Ground/Sea Return with Electrode Systems for HVDC Transmission

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Abstract-- **HVDC transmission is booming worldwide. Despite electrode systems are one of the frontiers of DC technology, being a key component of HVDC links, they are seldom treated in the literature. Aiming at filling this gap, this paper is a survey on ground/sea return with electrode systems for HVDC links. The configurations of HVDC systems (monopolar, homopolar, bipolar) are recalled first, highlighting the advantages of ground/sea return. Then, ground electrodes are treated, treating 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.**

***Index Terms*-- DC Power Transmission, Ground Return, Ground Electrodes, Sea Electrodes, Shore Electrodes.**

I. 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.

Despite several aspects of HVDC transmission are treated in many papers and books [1]-[4],[7], ground/sea return and electrode systems are scarcely dealt with in the literature. Nevertheless, they 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 tutorial survey about ground/sea return with electrode systems for HVDC transmission. As such, it relies on reference literature papers and books. The various HVDC schemes (monopolar, bipolar, homopolar) are recalled in Section II with peculiar reference to ground/sea return. The basic parameters and the geometrical arrangements for the design of ground electrodes are dealt with in Section III. The design of sea electrodes is illustrated in Section IV. Section V 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 VI.

II. 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 [1]. Monopolar HVDC systems work with only one HV pole (Fig. 1.a), 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. 1.b).

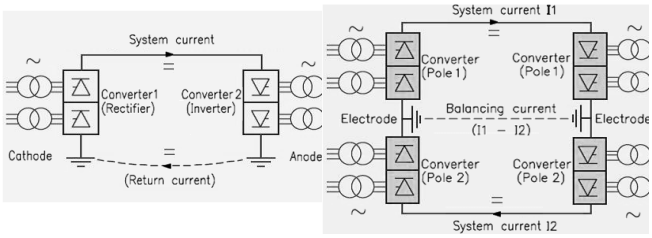
Under theoretical duty the current in each pole is equal, thus the current flowing in the electrodes is zero. Under practical duty, some amps only flow due to the inevitable small deviations of equipment parameters and consequently a negligible imbalance between the pole currents occurs.

III. Ground Return

A. Properties of the Soil

Ground electrodes are electrodes installed in the ground. Since current between ground electrodes passes through the

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011



a) b)

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

soil, an accurate knowledge of the following electrical and thermal properties of the soil is needed for a proper design.

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 [8].

2) Thermal Conductivity: The significance of thermal conductivity for ground electrode design lies in the necessity to predict the effectiveness of the soil where the electrode is located to dissipate the heat caused by current in the earth [9].

3) Heat Capacity: Heat capacity primarily has to do with the rate at which heat builds up in the vicinity of 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 [10].

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 acts as a heating element, raising the temperature of the adjacent medium.

5) *Soil Moisture Content*: Water in the soil fosters not only electrical conduction, but also thermal conduction, since it has ≈ five times the thermal conductivity of average dry soil.

B. Design Criteria of Land Electrodes

The design of ground electrodes relies on the laws of thermodynamics, geophysics and electricity conduction. The design criteria of HVDC system electrode are as follows [1]:

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.

2) Ground Potential Rise (GPR): The allowed potential rise (V_e) of an electrode to remote ground is determined by electrode site physical properties of heat conductivity and electrical resistivity and allowable temperature rise. It holds [1]:

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

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

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

$$R_e = \frac{V_e}{I_d} \quad [\Omega] \tag{2}$$

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

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

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 [12]:

$$E_{max} = \frac{\rho I}{2\pi l d} \quad [V/m] \tag{4}$$

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

5) 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 [13]:

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

where time constant T is equal to [14]:

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

where γ is soil heat capacity [J/m^3·°C], J is current density [A/m^2] and A_e is the surface area of the electrode [m^2]. The

6) 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.

7) 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 [15].

8) Polarity (for ground, sea and pond/shore electrodes): The polarity of an electrode depends on whether the elec-

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

trode 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.

