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Review

An Overview on Reversible Sea Return Electrodes for HVDC Links

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Abstract: HVDC electrodes are usually implemented in HVDC links to avoid the installation of a metallic return. Submarine cables, especially those dealing with lengths of thousands of kilometers, are expensive, and high costs of laying are normally expected. Due to the high number of reversible HVDC links, the marine electrodes must be able to withstand both anodic and cathodic operations, which leads to careful considerations in terms of the material to be used. This paper shows the state of the art of the currently installed reversible sea return electrodes, focusing on the type of installation (sea, shore or pond electrodes) and on the material used, from the first plant installed in 1954 up to the more recent ones established during the XXI century. All reported data derive from publicly available sources. Moreover, since nowadays environmental issues are among the most important topics, for each material and for each type of installation, a guideline on the possible interferences caused by marine electrodes with the surrounding environment is proposed.

Keywords: HVDC; electrodes; environmental issues

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1. Introduction

Nowadays, High-Voltage Direct-Current (HVDC) links are increasing their capability of integrating renewable energy sources, improving power systems performances and interconnecting grids. In the past, HVDC monopolar connections were mainly based on line-commutated converters (LCC) [1], which guaranteed that the current would flow in a single direction. Further on, the technology moved to voltage-sourced converters (VSC), able to guarantee more flexible solutions [2–6] but having to manage a return current of either sign.

Despite the converter technology installed, the presence of electrodes in HVDC links depends on the type of configuration. The monopolar configuration, characterized by a single pole, needs a return path for the current which can be provided by a metallic return or an electrode. In this case, the electrodes have to withstand the rated current for the whole operation time of the HVDC link [7,8]. Bipolar configurations, i.e., characterized by two poles and typical of those cases where the power flow is bidirectional, can be divided in two main categories: symmetrical (or balanced) and asymmetrical (unbalanced). In the first one, the current in the two poles is exactly the same, and any asymmetry between the two poles, although minimal, gives rise to a voltage difference with respect to the ground of the two pole voltages. On the other hand, asymmetrical systems (i.e., systems that can operate independently of the two poles) deal with small differences between the currents flowing in the two poles for the inevitable (small) asymmetries between the two poles. As a consequence, a ground return current is unavoidable when the voltages of the two poles are maintained equal with respect to the ground, and such imbalanced current passes through a metallic return or through the sea/ground by means of electrodes, depending on which solution is adopted. Generally, such unbalanced current is less than 1% of the pole current.

However, if one of the poles is out of service, the electrodes have to take up the healthy pole current for the period of time necessary to restore the faulted pole back in operation. Other typical configurations involve the multiple-pole configuration (for example, installed in the Skagerrak HVDC [9] connection, with four poles), which aims at minimizing the return current, and the homopolar configuration, i.e., two poles of the same polarity and a common ground return current path [7,8].

The installation of a ground return path strongly depends on the available sites for the electrodes, local regulations and the possible structures affected by interferences caused by the ground return current. While the installation of a metallic return path (a dedicated overhead line and/or a cable line) causes less interferences with the surrounding environment, it can lead to a high increase in the costs (especially for a dedicated cable). In HVDC applications, characterized by long links, this can lead to a strong reduction—or even the elimination—of the economic return of the investment. This aspect is typically related to submarine HVDC links due to the not negligible impact of the production and laying costs. For this reason, this article will focus the attention on the existing submarine HVDC links characterized by ground return current, i.e., with the presence of electrodes [10].

Among them, reversible electrodes, i.e., those able to operate as cathode and anode (bidirectional power flow in VSC converter technology), will be described in terms of type of installation (sea, shore and pond) and in terms of material used for their construction.

Section 2 describes the type of reversible marine electrodes, Section 3 presents the existing installations around the world, classifying them according to geographic area, connection length, rated voltage and rated power. Section 4 is dedicated to environmental issues, and Section 5 illustrates the conclusions.

2. Types of Electrodes

2.1. Sea Electrodes

Sea electrodes are completely immersed in the seawater and laid on the seabed. According to [7,11], sea electrodes are those that are located away from the shoreline at a distance from the coast greater than 100 m.

