

Review

Ground/sea return with electrode systems for HVDC transmission

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ARTICLE INFO

Keywords:

DC power transmission
Ground return
Ground electrodes
Sea electrodes
Shore electrodes

ABSTRACT

HVDC transmission is booming worldwide. Despite electrode systems are one of the frontiers of DC technology, being a key component of HVDC links, in the experience of the Authors many aspects of their manufacturing, design and operations are less known among the HVDC community with respect to other components, like cables and converters. Aiming at filling this gap, this paper is a survey on ground/sea return with electrode systems for HVDC links, particularly focused on the preliminary design. The configurations of HVDC systems (monopolar, homopolar, bipolar) are recalled first, highlighting the advantages of ground/sea return. Then, ground electrodes are treated, illustrating the basic parameters and geometrical arrangements for the design of ground electrodes. Later, shore and sea electrodes are illustrated. Considerations relevant to ground current close the paper.

1. Introduction

Although dating back to the 1930s [1], High Voltage Direct Current (HVDC) transmission systems are now becoming more and more competitive compared to High Voltage Alternate Current (HVAC) transmission systems, especially for bulk power transmission over long distances [2]. Indeed, the improvements in reliability, performances, costs and losses of AC/DC converters have highlighted the many technical and commercial advantages of HVDC transmission. Thus, many HVDC systems have been put in service recently [3,4].

However, the design of electrodes for HVDC transmission is not trivial, since many requirements have to be taken into account, e.g. low electrical resistance to cut transmission losses, reduced and easy maintenance, high environmental compatibility for the safety of human beings and fauna [1,5,6]. Furthermore it is important to select the electrode site so as to not interfere with the grounding systems of the converter station and to prevent the risk of electrolytic corrosion of buried/immersed metallic structures.

Several aspects of HVDC transmission are treated in many papers and books [1–4,7], with great emphasis on lines and converters. However, as for the Authors' experience, many aspects of electrode systems manufacturing, design and operations are less known among the HVDC community. Nevertheless ground/sea return and electrode systems are fundamental in the performances of HVDC links, since they enable the operation of the system as a monopole with ground/sea return. This leads to two main advantages also for bipolar systems: (1)

the bipolar dc systems can be realized in sequence, i.e. one pole first and the second later, so as to put the system in service as a monopole until the commissioning of the second pole; (2) in the final bipolar operation, in case of outage of one converter or one pole. In this condition, the DC system can transmit half its rated power; this greatly enhances the reliability and the flexibility of bipolar systems, and allows multiple configurations and operations of the dc link [2]. In addition bipolar systems equipped with electrode for ground/sea or dedicated metallic return (unbalanced bipolar systems), can switch immediately from bipolar to monopolar operation (e.g. when a fault occurs in one converter or pole) without shutting the whole system down.

This paper is a survey on ground/sea return with electrode systems for HVDC transmission, based on reference literature papers and books. The various HVDC schemes (monopolar, bipolar, homopolar) are recalled in Section 2 with peculiar reference to ground/sea return. Analytical and numerical methods to study the behavior of HVDC ground electrodes are compared in Section 3. The basic parameters and the geometrical arrangements for the design of ground electrodes are dealt with in Section 4. The design of sea electrodes is illustrated in Section 5. Section 6 is devoted to particular issues related to ground current, i.e. electrolytic corrosion, chemical aspects, interactions with pipelines, electrical effects. Conclusions can be found in Section 7.

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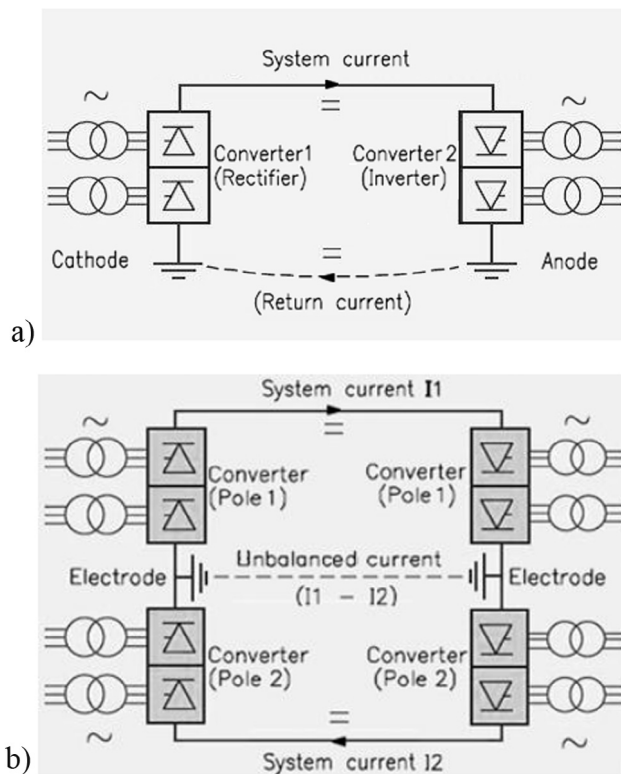


Fig. 1. (a) Monopolar HVDC scheme; (b) bipolar HVDC scheme.