9) Temperature: An important design parameter of ground electrodes is the maximum temperature reached by the electrode while working at full rated current, within its time rating.

C. Design of Land Electrodes

Land electrodes should be located in low resistivity soil and far from: the converter station, other substations and 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 [16].

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

1) Shallow Horizontal Electrodes: The most 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 [17]:

a) *Ring electrodes:* The typical arrangement of a ring electrode in the continuous shallow configuration is shown in Fig. 2.a. The ring can be deformed from a perfect circle if earth conditions make it necessary, but regularity is preferable. Compared to the other patterns, 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 [18]:

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

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.

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.

b) Star electrodes: The star arrangement, shown in Fig. 2.b, is an alternative configuration used especially where land conditions are not suitable for the ring pattern. The advantage of the star pattern lies in its ability to conform to areas of varying geotechnical properties, since the pattern does not need to be perfectly regular and the number of legs can be arbitrary. The disadvantages are that the star requires somewhat more area than the ring and that there is a relative concentration of current at the extremities and in the center of the legs: for this reason star electrodes may have any number of legs from three up, but more than six legs are not practical.

The equivalent of (7) for the star electrode is

$$R_e = \frac{\rho}{\pi l}\left[ln \frac{2l}{nb} + N(n)\right] \quad [\Omega] \tag{8}$$

where l is the total length of the electrode, n is the number of legs in the star, and $N(n)$ is a factor depending on n.

When a star electrode is fed only at the center of the array, the electrode to ground resistance should be corrected to account for uneven current distribution by means of (9) [6]:

$$R_{in} = \mathrm{R_e}\left(\frac{\mathrm{R_l}}{\mathrm{R_e}}\right)^{\frac{1}{2}} \coth\left(\frac{\mathrm{R_l}}{\mathrm{R_e}}\right)^{\frac{1}{2}} \quad [\Omega] \tag{9}$$

where R_{in} is the corrected and R_e the uncorrected electrode to ground resistance and R_l is the longitudinal resistance, each of one single electrode leg. The correction is applied to each leg separately. If current is supplied evenly down each leg by distribution cables, correction is not necessary. Resistance to remote earth is found with the same procedure as for the ring.

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

The external ground circuit is normally brought to the center of a star electrode, where it is distributed to each leg through disconnecting switches, which serve to isolate individual sections. Thus, any section can be removed from service for maintenance while still permitting at least partial rated load through the remaining sections. The use of distribution cables along the legs of the star is highly recommended for better equalization of current density [19].

c) 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 appreciably less than for a star and are competitive with those for a ring. The linear pattern shares with the star the disadvantage that there is a relatively higher current density at its end points [1],[6].

The classical design equation for a linear electrode is

$$R_e = \frac{\rho}{\pi l}\left[ln\frac{2l}{b} - 1\right] \quad [\Omega] \tag{10}$$

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. 2.c [6].

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. 2.d 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 >> than its diameter a) is (11)

$$R_1 = \frac{\rho}{2\pi l}\left(ln\frac{4l}{a} - 1\right) \quad [\Omega] \tag{11}$$

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 (12)

$$R_n = \left[R_1 + \frac{\rho}{2\pi s}\left(\frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}\right)\right] \quad [\Omega] \tag{12}$$

where R_1 comes from (11), n is the number of elements in the array and s is the spacing between elements.

