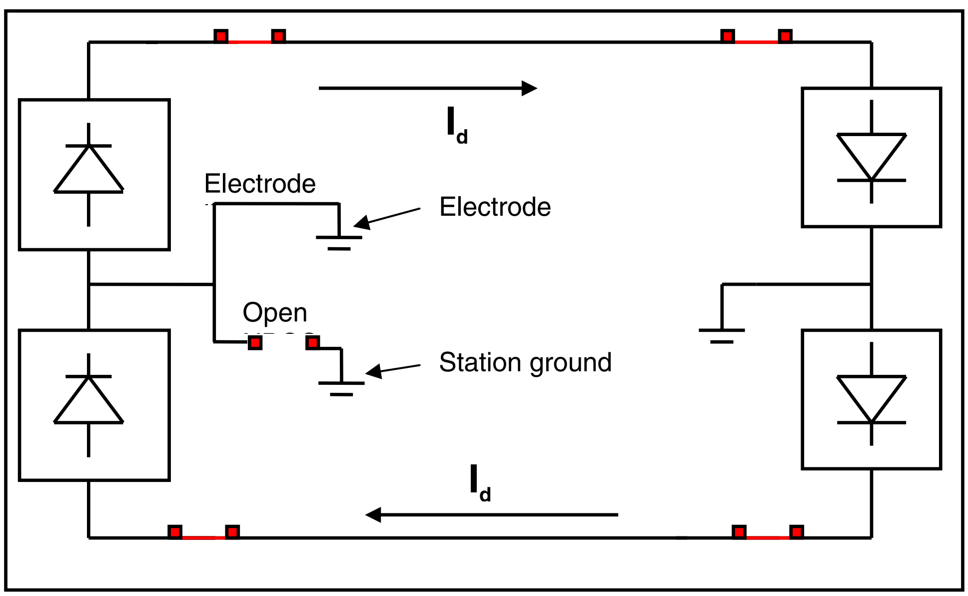

Figure 1-9
Bipolar System in Steady-state Operation with Healthy Electrode Line

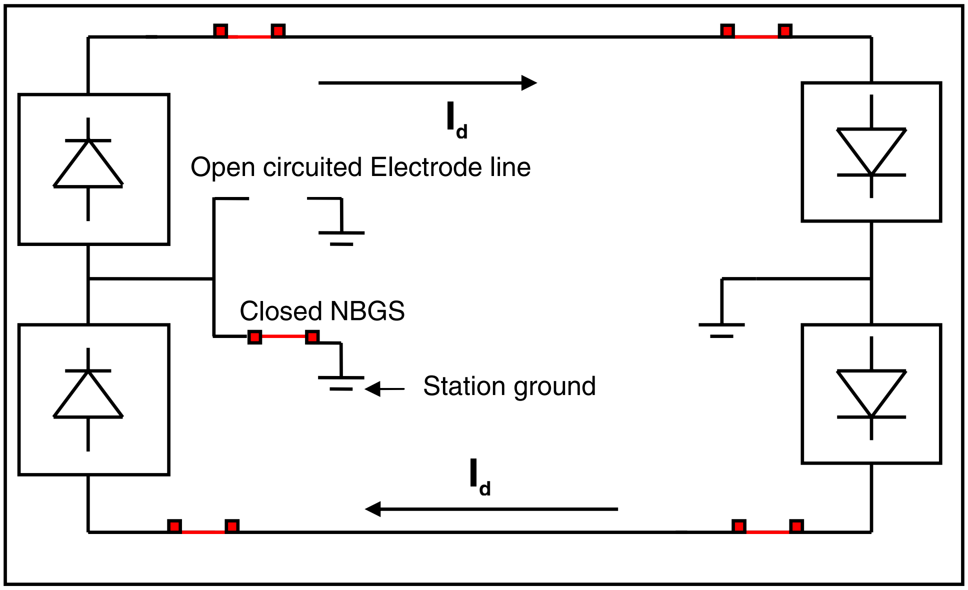

Figure 1-10
Bipolar System in Steady-state Operation with Broken Electrode Line

Electrode Classification

Electrode stations can be categorized into three categories based on the location of the electrode as shown in Table 1-1.

Table 1-1
Classification of Electrodes Based on Location 7

Type of Electrode	Description
Land Electrode	Located on the land away from the sea or freshwater lakes
Shore Electrode	Located on a shore against (salt) seawater. Shore electrodes can be located either on the beach without direct contact with seawater at a short distance (< 50 m) from the waterline or in the water, but protected by a breakwater
Sea Electrode	Located (typically on the seabed) in the water at some distance (> 100 m) from the coastline

Current Blocking Devices

DC currents between ground electrodes cause potential gradients on the surface of the earth. As a result of these earth potential gradients, dc currents may enter the neutrals of transformers. Current in transformer neutrals will lead to core saturation and may also cause corrosion. Such dc currents must be minimized or eliminated. Transformer neutral blocking devices can be applied, as shown in Figure 1-11; however, these solutions can be expensive depending on the number of transformers involved.

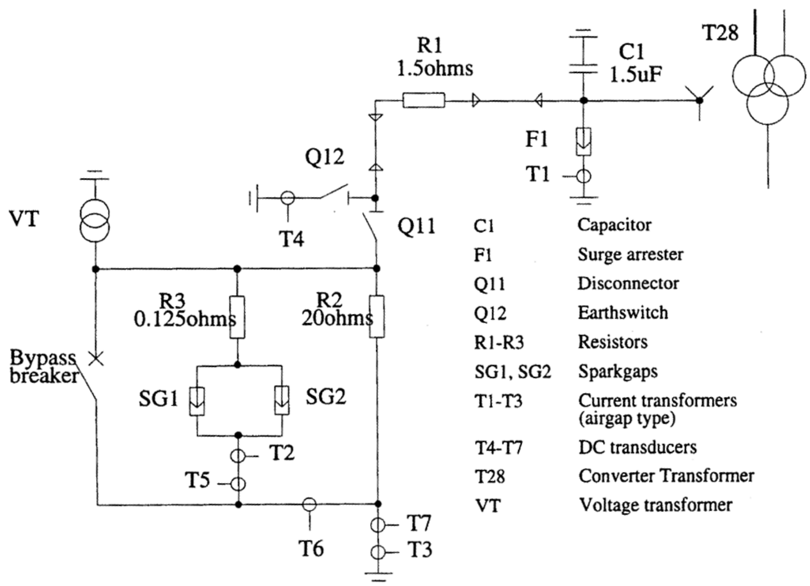

Figure 1-11
Schematic of Diagram of Transformer Neutral Blocking Device [9]

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2
LATEST HVDC GROUND ELECTRODE TECHNOLOGIES

Introduction

The technology employed for ground electrodes has not changed much during the last 30 years. However, there are advancements in measuring parameters such as ground resistivity and finite element modelling of effects due to the electrode operation. This section provides an overview of the state-of-the-art of ground electrode technology as applied today.

Advancement in Present Ground Electrode Technologies

Electrical Resistivity and Electric Field Calculation

The selection of a proper ground electrode site is of paramount importance for the reliable operation of HVDC systems. A properly selected ground electrode site can not only ensure smooth system operation but also rule out the need for mitigation measures against adverse ground current effects. It is prudent to carry out a thorough soil investigation at the proposed location. For such investigations, it is practical for the power utility to make use of the experience of other organizations / research institutes involved in geological explorations such as oil and gas exploration companies and other organizations involved in geophysical research and mapping.

In selecting a particular site, the utility should perform geographical and geophysical surveys that consider various factors, namely

- Electrical resistivity of earth and water
- Thermal properties such as thermal conductivity and thermal capacity
- Porosity (water and gas permeability)
- Penetration of moisture and influx of water
- Buried and earthed metallic structures within the area of influence
- Electrical infrastructure within the area of influence
- Environmental/land use/landowner considerations
- Accessibility

The current practices of geographical and geophysical surveys are discussed in detail in the EPRI ground electrode design manual [1]. This section highlights several technological advancements in the area of electrical resistivity measurements and electrical field calculations.

Low surface electrical resistivity in the local electrode area (i.e., earth or seabed and sea) is important in order to keep the step-and-touch voltage in the close vicinity of the electrode within safe limits. The deep earth layers in a larger area are more important in reducing the electrical field distribution, which in turn, keeps the voltage gradient in the general area of ground electrode within acceptable limits. A low-voltage gradient ensures that the ground current does not cause corrosion of buried metal structures and does not enter the neutrals of transformers installed in the area of the electrode station. For this reason and also to optimize the cost of the ground electrode, it is important to know the electrical resistivity of the earth up to a depth of 20 km, covering an area with a radius of 10- 20 km from the ground electrode site.

Galvanic and inductive methods have been used to estimate the ground resistivity since the early days of the ground electrode design [1, 2]. The modern versions of these techniques are:

1. High-resolution multielectrode DC resistivity imaging techniques suitable for shallow resistivity measurements
2. Magnetotelluric techniques suitable for deep resistivity measurements. These methods were used in recently completed projects [3, 4].

High-resolution Multielectrode DC Resistivity Imaging Techniques

The high-resolution multielectrode DC resistivity imaging method is an active source method and provides high-resolution images of the electrical resistivity structure up to depths of several hundreds of meters. Obtaining the resistivity structure up to few kilometers using this method is possible, but typically not used, because the large amount of current that needs to be injected into the ground, employing large electrode separations, is unrealistic. Multielectrode DC resistivity imaging is a fully automated technique that uses a linear array of multiple current and potential electrodes connected to a multicore cable. The current and potential electrodes are organized according to a preprogrammed electrode array configuration. A sequence of measurements of potential difference are measured and recorded for a number of ordered combinations of current electrodes injecting a preprogrammed amount of current. Commercially available software is used to process these measurements into an image of ground resistivity-depth profile.