Depending on the value of the current density, they can be placed in the seabed with or without barriers in order to eventually avoid fishes or scuba divers to be exposed to potentially high electric field values. The sea electrodes are usually anchored in order to avoid any risk of dragging by the sea current or, alternatively, are completely buried in the seabed. The latter solution is quite uncommon, since their maintenance and inspection would be more difficult.

In order to reduce the value of the current density, an electrode covering a wide area should be installed. One of the typical solutions is represented by a titanium net, usually composed of several modules (Figure 1) made of a special titanium-coated mesh, inserted between protective polyethylene rods; the surface of one commercial module [12–14] is around 20 m^2. The net can be laid with or without concrete frames on the seabed. An alternative approach is to use a HDPE/fiberglass frame (Figure 2) as a support structure for the titanium electrode module. The titanium modules were initially designed to be operated as anodes only (since, because of the type of coating used, chlorine production is strongly reduced with respect to other materials). Subsequently, due to the intrinsic resistance of titanium to surface anode reactions, interest in extending such material to the cathode developed. For cathode applications, the current density shall be reduced to avoid as far as possible hydrogen development for unit area. In fact, titanium is easily affected by hydrogen embrittlement forming titanium hydride that gives rise to swelling and, consequently, to serious net damages.

Figure 1. Titanium module (the figure is from the authors' database).

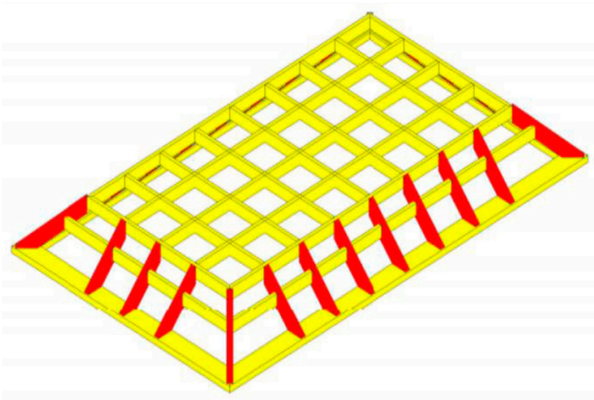

Figure 2. Titanium net with a fiberglass structure (the figure is from the authors' database).

If it is not possible to cover wide areas, the current density will be higher, leading to high values of the electric field, which cannot be tolerated, for example, by fishes and scuba divers. For this reason, in these cases, the electrodes are usually made of a graphite bar, platinized titanium or mixed-metal-coated titanium inserted inside a box [15], eventually filled with coke. The function of coke is to reduce the corrosion rate of the active parts, since the conduction mechanism between the active parts and coke is mostly electronic instead of ionic, and thus, corrosion is greatly reduced. On the other hand, the conduction between coke and water is indeed ionic, but since the coke surface is much wider than the bars surface, the corrosion velocity is significantly reduced. Moreover, coke helps to achieve a more uniform electric field in the immediate vicinity of the electrode.

If the box is not filled with coke, it has the function of secluding the high-field areas close to the active parts only, inhibiting the access of living creatures. An example of a box electrode is shown in Figure 3.

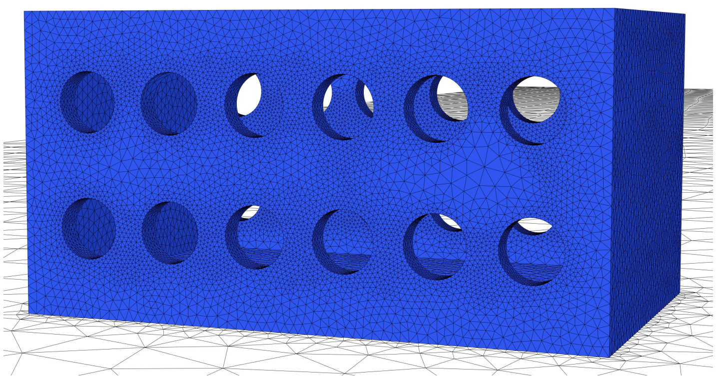

Figure 3. Example of a box electrode in Finite Element Method algorithm.