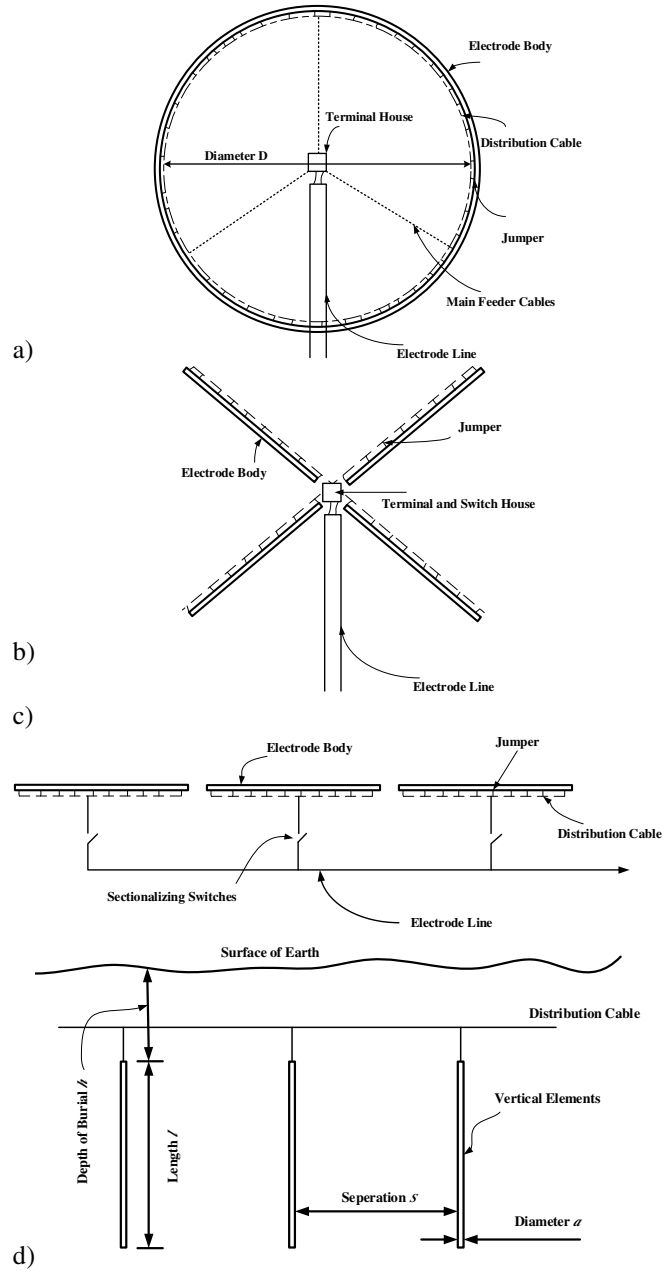


Fig. 2. Typical arrangement of: (a) continuous ring electrode; (b) star electrodes; (c) linear electrodes; (d) vertical, non-continuous electrodes

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 [19].

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 (10 m) depths, but they are more frequently built at depths of 60 m or greater (usually referred as deep hole electrodes) in order to reach earth of lower resistivity than that found

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

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 is must be particularly resistant to self-corrosion [20].

D. *Materials for Land Electrodes*

The criteria for the selection of materials for a land electrode include electrical properties, such as conductivity and physical qualities, such as resistance to mechanical abuse and corrosion [21]. 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 operations most of the materials fur up.

Various materials have been used. Iron in the form of mild steel, cast iron, SiCrFe rods and graphite rods had the widest application. Mild steel or "black iron" pipe has the advantages of: low cost; ease of shipment, handling and installation; large surface area, thus low current density. Cast iron pipe corrodes at a slower rate than steel, but it is more difficult to ship and handle. SiCrFe rods normally cover only a part of the total length of the coke filling, hence the coke column is used also for longitudinal flow of current. There is a certain risk of an uneven current density on the outside of the coke filling. Also graphite rods, as SiCrFe rods, cover only a part of the length (or depth) covered by the coke [11], [19]. Anyway, as the coke has far higher electrical conductivity than ground, the trench can be regarded as approximately equipotential.

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 [22].

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 [22].

IV. 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 [23], not only to interconnect different transmission grids separated by sea bodies as usual [24]-[26], but also to bring the energy generated by off-shore 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.