High-resolution multielectrode DC resistivity imaging methods can also be used for shallow resistivity measurements [3]. One candidate electrode site occupying an area of approximately 600 meters by 600 meters was covered with seven multielectrode DC profiles at 100 meters separation to image the shallow structure up to a depth of 150 meters. A multielectrode resistivity imaging system with 80 electrodes at 10-meter intervals was used, and this setup gave a total profile length of 790 meters and a penetration depth of more than 120 meters. A typical resistivity image of shallow ground obtained during the data processing is shown in Figure 2-1. In these measurements, a Wenner-Schlumberger configuration was employed.

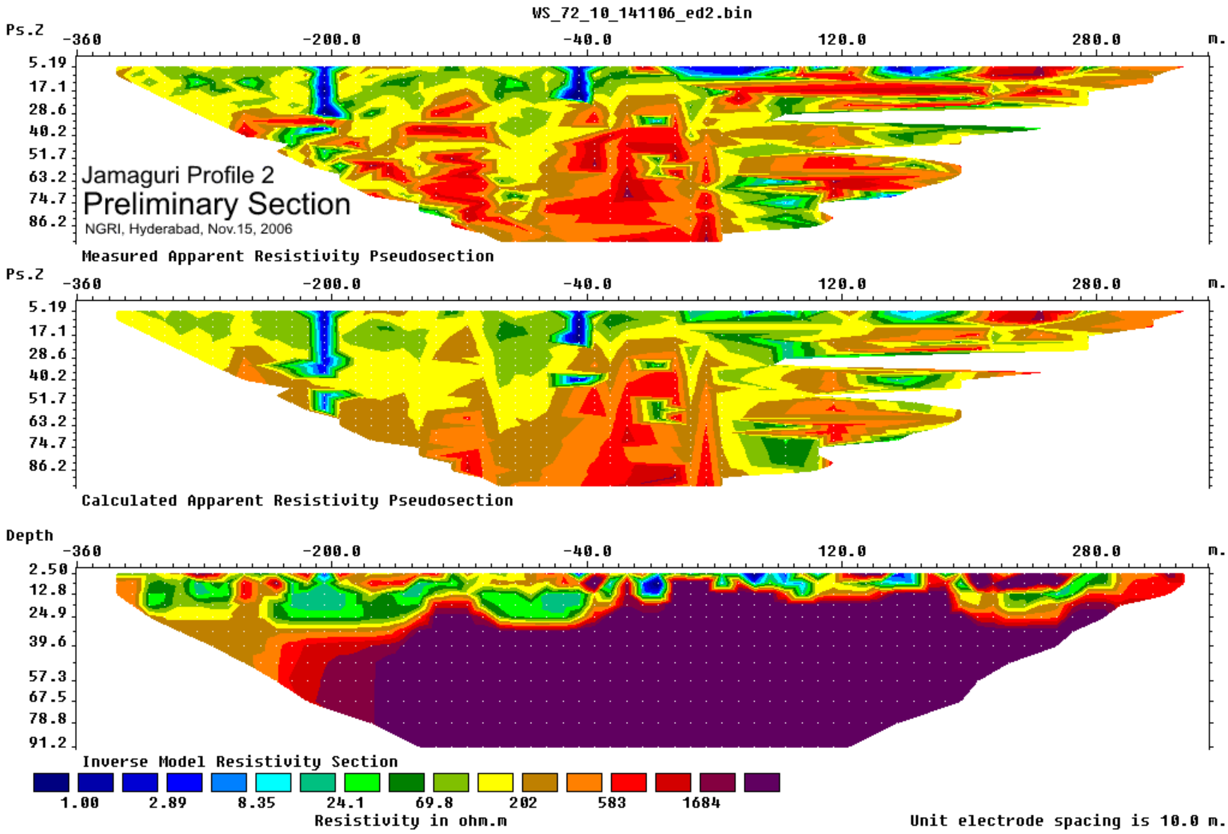

Figure 2-1
Typical Resistivity Image Obtained from High-resolution Multielectrode DC Resistivity Imaging Method [3]

Magnetotelluric Technique

The magnetotelluric (MT) technique is also a fully automated technique. Two basic types of MT methods available for deep resistivity measurements are natural source MT and controlled source MT.

In the natural source MT technique, natural electromagnetic (EM) waves are used to determine the earth's electrical resistivity structure from a few hundred meters to several hundred kilometers deep, depending on the frequency of the signal. These natural sources are mainly located in the magnetosphere and ionosphere, separated from the earth's surface by the nonconductive atmosphere. Because the earth is a conductor, these natural sources induce secondary fields in the earth.

In the controlled source MT technique, a current source of variable frequency is used to inject the current into the ground. Depending on the frequency of the injected current, different depths of penetration of the current into the earth takes place. The basis for the MT theory is provided by Maxwell's equations, which relate electrical and magnetic fields. The deep resistivity structure is determined by measuring five components of time series data consisting of three magnetic field and two electric field components [3].

Deep resistivity investigations were carried out using wide-band natural source MT equipment in India [3]. This equipment consisted of a six-channel data acquisition unit, three highly sensitive magnetic induction coils, and a GPS module. Commercially available software was used to analyze the time series data and generate an image of the ground resistivity depth profile. In one candidate site, an area with a 10 km radius from the earth electrode site is covered by about 13 MT measurements, each with a time series recording of one day to achieve the desired depth of investigation, assuming moderately conducting ground conditions. This was done to ensure that resistivity data of up to a 5-second period with a good signal/noise ratio is obtained. A typical resistivity image of deep ground obtained during the data processing is shown in Figure 2-2.

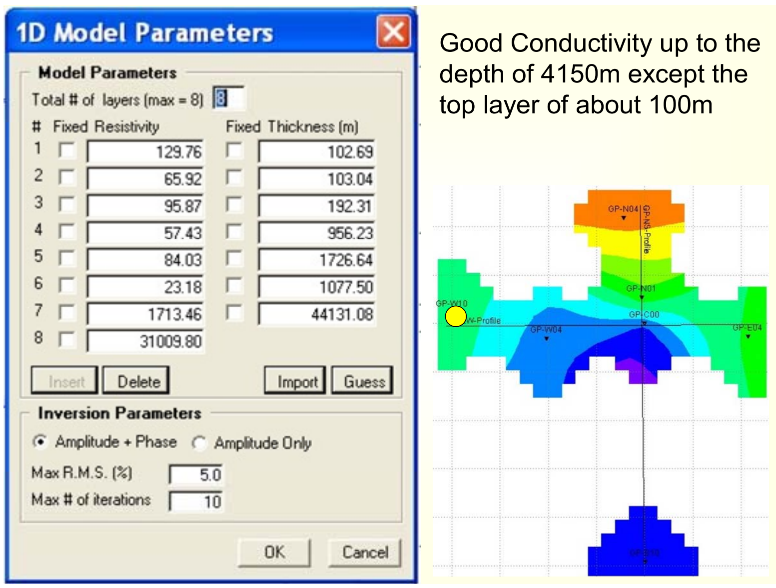

Figure 2-2
Typical Deep Earth Resistivity Image Obtained from MT Resistivity Imaging Method [3]

The ground electrode site selection process for the Caprivi Link in Namibia [4] also employed the multielectrode DC resistivity imaging technique for shallow earth resistivity imaging and the MT technique for deep resistivity imaging. The three-dimensional cube shown in Figure 2-3 represents a 27 x 27 x 20 km earth resistivity model developed for the electrode site.

Once the ground resistivity data is available, as shown in Figure 2-3, commercially available finite element programs could be employed to estimate the potential distribution in the area of the ground electrode station due to the dc current injected/received at the electrode station.

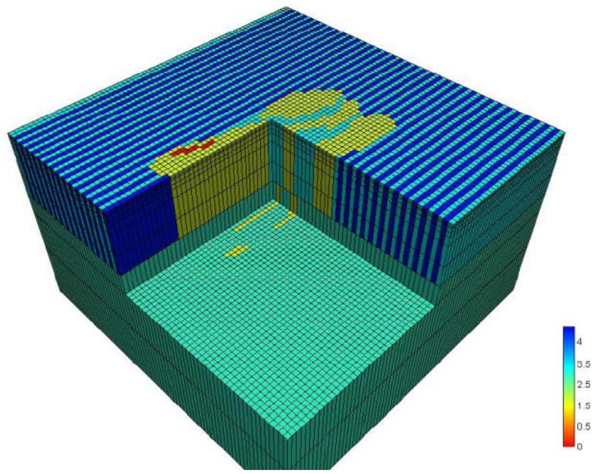

Figure 2-3
Example of Three-dimensional Earth Resistivity Model That Was Employed to Estimate Potential Distribution due to the Earth Electrode in the Area. The Color Scale Shows the Logarithm of Resistivity in Units of Ωm [4]

Figure 2-4 depicts the iso-potential contours for a current injection of 1000 amperes at the ground electrode [4].