2. Ground/sea return configurations

HVDC systems can work in three modes with ground/sea return: monopolar and homopolar systems in normal operation and bipolar systems in emergency operation [11]. **Monopolar** HVDC systems work with only one HV pole (Fig. 1a), and current return is via earth/sea or a metallic conductor/cable. **Homopolar** HVDC systems have two poles but operated with same polarity voltage and current return via ground/sea or a metallic conductor/cable. **Unbalanced bipolar** systems work with two poles at opposite voltage polarity with the “DC neutral” (i.e. the common point of the two converters) connected to the electrode or to the metallic conductor/cable (Fig. 1b).

Under theoretical duty the current in each pole is equal, thus the current flowing in the electrodes is zero. Under practical duty, some amps only flow due to the inevitable small deviations of equipment parameters and consequently a negligible imbalance between the pole currents occurs.

3. Analytical vs numerical methods

To properly study the behavior of HVDC ground electrodes, the distribution of electrodynamic field inside the surrounding media must be assessed. The resulting problem is a mathematically simple problem (governed by Laplace equation) defined inside a domain which can often be geometrically very complex. For this reason, until the numerical solution of Partial Differential Equations started to be used for industrial applications, the forced choice was to use analytical methods. The main drawback of analytical methods is that their applicability is limited to very simple geometries, and often they compel to somewhat simplify the physical underlying problem. The practical advantage is their high speed.

Over the years many numerical methods were developed, starting with the Finite Difference, then the Finite Element and the Finite Volume (citing the methods based on a differential approach) [8]. Also other methods based on an integral approach were developed, such as

the Boundary Element Method and the Complex Image Method. Some of these methods can easily take into account the longitudinal resistance of dispersing elements, as well as the resistance of feeding conductor, by solving a coupled problem field-circuit [9]. All these methods have pros and cons; however, even though they can potentially produce results of higher quality than those produced by Analytical methods, they normally require skilled analysts and a very detailed knowledge of the problem, which is often unknown in the preliminary phase of study. In other words, if a possible electrode location must be evaluated among a dozen of possible locations, it is unrealistic to perform a detailed survey in each candidate location. For these reasons in this paper only the Analytical and Semianalytical methods reported in literature will be described, citing the relevant Numerical Methods as reference papers. Of course, as the design is developed, the initial results must be refined using appropriate Numerical Methods, which become fundamental for the final verifications of electrode parameters. For all the aforementioned reasons, no “perfect” and self-standing Numerical Method does exist, but the skilled designer should suitably choose the right Method from a set of available Methods, both Analytical and Numerical. By the way, this approach is consistent with the relevant IEC Technical Standard [5], reporting simple Analytical Methods in its body, and quickly describing the use of the Finite Element Method in its Appendix.

4. Ground return

4.1. Properties of the soil

Ground electrodes are electrodes installed in the ground. Since current between ground electrodes passes through the soil, an accurate knowledge of the following electrical and thermal properties of the soil is needed for a proper design.

4.1.1. Resistivity

The earth core consists of low resistivity hot molten magma, but most ground current flows in the earth crust, whose resistivity is the most important factor to consider when locating and designing a ground electrode [10].

4.1.2. Thermal conductivity

The significance of thermal conductivity for ground electrode design lies in the need to predict the effectiveness of the neighboring soil to dissipate the heat caused by current in the earth [11].

4.1.3. Heat capacity

Heat capacity primarily affects the rate at which heat builds up close to a ground electrode in the earth. This parameter is a direct function of the density as well as of the moisture content of the soil [12].

4.1.4. Temperature

The natural temperature of the medium, earth or water, where an electrode is placed is important for the design of the electrode because the electrode raises the temperature of the adjacent medium.

4.1.5. Soil moisture content

Water in the soil fosters not only electrical, but also thermal conduction, since it has $\approx$ five times the thermal conductivity of average dry soil.

4.2. Design criteria of land electrodes

Design criteria of land electrodes rely on the laws of thermodynamics, geophysics and electric conduction. As a general rule, land electrodes should be located in low resistivity soil and far from: the converter station, other substations, densely populated areas, power plants, pipelines, railways, so that problems of electrolytic corrosion or

interference are strictly avoided. The distance generally should be ≥ 8 km [13]. More specific criteria relevant to the main design parameters are as follows [1]:

4.2.1. Current

Both dc and harmonic components of converter current should be carefully investigated. The dc component affects electrode size, whereas the harmonic components may interfere with communication and signaling systems. The “duty-cycle”, i.e. the definition of electrode usage when the use is discontinuous, should also be specified.

4.2.2. Ground Potential Rise (GPR)

The allowed potential rise (V_e) of an electrode to remote ground is given by electrode site thermal and electrical conduction properties, as well as allowable temperature rise. It holds [1]:

$$V_e = \sqrt{2\lambda\rho\theta} \quad [\text{V}] \quad (1)$$

where λ is soil thermal conductivity [W/m °C], ρ is soil electrical resistivity [Ω m], θ is electrode temperature rise [°C].

4.2.3. Electrical resistance

The electrode must be designed so that its voltage rise to remote ground is limited to V_e for the rated design current I_d . These requirements dictate the electrode resistance to remote ground R_e , which is given by

$$R_e = V_e/I_d \quad [\Omega] \quad (2)$$

4.2.4. Potential gradient

The land electrode must be designed so that it is electrically safe for human beings and animals; or it has to be fenced. A simplified expression of voltage gradient E on ground surface nearby a horizontal electrode is:

$$E = \left(\frac{\rho I_d}{\pi l} \right) \frac{x}{x^2 + h^2} \quad [\text{V/m}] \quad (3)$$

where x is lateral distance from electrode [m], h is depth to center of electrode [m], l is length of electrode [m]. The maximum voltage gradient E_{max} from a horizontal electrode occurs at a distance d from the electrode and is equal to [14]:

$$E_{max} = \frac{\rho I_d}{2\pi l d} \quad [\text{V/m}] \quad (4)$$

A land electrode must be sized so that the maximum voltage gradient E_{max} is less than the tolerable step voltage.