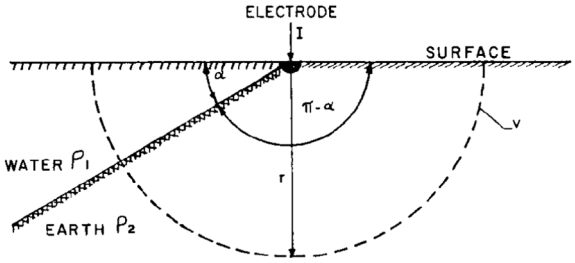


Fig. 3. Section of a typical shore electrode (after [28]).

A. *Design of Shore Electrodes*

Shore electrodes may be divided into two groups: beach electrodes and pond electrodes [27]. 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.

Figure 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 [28],[29] 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 (13) and (14):

$$V = \frac{I}{2r\left(\frac{\alpha}{\rho_1} + \frac{\pi}{\rho_2}\right)} \quad [V] \tag{13}$$

$$R_e = \frac{1}{2a\left(\frac{\alpha}{\rho_1} + \frac{\pi}{\rho_2}\right)} \quad [\Omega] \tag{14}$$

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 (15):

$$1/\eta = \frac{R_{ee}}{R_{es}}\left[\left(\frac{\alpha}{\pi}\right)\left(\frac{\rho_2}{\rho_1}\right) + 1\right]^{-1} \tag{15}$$

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

Equation (15) 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

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

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 [30].

The electrical resistance of an individual vertical element of a shore electrode which is simply suspended in water can be calculated by means of (11), considering only the resistivity of the water. For an element installed in a pipe, the electrical resistivity of the various surrounding media must be considered.

B. 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) [31]. An efficient method to determine the main electrode parameters is described in [32]. 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) [33].

C. 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:

a) *sea electrodes using titanium as their active part (anodic operation only)*: 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.

b) *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.

c) *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.

V. 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

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

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]:

$$m = K_{ec}q = K_{ec}\int_0^t idt \quad [kg] \tag{16}$$

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 [34].

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].

Electrolysis takes place both in the soil and in the water. In the case of soil the production of oxygen at the anode and hydrogen at the cathode are negligible due to the scanty amount of water and furthermore.

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 [35]:

anodic oxygen $$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{17}$$

anodic chlorine $$2Cl^- \rightarrow Cl_2 + 2e^- \tag{18}$$

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 [36].

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 [36].

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:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{19}$$

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

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \tag{20}$$

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 [35].

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 [35], unless a significantly-reduced value of current density is imposed.

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

A. 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 [37]. 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. 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 [38]:

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 a battery having the protected object as cathode, and no separate battery is needed. Inside any battery 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 [39] and specific simulations are needed.

B. 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 [40], [41]:

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.

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.

3) Transformer core saturation: a related problem arising from dc currents in neutral circuits is transformer core saturation. 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 [42].

VI. 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 –and rarely 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 lose their attractive. Environmental risks can be minimized, by performing detailed design studies and simulations.

VII. References

[1] E.W. Kimbark, *Direct Current Transmission*, Vol. 1, John Wiley and Sons, New York, 1971.

[2] M.P. Bahrman, B.K. Johnson, "The ABCs of HVDC transmission technologies", *IEEE Pow. En. Mag.*, Vol. 5, No. 2, pp. 32-44, Mar-Apr. 2007.

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011

[3] T.J. Hammons, V.F. Lescale, K. Uecker, M. Haeusler, D. Retzmann, K. Staschus, S. Lepy, "State of the art in Ultrahigh-Voltage transmission", *Proc. of IEEE*, Vol. 100, No. 2, pp. 360-390, 2012.

[4] G. Mazzanti, M. Marzinotto, *Extruded Cables for High Voltage Direct Current Transmission: Advances in Research and Development*, Power Engineering Series - Wiley-IEEE Press, New York, Jul. 2013.

[5] IEC PAS 62344 "General guidelines for the design of ground electrodes for HVDC links (NPPAS)", CIGRÉ 2007-05.