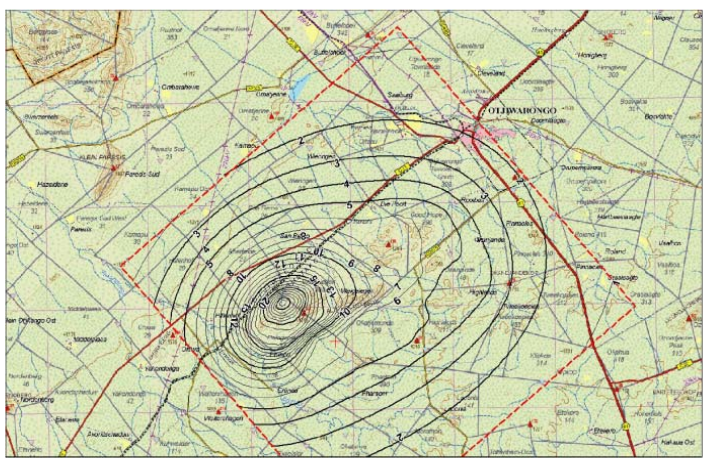

Figure 2-4
Contours of Potential Distribution Estimated for a 1000 Amperes of Hypothetical Current Injection at the Ground Electrode Station Using Three-dimensional Resistivity Model [4]

Finite Element Modeling Software Programs

Modern software programs such as the Current Distribution Electromagnetic Interference Ground and Soil Structure Analysis (CDEGS) program [5, 16] have interfaces to accept field measurements of resistivity data or resistivity models compiled by other software programs. Once the resistivity model is available, a three-dimensional finite element model of the electrical and magnetic field is developed. Quantities such as electric and magnetic field strengths, as well as step-and-touch potentials required for electrode design, could be obtained from these programs. Additionally, modules are also available for electrode size optimizations.

In addition to estimating the resistivity profile and electromagnetic field distribution, software programs are utilized to calculate chlorine distribution caused by a sea or beach electrode. Figure 2-5 shows the predicted chlorine concentration distribution for an upgraded SACOI beach electrode at Punta Tramontana, Italy.

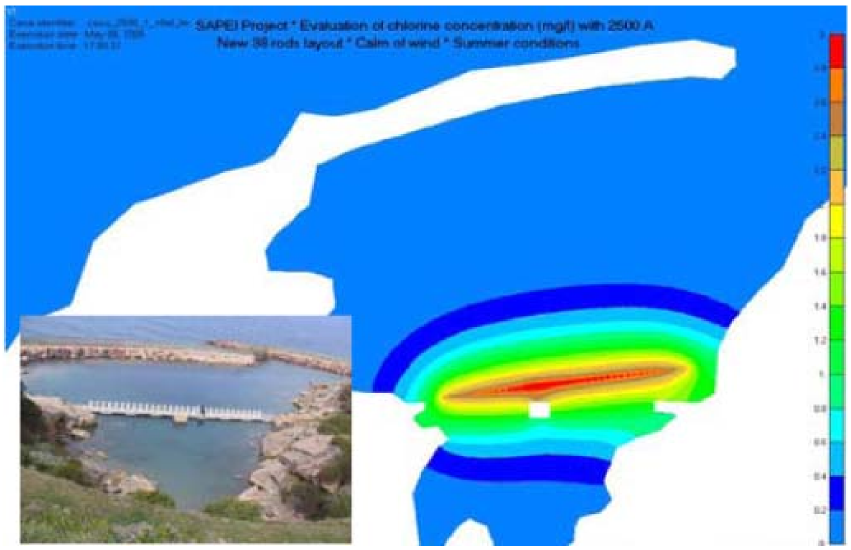

Figure 2-5
Representation of Chlorine Concentration Distribution [6]

Design of Ground Electrodes

The design criterion for electrode stations is typically 50 years. A CIGRE technical brochure for ground electrodes design published in 1998 [7] and the EPRI ground electrode design manual published in 1982 [1] provide detailed explanations of ground electrode design. This subsection on design of ground electrodes provides a summary of ground electrode design including the latest developments in the area of electrode design.

Design of Land Electrode

The design aspects of land electrodes have not changed much since the early days of their application. Some of these design aspects are common for all land electrodes, and some are specific for given location and electrode design. This subsection discusses five aspects listed as important in [7].

Heating of Soil

Heating of soil close to the electrode surface is an important quantity to consider in electrode design. The current industry practice [7] is to design the electrode so that the maximum temperature is limited to the boiling temperature of the water.

The boiling temperature of water depends on the water pressure; therefore, the boiling temperature depends on the height of the water column and the altitude of the electrode site. Typically, a soil temperature of 85°C is considered as the threshold, and temperatures in excess of this could cause steam formation [7]. The danger of steam formation is that the steam trapped inside the soil might develop excessive pressures that may cause the electrode to explode. In general, the overheating of soil reduces the moisture content, and drip irrigation techniques may be adopted to maintain the soil moisture level for prolonged ground return mode of operation. However, if the electrode is buried deep below the earth surface and there is water column above it, the boiling temperature increases and a suitable correction to the maximum temperature must be made.

The temperature rise of the electrode surface is calculated by using a formula first derived by Kimbark [8]. This formula assumes a uniform heat conductivity and earth resistivity, and relates the temperature rise at the electrode surface to the potential of the electrode using earth electrical resistivity and thermal conductivity. The adopted industrial practice to estimate earth resistivity and thermal conductivity is to use a soil sample extracted close to the surface of the electrode.

A CIGRE brochure [7] shows that this formula provides a pessimistic estimation of the temperature rise due to the simplified assumptions, and it suggests the use of a correction factor of 5 for continuous operation of ground electrode with burial depth less than 3 meters, and a correction factor between 5 and 1 for deeply buried electrodes with burial depth between 50 meters and 500 meters.

Moisture Content of Soil/Electric Osmosis

Electrodes cannot be successfully operated in dry lands such as dry sand or hard rock areas. Watering (irrigation) systems to maintain moisture content have been applied to ground electrode sites. Such practices have been successfully applied in the Nelson River scheme in Canada and Rihand-Delhi scheme in India.

The current density at the surface of a land electrode must be limited to 1 A/m^2 to avoid electro-osmosis (i.e., movement of water in the direction of electrical field) [9]. The Rice Flats electrode of Pacific Intertie used a current density of 0.5 A/m^2, whereas in the case of Danish shore electrodes, a current density of 5 to 8 A/m^2 is used because the presence of water is ensured by the location of electrodes (below sea level, 20 meters towards the beach) [7].

Geometric Layout

The resistivity profile at the ground electrode station indicates what geometric type of electrode is suitable and whether one single electrode or a parallel combination of a number of subelectrodes is required. Land electrodes could be categorized as vertical or horizontal electrodes based on their geometric layout.

Vertical Arrangement (Borehole Electrodes)

A vertical electrode design is used for electrode stations with conducting layers at some depth. In addition, vertical electrodes require less land space, and hence this design is an attractive option for HVDC schemes associated with high currents. This is because a maximum current density associated with the soil properties and material is used in electrodes. In the case of vertical electrodes, longer electrodes buried deep into the soil could be used to maintain current density, whereas horizontal electrodes need a higher cross section, which means a greater land area to limit the current density.

Vertical electrodes consist of several subelectrodes with each subelectrode having a depth of 50 to 200 meters. Each subelectrode has an inner conductor surrounded by a backfill of a conductive layer. Figure 2-6 shows a typical cross section of a vertical electrode.

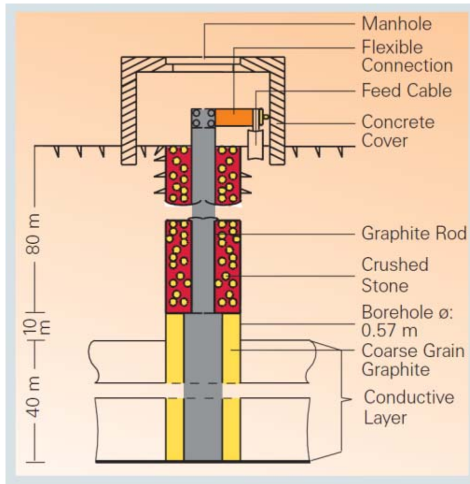

Figure 2-6
Cross section of Typical Vertical Electrode Arrangement [11]

<u>Horizontal Arrangement</u>

Similar to the vertical arrangement, a horizontal arrangement also has an inner conductor surrounded by backfill of a conductive layer. Typically, the active part (inner conductor) of the horizontal electrode is buried about 2 meters below the earth surface. A cross section of a typical horizontal electrode is shown in Figure 2-7.

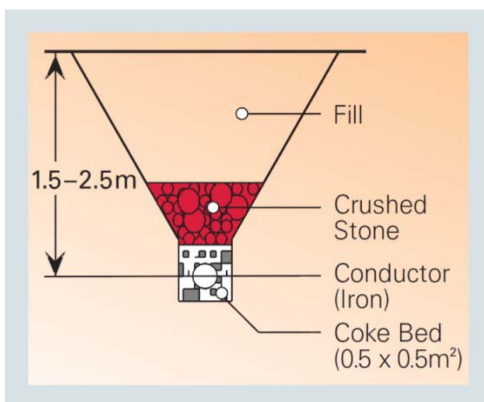

Figure 2-7
Cross section Through Horizontal Land Electrode [11]

Many different configurations, depending on the specific design, are possible for horizontal electrodes. Refer to Appendix A for different configurations. In general, the configurations can be linear, ring-shaped, or star-shaped arrangements. Symmetrical ring configurations have the advantage of even current density along the electrode circumference, provided that the ground resistivity in the area of ground electrode is uniform. All the other configurations have uneven current distribution and hence unequal current density. Linear electrodes have a higher current density at the two ends. High current density in an area increases the step voltage along the surface of the earth. This could be mitigated by burying a part of the electrode at a greater depth compared to the other parts of the electrode. For example, outmost tips of a star-shaped land electrode at Bog Roy are buried to a greater depth than the other parts of the electrode to mitigate high step voltages [12].