4.2.5. Temperature

An important design parameter of ground electrodes is the maximum temperature θ_{max} reached by the electrode while working at full rated current, within its time rating.

4.2.6. Time constant

Temperature θ of a land electrode rises with time t from the earth temperature at zero current, θ_{amb} , to its final steady-state temperature, θ_{max} , as follows [15]:

$$\theta = (\theta_{max} - \theta_{amb}) \left(1 - e^{-\frac{t}{T}} \right) + \theta_{amb} \quad [^\circ\text{C}] \quad (5)$$

where time constant T is equal to [16]:

$$T = \frac{\gamma}{2\lambda} \left(\frac{V_e}{\rho J} \right)^2 = \frac{\gamma}{2\lambda} \left(\frac{R_e A_e}{\rho} \right)^2 \quad [\text{s}] \quad (6)$$

where γ is soil heat capacity [J/(m³ °C)], J is current density [A/m²] and A_e is the surface area of the electrode [m²].

4.2.7. Lifetime

The lifetime of an electrode is the time the electrode can work at its rated current and operating criteria. The electrode design should grant that it remains in good working conditions throughout the whole system rated life. Lifetime strictly depends on the current density on the interface electrode-soil, which varies with the electrode material and is usually specified by the manufacturer. Normally the requested lifetime ranges from 25 to 40 years.

4.2.8. Reliability

To increase reliability and ease maintenance, the total electrode is sectionalized into discrete pieces, each fed by a disconnecting switch. In this way, maintenance, repair or replacement work can be done in one section while the other sections remain in service – provided that the out-of-service electrode section is far enough from the in-service sections. Reliability is further improved by setting more electrode lines and switches at the converter or electrode stations [17]. Related with reliability is redundancy, i.e. an agreed level of electrode oversizing, to allow it to be operated at full rated current even when a given number of sections are not in operation, for maintenance or fault.

4.2.9. Polarity (for land, sea and pond/shore electrodes)

The polarity of an electrode depends on whether the electrode is operated as a cathode to which current flows from the earth, or as an anode from which current flows into the earth. An electrode ordinarily operated as either cathode or anode is referred to as “unidirectional” electrode, while an electrode able to operate both as cathode and as anode is referred to as “bidirectional” or “reversible” electrode. Bidirectional electrodes differ from unidirectional electrodes both in design and materials; special care in design and materials has to be taken when the electrode is ordinarily operated as anode. The choice between unidirectional or bidirectional electrodes is dictated by economic and operating conditions of the system; the experience of bidirectional electrodes is still weak but their flexibility makes them more and more attractive today especially for HVDC-VSC systems.

4.3. Geometry of land electrodes

The geometric layouts of land electrodes fall into two main groups, i.e. shallow horizontal elements and vertical elements.

4.3.1. Shallow horizontal electrodes

A frequently encountered pattern of earth resistivity is the lowest in a fairly thin layer near the surface and higher in underlying layers. For this reason, and because of ease and economy of construction, most land electrodes in service are buried at shallow depths. Shallow horizontal electrodes are classified according to the pattern whereby they are arranged as [18]:

4.3.1.1. Ring electrodes. The typical arrangement of a ring electrode in the continuous shallow configuration is shown in Fig. 2a. The ring can be deformed from a perfect circle if earth conditions make it necessary, but regularity is preferable. Compared to the other patterns, and assuming that suitably-spaced feeder cables are installed, the ring pattern has the advantage that its surface current density is uniform throughout its length and that its total length for a given current is the least. A disadvantage of the ring pattern is that it requires a large area of land – with unused space in the center – which may be difficult to find. The preliminary sizing of a ring electrode expresses its resistance to remote earth as follows [19]:

$$R_e = \frac{\rho}{\pi^2 D} \ln \frac{4D}{b} \quad [\Omega] \quad (7)$$

where D is the diameter of ring center line, $b = \sqrt{dh}$ where d is the diameter of conductor and h is the burial depth from the surface of the earth to the center point of the electrode.