[6] EPRI EL_2020 Research project 1467-1, "HVDC Ground Electrode Design".

[7] J. Arrillaga, *High Voltage Direct Current Transmission*, IEE Publ., London, UK, 1998.

[8] H. Thunehed, U.Åström, B. Westman, "Geophysical and geological pre-investigations for HVDC-electrodes", IEEE PES Conference and Exposition in Africa, pp. 1-3, Johannesburg, South Africa, 16-20 Jul. 2007.

[9] H. Greiss, D. Mukhedkar, P.J. Lagace, "Computations of soil temperature rise due to HVDC ground return", Proc. of 1989 ACM/IEEE Conference on Supercomputing, pp. 86-95, 1989.

[10] H. Greiss, D. Mukhedkar, P.J. Lagace, "Transient analysis of heat dissipation due to a HVDC ground electrode", *IEEE Trans. Power Del.*, Vol. 4, Vol. 4, No. 2, pp. 916-920, 1989.

[11] F. S. Prabhakara, J.F. Torri, D.M. DeCosta, T.W. Williams, "Design, commissioning and testing of IPP ground electrodes", *IEEE Trans. Power Del.*, Vol. 3, No. 4, pp. 2037-2047, 1988.

[12] W. Ruan, J. Ma, J. Liu, F. P. Dawalibi, R. D. Southey, "Performance of HVDC ground electrode in various soil structures", International Conference on Power System Technology, pp. 962-968, 13-17 Oct. 2002.

[13] Y. Shi-chao, Z. Dan-yang, S. Fei, C. Run-hui, C. Wen-han, Z. Hao, "Research on common grounding electrode in HVDC", 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011.

[14] H. Greiss, D. Mukhedkar, P. J. Lagace, "Heat dissipation computations of a HDVC ground electrode using a supercomputer", *IEEE Trans. Power Del.*, Vol. 5, No. 4, pp. 1802-1810, 1990.

[15] S. Zhenxia , L. Jiang , L. Yu , Z. Qiang, "Research and application of the control and protection strategy for the ±500kV Xiluodu-Guangdong double bipole HVDC project", 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011.

[16] Y. Yang , X. Liu, F. Yang, "Soil structure effect on transformer DC bias", IEEE International Conference on Industrial Technology (ICIT), pp. 535-540, Feb. 26 - Mar. 1, 2014, Busan, Korea, 2014.

[17] M. Jinxi, F.P. Dawalibi, W. Ruan, "Design considerations of HVDC grounding electrodes", IEEE/PES Transmission and Distribution Conference and Exhibition, pp. 1-6, Dalian, China, 2005.

[18] P. Girdinio, P. Molfino, M. Nervi, M. Rossi, A. Bertani, S. Malgarotti, "Technical and compatibility issues in the design of HVDC sea electrodes", International Symposium on Electromagnetic Compatibility (EMC EUROPE), 17-21 Sep. 2012.

[19] R.J. Holt, J. Dabkowski, R.L. Hauth, *HVDC Power Transmission Electrode Siting and Design*, Oak Ridge National Laboratory, 1997.

[20] A.B. Permascand, *Apparatus and Method for Transmission of High Voltage Direct Current*, World Patent WO 95/00984, 1995.

[21] IEC TS 62344, Design of earth electrode stations HVDC links – General guidelines, Ed. 1.0, Jan. 2013.

[22] R. J. Moore, "Cahorabassa-Apollo HVDC link", 4th IEEE AFRICON, Vol. 2, pp. 699-704, 1996.

[23] T. Worzyk, *Submarine power cables*, Spinger-Verlag, Berlin, 2009.

[24] R.Rendina et al., "The realization and commissioning of the ±500 kV 1000 MW HVDC link Sardinia Island – Italian Peninsula (SAPEI)", CIGRE Session paper B1-101, Paris (France), Aug. 2012.