In addition to their different shapes, electrodes can be categorized as continuous and noncontinuous configurations based on the continuity of the inner conductor. Continuous conductor configurations have continuous backfilling trenches.

Noncontinuous conductor configurations have continuous or noncontinuous backfilling trenches depending on whether a clear separation of the electrode is required. The inner conductor must be connected to a common feeding point such as a bus bar where the ground electrode line is terminated. Typically, the inner conductor is connected to the common point at a number of equally spaced points along the circumference of the electrode. The idea of noncontinuous configurations is to subdivide the electrode into separate parts so that irregularities in the current feeding into each segment can be controlled separately. In some schemes, a small resistance is added in series with the segments of electrode to reduce the current density around certain segments. It is also possible to have irregular current distribution as a result of local resistivity variations. This situation could cause high current densities, causing electric osmosis or heating of soil in local areas. Segmenting of electrodes is also useful for maintenance where the segment under maintenance could be disconnected while other segments are in-service.

Material Selection

Almost all the land electrodes built so far have an inner conductor surrounded by some form of backfill containing carbon to give good contact between soil and the electrode. A CIGRE brochure that provides guidelines on ground electrode design [7] describes inner conductor material and backfill material containing carbon, as shown in Table 2-1.

Table 2-1
Inner Conductor and Backfill Material [7]

	Conductor Material
1	Steel or "mild" steel rods or tubes, 30-40 mm in diameter. The steel conductor is mostly covering the length of the electrode continuously.
2	SiCrFe rods, commonly 45 mm in diameter, length 1.25-1.75 m. These electrode bars are normally only partially covering the total length of the coke filling, 30-50 percent, which means that the coke column is used also for longitudinal flow of current. There is a certain risk of an unequal current density on the outside of the coke filling.
3	Graphite rods, commonly 100 mm in diameter, 1.2-2.4 m in length. As for the SiCrFe rods, the graphite rods only cover part of the length or depth covered by the coke.
	Backfill Material
1	Coke breeze—small particle solid residue left by the cracking process of petroleum refining.
2	Coke —Result of distillation of bituminous “raw” coal.
3	In one electrode station the carbon material is described as graphite powder emulsion.

Step and Touch Voltages

Step voltage is the voltage difference across a step of humans or animals. Touch voltage is defined as the voltage between the ground surface and any object such as a fence that might be touched by a person standing close to the object. The permissible touch and step voltages [13] to which an individual may be subjected to when the electrode is carrying DC current are determined, based on standards such as IEC standards 60479-1 and 60479-2 and IEEE standard 80. Typical values of potential gradient and touch and step potential are given below. It is important to note that, during the design and operation stages, due consideration should also be given to local regulations regarding safety and interference in addition to the conditions at the electrode site and the general vicinity of the electrode station.

- Touch voltage is typically 20 V. Excessive touch voltages can be mitigated by distance or section insulation of the objects such as fences.
- Potential gradient on the surface is typically 2–20 V/m. Excessive potential gradients can be mitigated by depth of burial.
- Step voltages at the electrode site are typically 2–8 V/m. Excessive step voltages can be mitigated by depth or fencing for areas exceeding such limits.

Both step voltages and potential gradients at a given location near the electrode station can be accurately calculated by using commercially available software, provided that the ground resistivity profile in the area of electrode station is known accurately.

Design of Sea Electrodes

In sea electrodes, the current is transferred directly from the electrode to the seawater. Sea electrodes are connected to the coast using a cable, which increases the project cost. On the other hand, sea electrodes do not cause electric osmosis problems because the electrode is fully immersed in the seawater. Existing sea electrodes can be categorized into three construction models based on the material used in the active part of the electrode [7]. These three models are:

- Sea electrodes using titanium
- Sea electrodes using graphite or silicon chromium iron (SiCrFe) rods
- Sea electrodes using bare copper

Sea electrodes using titanium as the active part (anodic operation)

At least four sea electrodes make use of a titanium anode:

- Fenno-Skan anode Dannebo
- Baltic cable anode Smyget
- Kontek anode Bogeskov
- Grita anode Corfù strait

Anodes in the Fenno-Skan, Baltic Cable, and Kontek electrodes consist of titanium meshes built by adding 20 m^2 modules. Each of 20 m^2 module with dimensions of 1.22 meters by 16.5 meters makes a subelectrode. Each subelectrode can be rolled in a cylindrical coil of 1.22 meter length and about 0.8 meters diameter for handling and transportation purposes. Forty 20 m^2 modules are in each of the Baltic Cable anode and Fenno-Skan anode, making the total meshed area

800 m^2. In the Kontek anode, there are one hundred 20 m^2 modules, making the meshed area 2000 m^2. The titanium meshes are covered with special thin layer (5-20 μm) of metals resistant to corrosion. The metal coating on the titanium mesh in the Kontek anode is described as several layers of precious metal oxides, which has the advantage of a very high percentage of gas emissions of oxygen instead of chlorine. Chloride development is low, because of the catalytic coating and a low current density, which is 2.5 A/m^2. Titanium meshes are mechanically protected by polypropylene tubes, fiber concrete, or a layer of natural stone backfill. In the Baltic cable and Kontek anodes, the current density at the mesh is about 2.5 A/m^2, and the resistivity of seawater is about 0.8 Ωm. The Dannebo anode electrode of Fenno-Skan also has the same physical size as the Baltic cable; however, the seawater has a resistivity of about 1.13 Ωm.

The Grita anode consists of 39 bars of titanium coated with noble-metal oxides, which is a material widely tested for cathodic protection and has a very high corrosion resistance as well as a long life expectancy.

Sea electrodes using Graphite or Silicon Chromium Iron (SiCrFe) as active parts (for reversible operation)

At least two sea electrodes use graphite as an active part of the anode, and at least one electrode uses SiCrFe rods:

- Risö electrode of the Konti-Skan scheme
- Grosoysoyla electrode of the Skagerrak scheme
- Santa Monica electrode of the Pacific Intertie Scheme

The Risö electrode in the Swedish side consists of 30 horizontal graphite electrodes laid on the seabed at a depth of 7-10 meters. The electrodes are individually covered with a concrete cover with coke backfilling. Figure 2-8 shows a diagram of a typical horizontal graphite electrode in a linear arrangement. The Grosoysoyla electrode in Norway consists of 61 graphite subelectrodes placed in a wooden structure with coke backfill. Some of these are connected in series to provide a better current distribution. The Santa Monica electrode consists of a linear array of 24 horizontal electrode elements made up of SiCrFe rods suspended 0.5 to 1.0 meters above the ocean floor and located within concrete enclosures. Both graphite and SiCrFe electrodes can be used in reversible operation (i.e., anodic or cathodic operation) [7, 14].

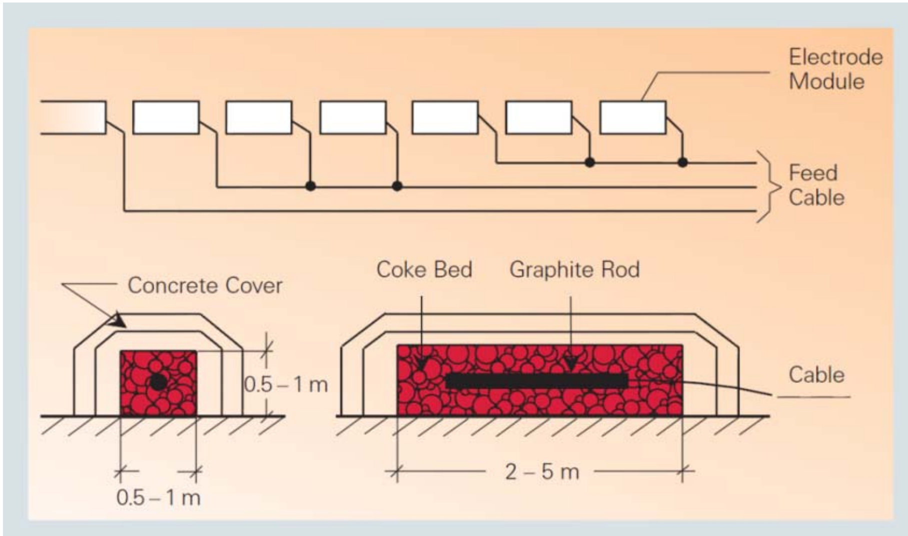

Figure 2-8
Linear Submarine Electrode (Anodic Operation) [11]

Sea electrodes using bare copper conductors as the active part (for cathodic operation)

Five electrodes in Europe use copper as the active part in the cathode:

- Baltic Kathode1 electrode on the German side of the Baltic Cable scheme
- Pampriniemi electrode on the Finnish end of the Fenno-Skan scheme
- Graal-Müritz electrode on the German side of the Kontek scheme
- La Torraccia electrode on the Italian mainland side of the Sacoi scheme
- Otranto Cape electrode on the Italian side of the Grita scheme

Although it is possible to use less expensive materials than copper as the cathode, copper has been the choice due to the possibility of making reliable clamp connections suitable for the sea environment by compression or welding. Although many physical configurations are possible, circular or elliptic shape loops have been used frequently. Table 2-2 tabulates the parameters of some of the above listed electrodes.