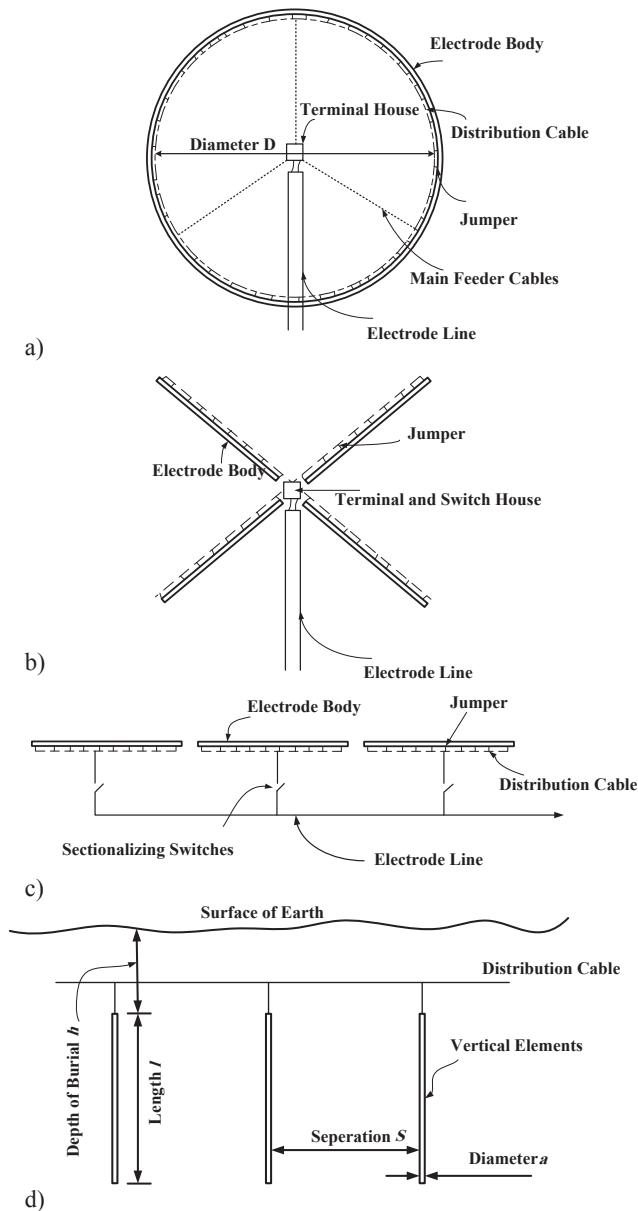


Fig. 2. Typical arrangement of: (a) continuous ring electrode; (b) star electrodes; (c) linear electrodes; (d) vertical, non-continuous electrodes.

When appropriate values are entered in (2), D is found via an iterative process by equating the value of R_e after (7) to the desired resistance to remote earth. After this preliminary design, compliance with other requirements is checked. The best electrode sizing is found in an optimization process whereby cost factors are applied to the results from the design equation.

4.3.1.2. Star electrodes. The star arrangement – shown in Fig. 2b for the sake of completeness, as this is a review paper – is an alternative configuration that was considered when land conditions are not suitable for the ring pattern [20]. However, the star arrangement has proven to be inefficient, as pointed out in the recently-issued CIGRÉ Technical Brochure 675: “in a star configuration, the elements close to the center 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 [6]”. In fact, as to the Authors’ best knowledge, there is only one electrode built using star configuration, which has been repaired a few times. Thus, star electrodes are not recommended anymore.

4.3.1.3. Linear electrodes. The linear electrode is simply arranged in a line, which needs not be perfectly straight. The linear pattern is applicable when a relatively long and narrow site is selected and a particularly suitable location would be along a river or stream, where the earth resistivity would be improved by the presence of water. The linear pattern is the most economical with respect to land requirements and it is the best suited to separation into independent sections. The material requirements of a linear electrode are competitive with those for a ring. The linear pattern has the drawback that the current density at its end points is fairly high [1,6].

The classical design equation for a linear electrode is

$$R_e = \frac{\rho}{\pi l} \left[\ln \frac{2l}{b} - 1 \right] \quad [\Omega] \quad (8)$$

where l is the length of the linear electrode.

If the linear electrode is fed only at its center, a single connection to the distribution system will suffice. However, provisions for maintenance can be readily provided by dividing the linear electrode into two or more equal sections, each fed through its own disconnecting switch, as shown in Fig. 2c [6].

4.3.2. Vertical electrodes

In addition to the type of continuous electrode buried in a horizontal configuration at shallow depth, as described above, ground electrodes on land can be constructed with a number of discrete elements whose major axes are vertical rather than horizontal. Fig. 2d shows a general arrangement of a vertical electrode consisting of multiple elements [6].

The main issue in designing vertical electrodes is ensuring that their total resistance is no more than the resistance to remote earth computed via (2). The approximate equation for the resistance to remote earth of one single vertical element (valid when its length l is $\gg$ than its diameter a) is (9)

$$R_1 = \frac{\rho}{2\pi l} \left(\ln \frac{4l}{a} - 1 \right) \quad [\Omega] \quad (9)$$

If n vertical electrode elements (assumed as having all the same diameter a and length l) are arranged in a straight line with equal spacing $s \geq l$, the total resistance R_n of the array can be found by means of (10)

$$R_n = \left[\frac{R_1}{n} + \frac{\rho}{2\pi s} \left(\frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{n} \right) \right] \quad [\Omega] \quad (10)$$

where R_1 comes from (9), n is the number of elements in the array and s is the spacing between elements.

The vertical elements are built up of carbon or metallic current distributors fixed in a bed of carbon material packed into the drilled hole. A cabling system feeds ground current to each of the vertical elements. A disconnecting switch can be installed at each element to isolate it if needed [20].

Gases generated by electrolysis are more difficult to vent in a vertical than in a horizontal electrode. In general, a vertical arrangement may be preferable if a better conducting layer is present at some depth; moreover, vertical arrangements need less space on the surface and also the step voltage on the surface is lower than in horizontal arrangements. In fact, vertical electrodes have been constructed at shallow depths (10 m), but they are more frequently built at depths of 60 m or greater (usually referred as deep hole or deep-well electrodes) in order to reach earth of lower resistivity than that found near the surface, and to channel the ground current away from possible objects of interference. One specific type of deep hole electrode has been developed and patented to be operated inside deep layers of highly conductive underground salty water; of course it must be particularly resistant to self-corrosion [21]. To be remarked that only a few electrodes of this type are in operations due to their high cost, especially during

Table 1
Materials and shapes typically used for land electrodes, with their main pros and cons.