[25] Y. Ohki, "Development of XLPE-insulated cable for High-Voltage DC submarine transmission line (1)", *IEEE Electr. Insul. Mag.*,Vol. 29, No. 4, pp. 65-67, 2013.

[26] M. Bacchini R. Grampa, M. Marelli, T. Westerweller, N. Kelley, "200 kV DC extruded cables crossing the San Francisco Bay", CIGRE Session paper B1-105, Paris, France, Aug. 2010.

[27] Nalcor Energy - Lower Churchill Project, "DC1250 - Electrode Review Types and Locations", Hatch Publ., Labrador, Canada, Mar. 2010.

[28] D. Kovarsky, L. J. Pinto, C. E. Caroli, N. Santos, "Soil surface potentials induced by Itaipu HVDC ground return current. I. Theoretical evaluation", *IEEE Trans. Power Del.*, Vol. 3, No. 3, pp 1204-1210, 1988.

[29] S. Rusck, "HVDC power transmission: problems relating to earth return", *Direct Current*, pp. 290-300, Nov. 1962.

[30] G. Kransnick, "Hawaii deep water cable program, phase II-C, task 1: environmental contraints to use of a sea electrode in a submarine transmission cable system in Hawaii", Parsons Hawaii Publ., May 1987.

[31] Y. Iossel, G. Kazarov, V. Koski, A. Poliakov, H. Gebhardt, "Sea electrode for a high voltage direct current transmission system", European patent specification, 2001.

[32] E. Uhlmann, *Power transmission by direct current*, Chapter 15, Springer-Verlag, New York, 1975.

[33] P. Molfino, M. Nervi, M. Rossi, S. Malgarotti, A. Odasso, "Concept design and development of a module for the construction of reversible HVDC submarine deep-water sea electrodes", accepted for publication in *IEEE Trans. Power Del.*, DOI 10.1109/TPWRD.2016.2555882, 2016.

[34] J. He, R. Zeng, B. Zhang, *Methodology and Technology for Power System Grounding*, Wiley-IEEE Press, New York, Jan. 2013.

[35] K. Tykeson, A. Nyman, H. Carlsson, "Environmental and geographical aspects in HVDC electrode design", *IEEE Trans. Power Del.*, Vol. 11, No. 4, pp. 1948-1954, 1996.

[36] P.J. Lagace, J.-L. Houle, H. Greiss, D. Mukhedkar, "Computer aided evaluation of pipeline current near toroidal HVDC ground electrodes", *IEEE Trans. Power Del.*, Vol. 4, No. 1, pp. 216-222, 1989.

[37] H. Rosenberg, "Electric power, HVDC from land to off-shore structures utilizing sea-electrodes for return current, concerns and precautions with regard to environment and corrosion", Balslev Consulting Engineers, Glostrup, Denmark, 2014.

[38] EN 50162, *Protection against corrosion by stray current from direct current systems*, Ed 1.0, Dec. 2004.

[39] DONG Naturgas A/S, "BalticPipe, Offshore Pipeline Environmental Impact Assessment", Appendix J, 2001. http://www.ens.dk/.

[40] Z. Rong, Y. Zhanqing, H. Jinliang, Z. Bo, Niu, "Study on restraining DC neutral current of transformer during HVDC monopolar operation", *IEEE Trans. Power Del.*, Vol. 26, No. 4, pp. 2785-2791, 2011.

[41] L. Bolduc, M. Granger, G. Pare, J. Saintonge, L. Brophy, "Development of a DC current-blocking device for transformer neutrals", *IEEE Trans. Power Del.*, Vol. 20, No. 1, pp. 163-168, 2005.

[42] X. Zhou, Z. Zhou, Y. Maa, "Research on DC magnetic Bias of Power Transformer", Proc. of 2012 International Workshop on Information and Electronics Engineering (IWIEE), *Procedia Engineering*, Elsevier, Vol. 29, pp. 452-455, 2012.

DOI: https://doi.org/10.1016/j.ijepes.2018.02.011