Table 2-2
Parameters of Electrodes Use Copper as Active Part [7]

Electrode station	Baltic Kathode1	Pampriniemi	Graal - Müritz	La Torraccia
Copper cross-section [mm^2]	300	300	400	300
Copper cable radius [mm]	11.5	11.5	13.0	11.5
Total electrode length [m]	5620	4500	5100	600
Surface of copper [m^2]	406	325	417	43.4
Rated current [A]	1364	1250	1500	1000
Current density [A/m^2]	6.72	7.87	7.20	46.13
Water resistivity [Ωm]	0.8	1.6	0.8	0.2
Gradient of surface [V/m]	5.37	12.60	5.76	9.23

Design of Shore Electrodes

The two types of shore electrodes are [7]:

1. **Beach electrodes:** the active part of the electrode is positioned on the beach, and the electrode is in direct contact with sand or ground water but not in direct contact with the seawater.
2. **Pond electrodes:** the active part of the electrode is positioned on a small part of the beach protected by breakwater against waves, and the electrode is in direct contact with the seawater. Figure 2-9 shows an aerial picture of a pond electrode of the SACOI HVDC system at Punta Tramontana, Italy.

Figure 2-9
Aerial Photo of Punta Tramontana Shore Electrode (Sacoi HVDC Scheme)

Beach electrodes

The Lovens electrode station of the Skagerrak HVDC system in Denmark, the Te Hikowhenua electrode station of the Benmore-Haywards HVDC system in New Zealand, and the Albuera (Leyte) and the Calabanga (Luzon) electrode stations of Leyte-Luzon HVDC system in the Philippines are examples of existing HVDC schemes using beach electrode stations. The Lovens electrode has number of parallel graphite electrodes arranged in concrete rings with a coke backfill. The Te Hikowhenua electrode has a linear array of high silicon chromium iron electrodes arranged in porous concrete cylinders. These cylinders are buried well below the lowest tide level. The Albuera and Calabanga electrode stations have a number of silicon iron rods installed in two parallel rows, with the depth of each rod or subelectrode varying from 10 to 13 meters. Current distribution between each subelectrode is balanced by means of resistors connected in series with the subelectrode cables. A linear array of subelectrodes parallel to the coast line is the best suitable geometric layout for beach electrodes [7, 14, and 15].

Usually beach electrodes are buried below the groundwater level, and the electrode current is transferred to the sea through the groundwater between the sea and the electrode. Groundwater in coastal areas typically has two layers: the top layer of freshwater above the sea level and a deeper layer of saltwater penetrated from the sea [7]. Therefore, these soil layers are saturated with either freshwater or saltwater depending on the depth of electrode.

If the active part of the electrode is buried within the freshwater level but above the seawater level, the anodic action of the electrode produces only oxygen, but there will not be any chlorine evolution. On the other hand, if the goal is to reduce the resistance of the electrode, it may be buried below the seawater level, resulting in some evolution of chlorine. Because the soil layers surrounding the electrode are saturated with water, heating of the soil or electro-osmosis is unlikely.

Pond electrodes

Pond electrodes are installed in a pondlike area, where the breakwater protects the electrode from tides (see Figure 2-9 for more details). Similar to sea electrodes, current transfer in a pond electrode is directly to the seawater, and therefore, chlorine and oxygen are produced as a result of the electrolysis process. Because pond electrodes are surrounded by seawater, heating of soil, or electro–osmosis, is not possible [7].

Among the advantages of pond electrodes is the small area required for the electrode station and lower installation cost compared to sea electrodes. Additionally, visual inspection of subelectrodes is simple because inspection requires only lifting the electrode rods out of the water.

The four existing HVDC schemes that use pond type electrode stations are:

- Punta Tramontana electrode station of the Sacoi HVDC scheme
- Sansum Narrows electrode of the Vancouver Island HVDC scheme
- Ekno and the Massange electrode stations of the Gotland HVDC scheme
- Haenam and the Cheju electrode stations of the Haenam-Cheju HVDC scheme

The Punta Tramontana electrode in Italy consists of 30 Platinum coated titanium pipes. The Sansum Narrows electrode in Vancouver Island, Canada consists of 28 graphite rods. The Ekno and the Massange electrodes in Sweden have 48 Magnetite (Fe_3O_4) rods in each electrode station. The Haenam and the Cheju electrodes in South Korea have 20 Duralumin rods in each electrode station.

Although, different geometrical arrangements are possible, a linear arrangement of rod electrodes is the most widely used configuration in existing electrode stations.

Conclusions

Recent advancements in HVDC ground electrode technologies include advancements in resistivity imaging techniques, finite element modeling of electromagnetic fields, computer-aided optimizing of electrode size with respect to the electrical characteristics such as touch and step voltages, and the development of new materials for the anode. . Additionally, online monitoring of the current and temperature distribution of electrode segments as explained in Chapter 5 could also be considered as a development in ground electrode technology.

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3
ENVIRONMENTAL CONSTRAINTS AND REGULATIONS

Introduction

Over the last 40 years, using an earth return for HVDC transmission has proven to be an economic and efficient solution for providing the current return path. Monopolar HVDC schemes without a metallic return utilize earth return for full-time operation. Bipolar HVDC systems have negligible earth return currents, which amount only to the unbalance between the two pole currents in bipolar operation and full pole current in monopolar operation. Based on recent survey results, [1] the earth return operating time for a bipolar system is normally less than 3% and is almost entirely related to controlled maintenance periods.

During the design stage, electrode locations are chosen such that surface voltage gradients are kept to safe levels and to avoid any corrosion impact on pipelines and to avoid direct current interaction with electrical system transformers. Generally earth electrode operational experience has been positive. There are some instances where earth electrode performance has not been successful due to unforeseen ground conditions [2] that were not identified in the planning stages. Most environmental and technical issues can be managed by conducting investigations and studies to locate a low-resistance electrode site.

Lessons learned from these experiences, plus the use of modern deep-earth geophysical measurement techniques, should make the science of planning earth electrodes and any associated mitigation requirements more predictable.

This chapter presents the environmental constraints applicable to ground electrode operation and then briefly discusses the practice and applicable regulations of ground electrode operation.

Environmental Constraints

Environmental constraints for ground electrode operation are mainly associated with the environmental impact caused by the following three issues:

- Electric fields and corrosion
- Electrolysis products from sea anodes
- Magnetic fields

Electric Fields and Corrosion

Current flow between two electrodes buried in land or sea causes an electric field between the electrodes. The magnitude and the distribution of the electric field depend on the resistivity of the layers of earth and the sea in the area of the electrodes. Stray currents created as a result of the electric field can flow in metallic structures such as pipelines, and increased corrosion could result where these stray current leave the metallic structure. In addition to corrosion, the electric field could induce currents through the grounded star point of a transformer, causing saturation of the transformer. Saturation is not a serious problem [1] for a large number of small transformers (less than 200 MVA) with three–phase, three-limb configuration; however, attention should be paid to large, single-phase transformers and large, three-phase transformers with five limbs.

Electrolysis Products from Sea Anodes

As a result of the electrolytic process, oxygen and chlorine are produced. Chlorine is unstable in seawater and produces hypochlorite, chloride, hypobromite, bromide, (chloroform), and (bromoform) after a series of reactions. Both chloroform and bromoform are toxic chemicals.

Magnetic Fields

HVDC cables generate static magnetic fields as a result of its dc current. The direction of the magnetic field depends on the direction of current, and the magnitude of the magnetic field depends on the magnitude of the dc current, as well as the distance from the HVDC cable. Two HVDC cables sharing the same right-of-way and carrying currents in opposite directions will generate two opposing magnetic fields. Consequently, HVDC cables connected to the positive and negative poles of a bipolar system and sharing the same right-of-way generate no or a negligibly small magnetic field. Monopolar HVDC systems, with a metallic return cable have similar cable arrangements and, therefore, create negligibly small magnetic fields. However, HVDC systems operating in monopolar mode with an earth return do not have the canceling effects and hence create a magnetic field.

Compass deviation and effects on magneto-sensitive fish such as eel and Atlantic salmon are two major concerns associated with the magnetic fields generated by HVDC cables. However, studies have found no series impact on magneto-sensitive fish [3, 4]. Compass deviation due to the cable magnetic field has been observed in shallow sea areas. This issue is not a worldwide problem and has only raised concerns in some countries.

North American Practice and Regulations

United States

The National Electric Safety Code (NESC) C2-1993, paragraphs 92, 215, 314, prohibits the continuous use of ground as a current carrying conductor. This limitation continues in the current version of NESC (the same paragraphs numbers in C2-2007) [5].

For this reason, after 1993, monopolar HVDC systems built in the United States must have a metallic return. However, NESC regulations allow for the monopolar ground return mode of operation for bipolar HVDC systems for a limited period of time for maintenance or during emergencies. NESC regulations do not specify what conditions are considered as emergencies or elaborate on the limited time period available for maintenance.

The application of these restrictions is evident in recent point-to-point HVDC schemes. The Neptune Cable HVDC link is a monopolar, line–commutated, converter-based system with a metallic return [6]. The Trans Bay Cable link uses Voltage Source Converter (VSC)-based technology, and the concept does not require an electrode [7].

HVDC schemes built before 1993 in the United States (e.g., Intermountain IPP, Pacific Intertie) are bipolar systems with ground electrode connections, and therefore, an earth return could be employed for monopolar operation during maintenance periods. In the case of the Hydro Quebec to New England scheme, the Sandy Pond station has a metallic return connection to Nicollet station, mainly due to the unavailability of a proper electrode site.

Canada

It is not known whether Canada has a regulation pertaining to ground return and ground electrode connections. However, discussions with various utility engineers indicate that there is no ban on ground return or ground electrodes. The last two HVDC projects completed in Canada are the Hydro Quebec to New England Transmission Line and the Nelson River Bipole 2. Both these schemes are bipolar systems and use ground electrode connections for emergency monopolar operation.