Materials/shapes	Advantages	Disadvantages
Iron (mild steel) pipes	Low cost; ease of shipment, handling, installation; large surface area $\Rightarrow$ low current density	Faster corrosion
Cast iron pipes	Slower corrosion	More difficult to ship and handle
SiCrFe rods	Cover only part of coke filling length $\Rightarrow$ coke length used also for longitudinal current flow	risk of uneven current density outside of the coke filling (but coke has $\gg$ electrical conductivity than ground $\Rightarrow$ trench approximately equipotential)
Graphite rods	cover only part of coke filling total length $\Rightarrow$ coke length used also for longitudinal current flow	Lack of mechanical strength

maintenance (the repair of a well may be unfeasible, for example, and new wells must be drilled), and because they have often shown a story of failures, mostly due to electro-osmosis and overheating, and in one case it was determined that the cables inside the electrode were damaged due to a large pH drop created by a low buffer effect [22–25].

4.4. Materials for land electrodes

The criteria for the selection of materials for a land electrode include electrical properties, such as conductivity, and physical properties, such as resistance to mechanical abuse and corrosion [26]. For anodes the requirements are the ability to conduct electricity efficiently through their surfaces, to resist the corrosive effects of electrolysis and to have sufficient physical strength to maintain their integrity in the environment where they are installed. The same materials can be used for cathode applications, but taking care that under cathode operation most of the materials fur up.

Various materials and shapes have been used for land electrodes, having the widest application. They are listed in Table 1, with their main pros and cons [6,20,27].

The operation of a ground electrode in the earth is improved if the anode material is enclosed in a bed of conductive backfill. The net result of the backfill material is lower temperature at the electrode-earth interface and longer life of the active materials. The materials generally used for conductive backfill are coke, and coke breeze [28].

Land electrode installation is usually performed digging a trench to fill it with coke to half the final depth, to lay the distributing conductors on this layer of coke, to put the remaining half of the coke on top of the lower half, and finally to backfill the remaining space in the trench to the original grade. The arrangement described has been used for practically all the land anodes yet constructed for high-power dc lines [28].

5. Sea return

Since sea water offers an optimal path for current return and water crossing is a prime feature of HVDC, electrodes in direct contact with water represent a very interesting solution in HVDC systems. In fact, many subsea HVDC cable lines have been realized in recent years [29], not only to interconnect different transmission grids separated by sea bodies as usual [30–32], but also to bring the energy generated by offshore wind farms to the mainland [2,4]. In many cases, electrodes built on the shore of a body of salt water or in seawater near the shore are the logical choice for these lines.

5.1. Properties of sea and seabed

5.1.1. Resistivity

Seawater presents an excellent electrical conductivity, around 4–5 S/m (resistivity of 0.25–0.2 Ω m), depending on water temperature and salinity; the electrical parameters of the seabed can be very complex, depending on the geological structure of the shore.

5.1.2. Shore morphological characteristics

According to the material the seabed can be sandy or rocky; the slope can be limited, allowing to lay the electrode on the seabed, or very high, inhibiting this possibility, et cetera.

5.1.3. Presence of corrosion prone infrastructures

It must be assessed whether in the area, at least 25–30 km are located long metallic structures such as pipelines, that could be adversely impacted by the corrosion caused by electrode operations.

5.2. Design criteria of sea electrodes

The main design criteria of HVDC system sea electrode are similar to that of ground electrodes (rated current, duty-cycle, GPR, electrical resistance, lifetime, reliability, polarity); normally the increase of temperature is null or negligible, unless the electrode is heavily secluded, like some Shore electrodes. The remarkable difference is about the definition of the Electric Field produced by the electrode during its operations. Differently from ground electrodes, where the area that can be accessed is the surface of ground, in the case of sea electrode both humans (swimmers and scuba divers, for example) and marine animals can swim and potentially reach submarine areas where the Electric Field is higher than the allowed safety limit. Different values can be found in literature. Normally a value around 1.25–2 V/m can be accepted as safe. To enforce this constraint the electrode modules must be properly designed, and its behavior must be verified, for example, using the Finite Element Method.

5.3. Design of shore electrodes

Shore electrodes may be divided into two groups: beach electrodes and pond electrodes [25]. Beach electrodes are located on the beach inside the waterline; the active part of the electrode is in contact with the soil or underground water, but not directly with seawater. Pond electrodes have their active part directly in contact with sea water, within a natural or artificial bay and protected against waves and marine currents.

Fig. 3 depicts a section of a typical shore electrode, showing how the electrode environment contains two materials of widely different resistivity: water and soil [6]. The angle α (in radians) is the seabed slope, which can be assumed constant without severe errors. Since the current densities in water and earth are inversely proportional to their resistivity, it can be shown [33,34] that the potential at any distance r from the electrode, either in earth or water, and the resistance to remote earth are equal, respectively, to (11) and (12):

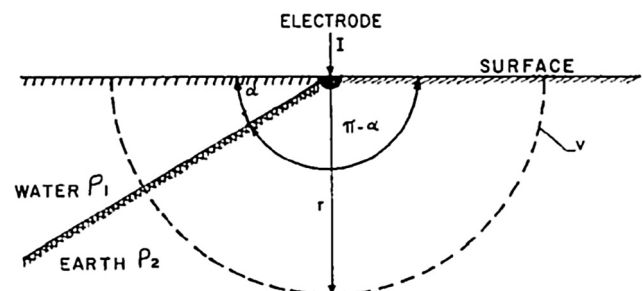


Fig. 3. Section of a typical shore electrode (after [33]).

$$V = \frac{I}{2r\left(\frac{\alpha}{\rho_1} + \frac{\pi}{\rho_2}\right)} \quad [\text{V}] \quad (11)$$

$$R_e = \frac{1}{2a\left(\frac{\alpha}{\rho_1} + \frac{\pi}{\rho_2}\right)} \quad [\Omega] \quad (12)$$

The superiority of a shore electrode in sea water over an electrode entirely in land is proven by the ratio of their resistances to remote earth, $1/\eta$. Such ratio, known as the efficiency of a shore electrode vs. a land electrode, is used in design formulas for shore electrodes and is equal to (13):

$$1/\eta = \frac{R_{ee}}{R_{es}} \left[\left(\frac{\alpha}{\pi} \right) \left(\frac{\rho_2}{\rho_1} \right) + 1 \right]^{-1} \quad (13)$$

where R_{ee} is earth resistivity and R_{es} is water resistivity.

Eq. (13) shows that: (1) the higher the earth resistivity vs. the water resistivity, the more efficient is a shore electrode; (2) the steeper the slope α into the water, the more efficient is a shore electrode, although physical constraints set a limit on α .

The design of shore electrodes presents a set of conditions and requirements different from those in the design of land electrodes. It is essential that the electrode elements always be in contact with the water, so that a pumping system may be needed. A constantly changing water supply is necessary in order to replace the chlorine and oxygen released by an anodic electrode, as well as to dissipate the heat generated at the electrode-water interface. Without water flow, corrosion of the anode and temperature rise increase greatly. In addition to water supply, the conducting elements in a shore electrode require support and physical protection of a different sort from that found in land electrodes [35].

5.4. Design of sea electrodes

Where land or shore electrodes are found to be undesirable due to lack of a suitable site or the need to avoid wave action or to reduce ground currents in the earth, the electrode can be located in the sea at any distance from the shore (in practice typically > 100 m) [36]. An efficient method to determine the main electrode parameters is described in [37]. Such reference provides also a method to assess the potential corrosion risk caused to nearby infrastructures. In order to reach a sufficiently-low grounding resistance, a sea electrode usually includes a large number of modules; such modules may be grouped into sub-electrodes, each sub-electrode being fed from a separate feeder cable, and comprising as active part at least one module. In this way redundancy is implemented, so as to account for possible damages to the electrode or to feeding cables.

A type of modules used to build sea electrodes can be realized with concrete “boxes” in which electrode active parts (bars) are suspended and in full contact with water or, alternatively, the bars are buried in the seabed surrounded with coke and then protected with gravel above. Coke has the effect of spreading the current field at maximum, helping to reduce the local field; furthermore it increases the lifetime of bars by much, as the conduction on the bar surface becomes mostly electronic (bars-coke), instead of ionic (bars-seawater). The gravel serves to prevent coke (normally lighter than water) from floating away and to keep it under mechanical pressure (increasing its electrical conductivity) [38].

5.5. Materials for sea electrodes

Typically, sea electrodes are assembled from prefabricated standardized parts, such as plates, sub-electrode elements and barriers; to date, three main types of sea electrodes are used:

5.5.1. Sea electrodes using titanium as their active part (anodic operation mostly)

They consist of a number of titanium nets horizontally laid on the sea bed or at ≈ 1 m above the sea bed. Each single net represents an electrode element; the nets are interlinked into an expanded mesh. Titanium net wires are coated with titanium oxides to prevent corrosion. A layer of noble metal oxide (called MMO, “mixed metal oxides”) can be added in order to further increase the selectivity for oxygen, i.e. the quantity of oxygen discharged with respect to chlorine, for a fixed value of electrical charge passing through the electrode. Therefore MMO, although sophisticated and expensive, performs the best as for the electrode environmental impact.

Each net is sandwiched with polyethylene pipes (some cm of diameter) properly spaced in order to prevent mechanical damages to the net. For nets directly laid on the seabed, a layer of gravel beneath and upon the net is usually provided to prevent local hot spots, uncontrolled current density and electric field values on the net surface due to the sand in direct contact with the net. On the other hand, nets installed above the seabed need a special support structure usually made of hard plastics. Then special countermeasures are taken to prevent marine currents from dragging support structures away (e.g. concrete blocks). Titanium nets can be used also as bidirectional electrodes, although wide experience is missing; however for bidirectional use a reduced current density compared to anodic operation only seems advisable, so as to avoid damage to the active elements during cathodic operation. This specific kind of damage is an embrittlement due to a reaction between metallic Titanium and the Hydrogen discharged in cathodic operations, which leads to the formation of Titanium Hydride.

5.5.2. Sea electrodes using bare copper conductors as active part (cathodic operation only)

Copper stranded conductors are usually selected. Furthermore copper can give reliable compression clamp connections or welding connections able to withstand the harsh environmental conditions. These electrodes are laid linearly at 1–1.5 m above the seabed to prevent local hot spots, uncontrolled current density and electric field values due to the sand in direct contact with the net. Properly spaced concrete blocks are used to support the conductor.