Practice in Other Parts of the World

It is not known whether any country in the rest of the world has actual regulations prohibiting or limiting the use of HVDC ground electrodes. However, the practice of allowing ground electrodes could be judged by recently built HVDC links and their operational practices.

The Greece to Italy (Grita), the Chinese (Three Gorges-Shanghai), the Indians (East South and Balia Bihwadi), and the Namibians (Caprivi) all have HVDC systems with ground electrodes built in last decade. In addition, it is known that Brazil and New Zealand allow HVDC schemes with ground electrodes, provided that no negative impact is foreseen.

Table 3-1 lists most of the HVDC schemes brought to service during the last decade. Note that the entries corresponding to HVDC schemes with electrodes are highlighted.

Nine of the sixteen HVDC schemes listed in Table 3-1 have ground electrodes, and only the Grita HVDC link between Greece and Italy has a sea return for continuous use. All the other HVDC links are bipolar and utilize earth return only when one pole is unavailable or during emergencies. All the bipolar schemes are equipped with a metallic return design with a metallic return transfer breaker to allow monopolar operation of the healthy pole on the out-of-service pole conductor.

Table 3-1
Recent HVDC Schemes in Other Parts of the World

	HVDC Scheme	Country/ Countries	Year	Comments
1	Kii Channel	Japan	2000	Bipole with metallic return
2	Directlink	Australia	2000	No ground electrodes required for this VSC
3	Moyle Interconnector	Scotland-Northern Ireland	2001	Two independent monopoles with metallic return
4	Thailand-Malaysia	Thailand-Malaysia	2001	Monopole with metallic return
5	Grita	Greece-Italy	2001	Monopole with sea return
6	Tian-Guang	China	2001	Bipole with electrodes
7	East-South Interconnector	India	2003	Bipole with electrodes
8	Three Gorges-Changzhou	China	2003	Bipole with electrode
10	Three Gorges-Guangdong	China	2004	Bipole with electrodes
11	Gui-Guang	China	2004	Bipole with electrodes
12	Bass Link	Australia	2006	Monopole with metallic return
13	Norned	Norway-Netherlands	2007	Monopole with mid-point ground but no ground electrode
14	Three Gorges-Shanghai	China	2007	Bipole with electrodes
15	Ballia Bhiwadi	India	2009	Bipole with electrodes
16	Caprivi link	Namibia	2010	Designed as a bipole with electrodes

The Norned scheme is a unique scheme that uses conventional line-commutated converters with the mid-point grounded and balanced current operation. The scheme does not operate if one converter is removed from service. The Norned link was originally proposed as a monopolar link with sea electrodes; however, complications related to environmental impact aroused in the licensing of the HVDC link necessitated the design change.

Similar to the Norned link, the Basslink scheme was originally proposed as a monopolar HVDC system with sea/land electrodes to avoid the high capital costs associated with the return cable. However, to eliminate a perceived environmental impact, a return cable was included in the design.

Often, monopolar HVDC schemes are originally proposed as monopolar systems with earth return; however, due to difficulties and delays at the licensing stage, earth return schemes are changed to metallic returns. Sometimes, environmental concerns are real, and changes to the original plan are required; on other occasions, environmental concerns are not backed by scientific evidence, but the uncertainty associated with the environmental impact causes a lengthy licensing process.

The EuroKabel and Viking Cable projects had many setbacks in the licensing process due to environmental concerns, and ultimately owners of these projects decided to terminate these projects. Reference [3] discuss details of experience obtained in the licensing process for submarine HVDC links in the Nordic region and stresses that the need for a well-prepared information strategy ahead of public discussion of the HVDC system is of vital importance to answer the claims of uncertainty associated with environmental impact.

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4
CHALLENGES AND ADVANTAGES OF LAND AND OCEAN TERMINATION

Introduction

The majority of ground electrodes used in existing HVDC schemes are land electrodes. The main reason is that most of the existing converter stations are located deep in land far from water. Designing an electrode for a converter station close to the sea presents the advantage of selecting an electrode location from land, sea, or shore. Although sea and shore electrodes are somewhat different in design and operation, there are many similarities between these two types of electrodes when compared with land electrodes. For this reason, discussion in this chapter is confined to the challenges and advantages of electrode ocean termination compared to the electrode land termination.

Ground Electrode Land Termination and Associated Challenges and Advantages

Selecting a site for land electrodes is a lengthy process, requiring various types of land surveys for data gathering and compiling the gathered data so that a suitable location for the land electrode is identified.

Challenges

- The main challenge with land electrode design is to find a suitable location for the electrode site.
- Another challenge is the electrical resistivity of the ground. Current injected from the electrode penetrates the shallow soil layers in close proximity to the electrode station and distributes into the deep soil layers. To prevent high step and touch voltages in the close vicinity of the electrode, the resistivity of the shallow soil layers at the selected electrode site must be adequately low. On the other hand, to prevent high step and touch voltage a few kilometers away from the selected electrode site, the deep ground resistivity up to 10-20 km deep in an area of 10-20 km radius from the site must be adequately low.
- The thermal resistivity and thermal capacity of the soil, as well as the soil moisture content close to the electrode surface, have to be measured. The thermal resistivity and moisture content may vary considerably and therefore require measurements over a period of time. Low thermal resistivity is important for efficient dissipation of heat generated at the boundary of the electrode and soil. High thermal capacity is important to limit the temperature rise caused by heat dissipation. When locating and designing the electrode, consideration must be given to electro-osmosis, a phenomenon associated with the anode operation because of net water flow from the electrode. Thus the moisture content of the soil is most important. In some projects, a wetting system is used in case of prolonged ground return. In addition to thermal properties, good porosity (water and gas permeability) of the soil is important for the healthy operation of the electrode.

- The high dependence on site conditions makes site testing important and challenging. Many projects have performed a pilot test electrode program to confirm the correct site selection.
- Another factor that is considered in locating a land electrode is the existence of buried and earthed metallic structures as well as electrical infrastructure within the area of influence. During the design stage, an effort should be made to locate the electrode so that it's influence on metallic structures and electrical infrastructure is minimal.
- The condition assessment of a land electrode may require the inspection of the electrode or part of it. This is not a straightforward process because it will require digging manholes close to electrodes or the removal of the electrode.
- Occasionally electrolytic corrosion occurs on land electrodes. The Chandrapur land electrode of the Chandrapur - Padghe HVDC bipole was found corroded due to electrolytic corrosion, and part of the electrode was replaced [1].
- Environmental concerns pose a major challenge in licensing of HVDC schemes that use a ground electrode regardless of its termination point (land or sea).

Advantages

- No electrolytic process-current transfer from the electrode to soil occurs through conduction, and hence no gases or chemical compounds are produced.
- The electrode line connection between the converter station and a land electrode is an overhead line. Construction of an overhead line is less expensive compared to the laying of a sea cable used for sea electrode.

Ground Electrode Ocean Termination and Associated Challenges and Advantages

Selecting a location for sea electrode is less tedious compared to site selection for land electrode.

Challenges

- The main challenges associated with sea electrodes are the gas and chemical compounds produced by the electrolytic processes and the possible impact of these chemicals on marine life. This issue has been addressed to a certain extent in modern designs. Electrodes using coated titanium as the active part emit oxygen and a very low amount of Chlorine.
- Corrosion of marine metal structures such as pipelines caused by electrode currents should be considered, and these effects are minimized in the design stage.
- Another challenge involves the impact on magnetic fields—compass errors.
- Similar to land electrodes, environmental considerations are becoming more focused on issues that would limit the usage of ground electrodes, although all studies and investigations, as well as experience, show no adverse effects provided that sound electrode designs are used.

Advantages

- The resistivity of seawater is more or less homogeneous and low in value. This will make locating a sea electrode easier, compared to finding a location for a land electrode.
- Water has a good thermal capacity. Heated water goes to the surface of the sea, allowing for natural heat exchange.
- Current transfer through a pair of sea electrodes travels through seawater and hence would not interfere with electrical infrastructure and metallic structures on/in land.
- The condition assessment of sea electrodes is relatively easy. In some existing sea electrodes, this assessment is done using divers.
- A simple cheap design consisting of loops of copper wire is available if the sea electrode is used only for cathode operation.

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5
CONDITION ASSESSMENT

Introduction

An electrode site normally requires minimal maintenance activities. The site is unmanned, and the status of the equipment and the electrodes is monitored remotely via communication links between the electrode sites and the converter stations. In addition, electrode site inspections can be carried out on regular intervals such as once a month or once every two months. This section provides a briefly summary of these measurements and inspections.

Current Methods and Techniques of Condition Assessment of Ground Electrodes

During the construction of an electrode, measurements should be made of any factors that are likely to be influenced by the operation of the electrodes—e.g., soil moisture content in the vicinity of the electrode. The condition of any objects that may be influenced by the operation of the electrode should also be recorded—e.g., weight and thickness of the active part of the electrode.

The condition of the electrode can be assessed using online measurements and electrode site inspections. Occasionally, visual inspection of the active parts of the electrode may be required.

Online measurements: DC current through the current distribution cables connected to each electrode segment as well as dc current through the electrode line can be measured continuously and transferred to the converter station through an optical fiber link or wireless communication link [1, 2, and 3]. In the case of land electrodes, soil temperature at each segment of the electrode can also be measured. Current measurements indicate any unusual unbalances between the electrode segments, and the temperature at each segment of the electrode indicates whether there is any unusual heating of the soil. In addition, computer analysis of the online measurements could reveal variations in electrode operation and could provide the early detection of any problems associated with the electrode.