5.5.3. Sea electrodes using coke or SiFeCr-rods as their active part (for reversible operation)

The electrode has cylindrical rods made of graphite or of SiFeCr alloy as active elements. A number of rods laid on the seabed, properly spaced and interconnected, form the electrode. As in the previous types, direct contact between sand and active elements has to be prevented so as to avoid hot spots, uncontrolled current density and electric field values leading to premature wear-out of the elements. Thus, again a gravel layer upon and beneath the elements helps avoiding direct contact of sand with the active parts.

6. Particular issues related to return current

Buried and immersed metallic structures are subjected to corrosion due to natural currents in the soil and in the water (e.g. telluric currents, tidal currents in immersed structure are also responsible of natural corrosion) [1]. Cathodic (where the currents enters in the metal) and anodic (where the current leaves the metal) reactions at the electrode soil/water interface strongly depend on the type of electrolyte and the local thermodynamic conditions. Anode reactions lead to corrosion and then wear-out of the metallic material, while cathodic reactions lead to formation of hard crusts (usually oxides and hydroxides of the species dispersed in the soil/water).

The metal rate of loss during an anodic reaction is dependent on the type of material and follows Faraday’s law. This law states that the amount of metal passing in solution is proportional to the charge exchange with the electrolyte [1]:

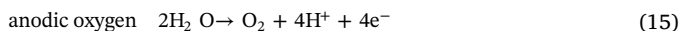
$$m = K_{ec} q = K_{ec} \int_0^t i dt \quad [\text{kg}] \quad (14)$$

where m is the mass of metal removed after time t , q is the exchanged charge [C] with the electrolyte, i is electric current [A], and K_{ec} is the electrochemical equivalent of anode material [kg/C].

In practice the current density is not uniform over the whole electrode surface. Thus the total surface shall be divided in sub-surfaces where the current density can be regarded as uniform and the contribution of metal loss on each single sub-surface shall be added. Otherwise, a mean value of current density can be taken for the whole electrode surface, thereby getting an approximate estimate of metal loss [39].

Following this approach, once the maximum permissible metal loss has been established, the maximum allowed current density of the electrode is evaluated. In any case the process is not so straightforward since other aspects shall be taken into account, e.g. electrode material characteristics, chemical compounds existing into the soil/water, chemical-physical aspects behind the possible chemical reactions that take place during both anodic and cathodic electrolysis, electrochemical phase boundary reactions, electrochemical kinetics, etc. [1].

Anodic process: in an anodic process in water of very low or zero salinity, O_2 (oxygen) is evolved, which is usually not seen as a problem since the atmosphere is partly made of O_2 . As salinity increases, also Cl_2 (chlorine) is formed, but a substantial production of O_2 still remains in salinities up to sea-water level. The sum of evolved gases matches the law establishing that the mass of decomposed material is proportional to the electric charge. The two chemical reactions are [40]:



The ratio “evolved Cl_2 ” over “evolved Cl_2 and O_2 ” is called the chlorine efficiency (or selectivity) and also corresponds to current percentage that forms chlorine. This value depends on electrode material, salinity (increasing with salinity), water temperature, pH and current density [40].

Immediately after the formation of chlorine gas, a hydrolysis reaction takes place, forming hypochlorous acid (HOCl), chloride ions and hydrogen ions. Hypochlorite ions are themselves unstable and give rise to further products. Normally such products react with other components normally present in seawater that further reduce their potential effects.

Aiming at reducing chlorine formation as much as possible, a low current density shall be selected, which means large size electrodes. Low current densities cannot be achieved with small-size sub-electrodes transferring the current to water – e.g. Si-Cr-Fe-rods directly in water – but the use of coke helps making low current densities feasible [40].

Cathodic process: at the cathode, where electrons leave the electrode and react with water molecules, gaseous H_2 (hydrogen) is released and partly dissolved in water. When H_2 concentration in water saturates and little or no exchange of electrolyte occurs close to the cathode, the chemical reactions are:



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



The hydrogen not dissolved in water is released to the atmosphere. If a little exchange of water occurs, a strong base NaOH (sodium hydroxide) comes up around the cathode. Deposits of chalk-like substances tend to form on the surface of cathodic sea electrodes (the so-called “cathodic fouling”). These deposits are not harmful to the electrode surface, but they may involve local extra resistance and then heating. If such heating is excessive, the deposit may even be blasted off

due to steam expansions inside the deposit itself [40].

The reversible operation or changes from anodic to cathodic operation may be a problem for some materials. When working as an anode, the electrode surface develops an acid chemical environment and is polarized accordingly, while a cathode develops a basic environment. Around both anodic and cathodic electrode polarization takes up. In case of reverse operation the chemical local environment changes switching from acid to basic and vice versa. Both coke and graphite are able to withstand basic environment and then they withstand current reversals well, on the contrary silicon iron does not. In fact the SiO_2 layer “bursts” under basic environment. However, the Santa Monica sea electrode of the Pacific Direct Current Intertie must be cited as an exception: it was built using Si-Cr-Fe-rods directly immersed in water and under reversible polarity. Apparently due to the limited usage, it was reported in literature that bars worked without particular problem also under reversed polarity. Likewise, titanium and coated titanium, which withstand the harsh anodic condition quite well, will not withstand cathodic conditions [40], unless a significantly-reduced value of current density is imposed.

6.1. Effects on a pipeline

An HVDC power transmission system may cause corrosion of pipelines or other underground structures located in the electric field produced by the HVDC ground electrode [41,42]. A method of protection of buried or immersed metal objects from corrosion is the cathodic protection, an effective electrochemical method for corrosion protection of metallic objects surrounded by an electrolyte (e.g. water and earth). In this method, the protected object is made a cathode by keeping it at a negative potential with respect to the surrounding soil or water, so that current enters the object from the soil. Then, current is drained from the object by a metallic conductor and delivered to one or more “sacrificial” anodes whereby it returns to earth. Sacrificial anodes are made of cheap material to be easily replaced and whose integrity is not so necessary as that of the pipe (cathode) for containing pressure, excluding moisture.

Cathodic protection involves that the potential of the protected object is lowered – or the potential of the drained charge is raised – from the corrosion potential to a potential differing for different metals and/or electrolytes. Three methods are typically used to raise the potential of the drained charge [43]:

- (1) forced drainage, where a dc source – e.g. a battery, a dc generator, or a rectifier – is used;
- (2) galvanic-anode drainage: the anodes are made of zinc, aluminum or magnesium, with negative electrode potential with respect to iron or lead. The ground moisture is the electrolyte of an element having the protected object as cathode, and no separate battery is needed. Inside any element on discharge, the current is raised in potential. Actually the battery electromotive force is the difference of changes of potential occurring at the contact surface between the electrodes and the electrolyte;
- (3) bus drainage, used principally to protect pipes near electric railways: pipelines are bonded to the most negative point available (e.g. ground bus at rectifier substation on the negative terminal of a negative feeder booster).

For submarine pipelines the only possible protection is the use of galvanic sacrificial anodes: typically evenly-spaced rings, concentric with the pipe, made of a particular aluminum alloy, designed to be efficient along the whole operational life of the pipeline. Normally the pipe is coated with a protective coating, to make the protection by galvanic sacrificial anodes more effective. Then things may be worse for HVDC electrode design, as the potential galvanic corrosion due to the HVDC current, instead of spreading all along the pipe, tends to concentrate on the small cracks of the coating, causing a quick, localized

corrosion known as “pitting corrosion”. In this case, extreme care must be taken to prevent adverse effects [44] and specific simulations are needed.

6.2. Electrical effects

The dc current may cause electrical interference problems on external installations. The main areas that must be studied in connection with this electrical interference are:

6.2.1. Railway signaling

HVDC ground currents picked up and discharged from railway tracks may deactivate railway signaling systems or even cause false signaling. The problem can usually be solved by using a higher battery voltage and a less sensitive track relay. If this is not enough, the track circuits can be turned into ac systems or coded track circuits.

6.2.2. Ac transmission effect

Many three-phase transmission lines terminate at both ends at substations. Zero-sequence direct currents may flow in such lines. These currents tend to saturate the magnetic cores unsymmetrically. Such troubles may be prevented by locating the dc ground electrode far enough both from the converter station itself and from other substation. Adequate separation of the electrode from substations is advisable also for another reason, i.e. reducing electrolytic corrosion of the substation structures and ground mat.

6.2.3. Transformer core saturation

A related problem arising from dc currents in neutral circuits is transformer core saturation [45–47]. A method for mitigating saturation, other than relocating the ground electrode, is to insert a small resistance in the grounded neutral connection. Another method – successful in mitigating direct current flow in distribution transformer – is to separate the neutrals on distribution transformers. By separating the neutrals and using separate ground rods, the direct current flow is reduced and saturation is not a problem. Other methods rely on a DC feeder, able to exactly compensate the DC that otherwise would flow through the transformer.

6.2.4. Electro-osmosis

Another issue that must be adequately taken into account is the electro-osmosis, i.e. the movement of charged water particles away from anodic ground electrodes, thereby reducing moisture levels. If this phenomenon is uncontrolled, the soil may run dry and therefore its electrical conductivity could greatly increase, leading to an increase of losses and unacceptable temperature rise or even electrode failures and decommissioning. Even though the occurrence of this phenomenon depends on many parameters such as temperature and pressure, its risk can be reduced by limiting the current density on electrode surface; a commonly adopted limit is 1 A/m^2 [6] or even lower, according to the local conditions. The use of a coke bed greatly increases the situation, as the conduction between the dispersing electrode and the coke is electronic, and the value of current density on the interface between coke and soil (i.e. where electro-osmosis may occur) can be greatly reduced by suitably dimensioning the coke trench.

7. Conclusion

Ground HVDC electrodes, successfully used since half a century, can be precious as they allow to reduce the cost of the link; in the past they allowed the use of a single conductor (for monopolar links, using at full time the ground as return conductor), now they allow to operate a bipolar plant at half power in case of fault (normally over short time-limited intervals). Without ground electrodes, the only alternative is the use of an expensive – although increasingly used – return conductor, of the same length of the link. The cost of such a conductor is similar to

that of one high voltage conductor. This can be acceptable for very short links, where a large fraction of the total cost is given by conversion stations; on the contrary, long HVDC submarine links could reduce their economic attractive. As environmental risks can be minimized, by performing detailed design studies and simulations, the use of metallic return can be limited.

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