In addition to the online measurements, visual inspection of land or shore electrodes sites is carried out periodically to observe any changes or abnormalities. The frequency of the inspections may vary between different utilities and their experience with the electrode. In the case of sea electrodes, water samples close to the electrode may be collected to be analyzed to determine the water's chemical composition. For example, a pH value of water close to the anode indicates the amount of chlorine emissions.

Occasionally, it might be required to visually inspect the electrode. In the case of sea electrodes, divers and video cameras may be used for this purpose. For land electrodes, survey holes are excavated to inspect the electrode condition underground.

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6
AREAS FOR FUTURE RESEARCH

The technology used in ground electrode design and implementation was developed many decades ago at the inception of HVDC transmission. Recent advancements in electrode technology include the development of technologies for accurate resistivity measurements of shallow and deep earth, computer-aided simulations of electromagnetic fields created by electrode operation, and the development of various materials for anodes of sea electrodes. These advancements have resolved some of the difficulties associated with the different stages of electrode design and operation; however, some areas need further research and development. This section briefly discusses key areas with potential for future research.

Measurement of Thermal Properties of Soil and Estimation of Soil Thermal Characteristics

The current practice of estimating thermal characteristics of soil layers around a land electrode is to measure the thermal properties of soil samples collected close to the electrode station and to obtain a solution for the thermal characteristics by making a number of simplifying assumptions. These assumptions include homogeneous soil structures and simplifications required for a closed form solution. It has been shown [1] that the actual temperature rise in the surroundings of existing land electrodes are much lower than the corresponding calculated values, and therefore, a correction factor based on heuristics is used to convert the calculated value. This calculation process is inaccurate, and huge margins with respect to the thermal constraints are allowed to cover the inaccuracies in calculations. Some research work has been done in this area [2-4] to model the nonhomogeneous nature of the soil structure using finite-element-based computer simulations. However, further research work is required to develop a commercial-level simulation program to model heat and temperature distribution of soil and, most importantly, how to measure the thermal properties of soil to be used in these programs. These developments are particularly important for the size optimization of land electrodes.

Monitoring and Condition Assessment of Electrodes

Monitoring and condition assessment of electrodes are limited to occasional visual inspections of the electrode site and rare inspections of the active part of the electrode. Inspection of sea electrodes needs divers, while inspection of land electrodes needs observation holes close to the electrodes. Additionally, in some land electrode stations, the temperature of the soil is measured. In a recent HVDC scheme [5], online measurements of soil temperature in the vicinity of electrode segments and current transfer into each segment of the electrodes are measured and transmitted to the monitoring station. Although, current and temperature distributions are important to identify changes and problems associated with electrodes, further research and development work is required to improve electrode monitoring techniques, so that the reliability of the electrode operation can be improved.

Comprehensive Studies Addressing the Environmental Impact of Ground Electrodes

Comprehensive studies addressing the environmental impact of ground electrodes and improving the public awareness of electrode operation are important topics. Regulations imposed by the National Electric Safety Code prohibit continuous use of an earth return in monopolar operation. In other parts of the world, no such known regulations prohibit or limit the use of an earth return. However, many HVDC projects planned with an electrode return faced difficulties in obtaining the necessary licenses, as a result of environmental concerns of adverse effects of the ground currents. For this reason, a comprehensive scientific study aimed at increased public awareness on the impact of electrode ground return and electrode operation is a much needed and timely research area.

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A

ELECTRODE CONFIGURATION

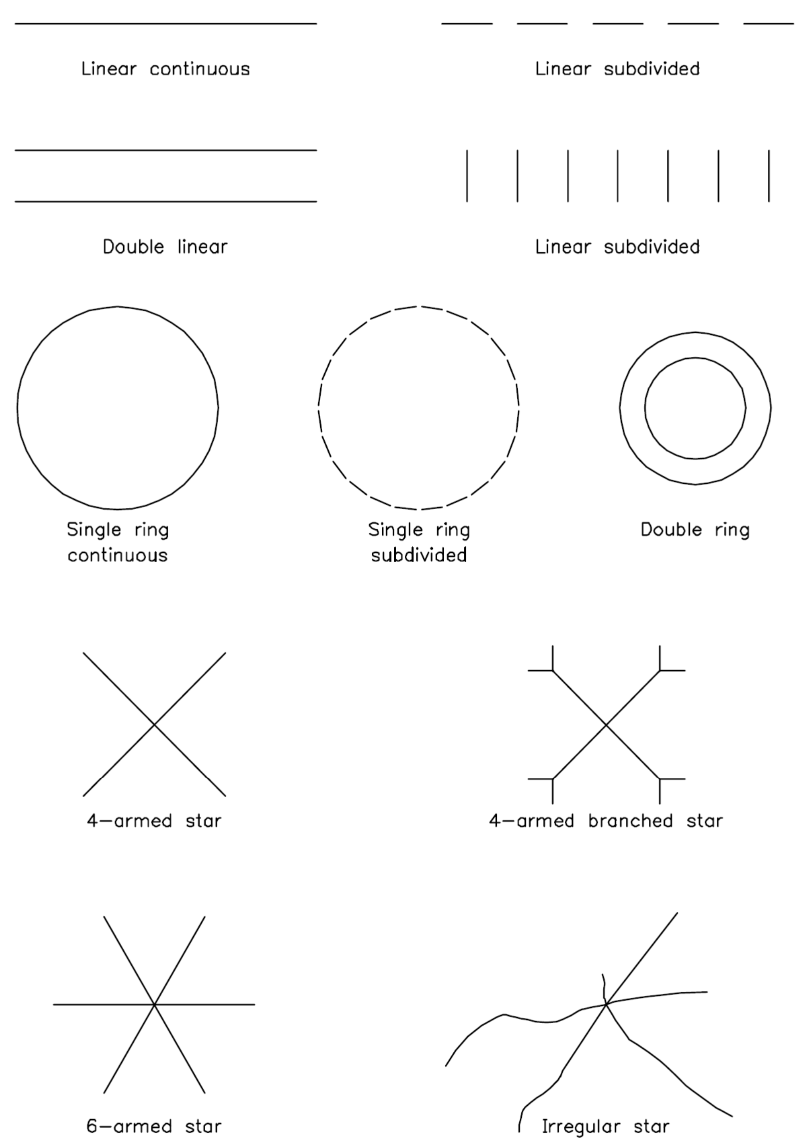

Figure A-1
Various Configurations Used in Horizontal Land Electrodes [1]

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B

HVDC SCHEMES WITH GROUND ELECTRODES

Table B-1
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description	
1	BALTIC CABLE	Sweden-Germany	450	600	1994	The anode on the Swedish side consists of forty 20 m^2 nets of titanium laid on the sea bottom and mechanically protected by plastic tubes and stones.	The cathode on the German side consists of a 1 km circular loop of bare 300 mm2 copper wire.
2	C.U.	U.S.A	±411	1128	1979	The Coal Creek Terminal is designed with 12 vertical electrodes, each approximately 60 meters deep and 0.3 meters in diameter coke backfill is used.	The Dickinson Terminal is designed with 15 vertical electrodes, each approximately 75 meters deep and 0.3 meters in diameter coke backfill is used.
3	CAHORA BASSA APOLLO	Mozambique -South Africa	±533	1920	1978	The electrode stations are at both ends designed as deep electrodes. Five graphite electrodes with a diameter of 100 mm, and length of 60 m, arranged in boreholes and spaced 10 m in a- coal layer down to 30 m below ground level. Graphite powder emulsion is used between rod and hole. Graphite electrodes with a diameter of 300 mm, arranged in vertical holes with a diameter of 750 mm. Four graphite chips are used between rod and hole and as drain is used coarse grained gravel filling. The electrodes are arranged in a 40 m conducting layer down to 130 m below ground level. These electrodes are going to be replaced by a different type using bitumen and graphite as backfill.	
4	CAPRIVI LINK	Namibia	350	300	2010	Silicon-chromium-iron boreholes were likely chosen for both Zambezi and Gerus electrodes.	
5	CHANDRAPUR-PADGHE	India	±500	1500	1998	Chandrapur station has a ground electrode designed for full current.	Padghe station has a ground electrode designed for full current.
6	FENNO-SKAN 1&2	Finland-Sweden	400	572	1989	The anode on the Swedish side consists of forty 20 m^2 nets of titanium laid on the sea bed ; R = 0.2 Ω	The cathode on the Finnish side consists of a 1500 m x 700 m loop of 300 mm^2 copper wire ; R = 0.11 Ω.
7	GESHA	China	±500	1200	1989/ 90	Gezhoba station has a ground electrode designed for full current.	Nan Qlao station has a ground electrode designed for full current.

Table B-1 (continued)
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description	
8	GOTLAND II-III	Sweden	150	260	1983/87	The electrode stations are located on the shore on both sides. They are designed as sea electrodes and are protected by breakwaters. There are 48 magnetite electrodes at each station. Västervik : 0.64 Ω	The electrode stations are located on the shore on both sides. They are designed as sea electrodes and are protected by breakwaters. There are 48 magnetite electrodes at each station. Ygne : 0.54 Ω
9	GRITA	Greece-Italy	400	500	2001	Cathode on the Italian side (Otranto Cape) consists of a bare copper conductor.	Anode on the Greek side (Corfù strait) consists of 39 bars of titanium coated with noble-metal oxides.
10	GUI-GUANG	China	±500	3000	2004	Ground electrode is used on both sides	
11	HAENAM-CHEJU	South Korea	±180	300	1998	Two shore electrodes, consisting of 20 Duralumin electrodes hanging in sea water below low tide in a lagoon protected by a rock-fill breakwater.	Two shore electrodes, consisting of 20 Duralumin electrodes hanging in sea water below low tide in a lagoon protected by a rock-fill breakwater.
12	I.P.P.(INTERMOUNTAIN)	U.S.A.	±500	1920	1986	Each ground electrode consists of 60 deep wells. The nominal well depths are 87 m in Utah and 70 m in California. Each electrode covers an area of approximately 0.65 km^2.	Each ground electrode consists of 60 deep wells. The nominal well depths are 87 m in Utah and 70 m in California. Each electrode covers an area of approximately 0.65 km^2.
13	INGA-SHABA	Zaire	±500	560	1982	Inga: linear ground electrode, 0.24 Ohms	Kolwezi: three-legged ground star electrode, 0.14 Ohms
14	ITAIPU 1	Brazil	±600	3150	1986	Foz do Iguaçu converter station has a ground electrode	São Roque converter station has a ground electrode

Table B-1 (continued)
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description	
15	ITAIPU 2	Brazil	±600	3150	1987	Foz do Iguaçu converter station has a ground electrode (separate from BP1)	São Roque converter station has a ground electrode (separate from BP1)
16	KONTEK	Denmark-Germany	400	600	1995	The sea electrode off Stevns (the Danish side) consists of a titanium mesh built up of 100 nos. 20 m^2 modules. Each module is a sandwich construction composed of an electrode mesh protected on both sides by a polypropylene mat. The electrode mesh is coated with several layers of precious metal oxides, so that the gas mainly developed is oxygen. Development of chloride is low because of the catalytic coating and a low current density, which is 2.5 A/m^2.	The cathode on the German side consists of a 1000 m circular loop of bare 400 mm^2 wire, 5100 m in length, with two connections inside the loop, which gives a current density of 3.75 A/m^2.
17	KONTI-SKAN 1 AND 2	Denmark-Sweden	±250 and 285	740	1965/ 88/ 2005	Danish Coast: an anode electrode station with 24 graphite electrodes, connected in parallel. Each placed in a wooden structure, where coke backfill is used. Resistance = 0.03 ohms total.	Swedish coast: consists of total 30 graphite electrodes on the sea bed at a depth of 7-lOm. The electrodes are individually placed in glass fiber sacks with coke backfilling. Resistance = 0.1 ohms total.
18	LEYTE-LUZON	Philippines	350	440	1998	The electrodes located in Albuera (Leyte) and Calabanga (Luzon) are composed of 40 sub-electrodes each having two units for a total of 80 units per site. The sub-electrodes are installed in two parallel rows over a distance of about 200 m along the shores at depths varying from 10 to 13 m. Currents between sub-electrodes are balanced by mean of resistors located in the electrode building and connected in series with each sub-electrode cable. Electrode line equipment required for detecting faults on the line is also housed in the same building.	

Table B-1 (continued)
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description	
19	NELSON RIVER 1	Canada	+463/-500	1854	1973/ 93	Radisson: It is located 11.2 km from the station and is of the ring type 305m in diameter. It comprises a steel rod and is installed in a low sulphur coke bed. Resistance: 0.16 - 0.37 ohms.	Dorsey: It is located 21.9 km from the station and is of the ring type 305m in diameter. It comprises a steel rod and is installed in a low sulphur coke bed. The Dorsey electrode is designed to accommodate both Bipoles 1 and 2. Resistance: 0.37 to 0.6 ohm.
20	NELSON RIVER 2	Canada	±500	2000	1978/ 85	Henday: It is located 11.2 km from the station and is of the ring type 548 m in diameter. It is comprised of a steel rod and is installed in a low sulphur coke bed. Resistance: 0.4 ohms.	Dorsey: It is located 21.9 km from the station and is of the ring type 305 m in diameter. It comprises a steel rod and is installed in a low sulphur coke bed. The Dorsey electrode is designed to accommodate both Bipoles 1 and 2. Resistance: 0.37 to 0.6 ohm.
21	NEW ZEALAND HYBRID	New Zealand	+270/-350	1240	1965/ 92	North Island: The station is designed as a shore electrode with 42 high silicon chromium iron electrodes in parallel connection. R = 0.122 Ohms.	South Island: The station is designed as a land electrode with branched star configuration. R= 0.35 Ohms.
22	PACIFIC INTERTIE	U.S.A	500	3100	1989	Celilo: The electrode is designed as a ring type 3255 m circumference, 1067 cast iron anodes, and 2' X 2' coke backfill is used. Total resistance in 2 parallel electrode lines and ground electrode =0.43 ohms.	Sylmar: consists of a linear array of 24 horizontal electrode elements made up of silicon-iron alloy rods suspended 0.5 to 1 m above the ocean bottom and located within concrete enclosures. Total resistance in 2 parallel electrode lines and sea electrode = 1.13 ohms.
23	QUEBEC-NEW ENGLAND	Canada-U.S.A.	±500	2250	1986/ 90/92	Duncan station has a vertical rod type ground electrode.	Des Canton station has a ring type ground electrode.

Table B-1 (continued)
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description	
24	RIHAND-DELHI	India	±500	1500	1992	Rihand-Delhi HVDC system utilizes land electrodes for ground return. It consists of double concentric rings. Further each ring is divided into a number of segments. In the event of one segment failing the load will automatically get distributed in the other healthy segments. In case one full ring is kept under shut down the maximum continuous reserve capacity available will be about 60% of the rated load. R = 0.034 Ohms.	Rihand-Delhi HVDC system utilizes land electrodes for ground return. It consists of double concentric rings. Further each ring is divided into a number of segments. In the event of one segment failing the load will automatically get distributed in the other healthy segments. In case one full ring is kept under shut down the maximum continuous reserve capacity available will be about 60% of the rated load. R = 1.0 Ohms.
25	SACOI	Italy-Corsica-Sardinia	±200	300	1967/ 85/ 93	In Sardinia the anode electrode station is designed as a sea electrode with 30 electrodes arranged in a little quiet bay, protected from the sea by a concrete break-water. The single electrode is made of platinum coated titanium pipe with cable connections to a busbar. Total resistance = 0.6 ohm (including cable connections)	On the mainland side, the cathode electrode is made of simple bare copper conductors supported by concrete blocks located 3 km from the shore where the depth of the water is about 28 m. Total resistance = 1 ohm (including cable connections).
26	SAPEI	Italy mainland-Sardinia	±500	1000	2009-2010	Has a sea electrode designed for full current.	Has a sea electrode designed for full current.
27	SILERU-BARSOOR	India	±200	100	1989	M.S. Ring/Bentonite graphite buried electrode with resistance less than One Ohm.	

Table B-1 (continued)
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description	
28	SKAGERRAK 1-3	Norway-Denmark	250/350	1050	1976/77/93	In Denmark the electrode is designed as a number of parallel connected graphite electrodes, arranged in concrete rings, each with d = 2.5 m and at a depth of 2 m. Coke backfill is used. R = 0.35 ohm.	In Norway the electrode is designed in a similar way except that the graphite electrodes are placed in a wooden structure with coke backfill; R = 0.23 ohm. The total number of electrodes on the Norwegian side is 61. Some of this are connected in series to give better current distribution in the cables to the electrode busbar.
29	SQUARE BUTTE	U.S.A.	±250	500	1977	At Center designed as circular trench, containing electrodes surrounded by coke; resistance =0.03 ohm.	At Arrowhead designed by using 800 prepackaged vertical anodes. R=0.3 ohm.
30	SWEPOL LINK	Sweden-Poland	450	600	2000	Starno station has a sea electrode designed for full current.	Slupsk station has a sea electrode designed for full current.
31	THREE GORGES CHANGZHOU	China	±500	3000	2003	Zhengping Land Electrode in double ring shape like stadium at a depth of 2.8 meter. Radius of inner oval = 150 m. Radius of outer oval = 225 m. Distance between centres of left and right ring = 400 m.	Longquan station has a ground electrode designed for full current.
32	THREE GORGES GUANGDONG	China	±500	3000	2004	Jingzhou station: Land Electrode in single ring shape like stadium at a depth of 2.5 meter. Radius of inner oval is 477.5 m. Electrode resistance: 0.0296 Ohm	Huizhou station: Land Electrode in trinary ring shape like stadium at a depth of 3.5 m. Radius of inner oval is 260 m. Radius of middle oval is 320 m. Radius of outer oval is 370 m. Electrode resistance: 0.206 Ohm.
33	THREE GORGES SHANGHAI	China	±500	3000	2007	Yldo station has a ground electrode designed for full current (intermittent).	Huaxin station has a ground electrode designed for full current (intermittent).

Table B-1 (continued)
Summary of Ground Electrodes [1, 2, 3]

	HVDC link	Country (s)	Voltage (kV)	Power (MW)	Year(s)	Electrode description
34	TIAN-GUANG	China	±500	1800	2001	Ground electrode information is not available
35	VANCOUVER	Canada	+260/-280	682	1968/ 77/79	The anode station is designed as a sea electrode at Sansum Narrows on Vancouver Island. It consist of 28 graphite electrodes connected as 4 x 7 electrodes in parallel. Total resistance (excl. overhead lines) is about 0.1 ohm. The cathode station on the mainland at Boundary Bay is designed as a land electrode. It consist of 40 copper-weld ground rods, divided in 2 groups, each with a length of about 9.2 meters. Total resistance (excl. overhead lines) is about 0.01 ohm.
36	VOLGOGRAD DONBASS	Russia	±400	720	1962	Electrodes are designed as land electrodes each with one single steel rod, with a diameter of 30 mm. Coke backfill is used.

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