Possible drawbacks of the sea electrodes are related to their installation cost caused by the depth of the sea, since if it is deeper than 30/35 m, the divers cannot work without special precautions (decompression, etc.), and usually, remotely operated underwater vehicles should be adopted [7]. Moreover, the sea electrodes can be seriously damaged by anchors, especially if they are not completely buried in the seabed. On the other hand, completely buried electrodes require larger active areas due to higher interface resistances and can be more subjected to local heating problems, which may even lead to damages.

In the following the properties of the materials for reversible sea electrodes are reported:

1. Graphite electrodes

They can work in reversible operation without restriction if properly impregnated with hot wax, linseed oil or resin. Otherwise, due to the porosity of graphite, water and oxygen would lead to the formation of carbon dioxide, causing electrode damage, as part of the graphite will transform into gas, resulting in a loss of solid material. One of the main drawbacks is the high amount of chlorine produced with respect to other materials, due to the high current density on their limited surface. Their typical configuration consists of rods characterized by a diameter of 10–12.5 cm and a length of 1.2–2.4 m. They should not be buried in the seabed, as this would accelerate their corrosion.

Considering the typical values of sea conductivity (i.e., 5 S/m) and a maximum electric field varying within the range of 1.25–2.0 V/m, the maximum recommended current density is about 6–10 A/m^2. Higher values can be achieved if the electrode is installed inside a box.

2. Titanium/titanium mesh-shaped electrodes

Titanium electrodes can work in reversible operation if they are properly coated with special mixed-metal oxides of noble metals (known as MMO), with a coating thickness in the range of 5–20 µm. Chlorine production is strongly reduced with respect to that typical of graphite electrodes, due to the MMO and to the lower current density normally adopted.

3. Silicon–Chromium–Iron (SiCrFe) electrodes.

Their reversible operation can be achieved successfully without a huge deterioration of the active parts, but on the other hand, their chlorine production is high. The current densities in open areas should be limited to 5–6 A/m^2 in order to limit the maximum electric field to 1.25 V/m.

2.2. Pond Electrodes

Pond electrodes (a typical scheme can be found in Figure 4) are installed on the seashore, usually within 100 m of the waterline, and are completely immersed in the seawater. With respect to the sea electrodes, they are protected against possible wave, damages, people and fishes by means of a dike/berm. Since they are directly in contact with the seawater, the conductivity of the medium is high, ensuring better performances with respect to shore electrodes due to the continuous water exchange between the pond and the adjacent seawater. Moreover, the lower part of the dike is always permeable to the water, allowing a reliable current path through the underlying sea.

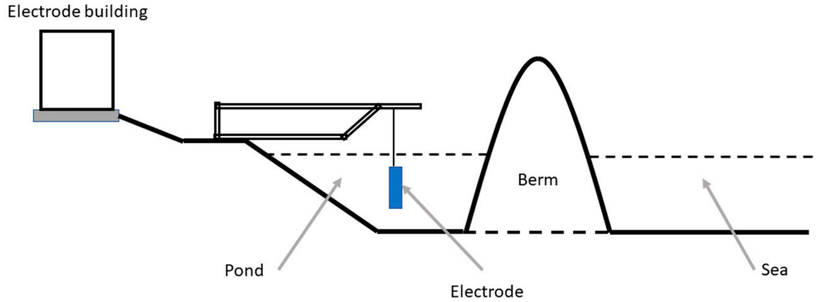

Figure 4. Pond electrode with electrodes suspended in the water.

The presence of the dike inhibits the physical access to the electrode. As a consequence, even if high values of current density and electric field are achieved inside the pond, they are not dangerous, as the area is secluded. Pond electrodes for reversible operations are usually made of a graphite bar or Silicon–Chromium–Iron (SiCrFe).

With respect to the sea electrodes, their maintenance and inspection can be achieved easily, leading to much lower costs.

The drawbacks are related to the possible restrictions on building a dike in particular areas which could be suitable as electrode sites, for example, if the chosen place is characterized by tight environmental constraints.

Properties of the Materials for Reversible Pond Electrodes

1. High-Silicon–Chromium–Iron (HSCI) electrodes

HSCI electrodes, also known as FeSiCr electrodes, are suitable for reversible operation due to their resistance to corrosion and low loss of material in anodic operation. Their consumption rate is lower than 0.32 kg/A/yr [16] due to the presence of a film of hydrated oxides of silicon that can reach a thicknesses ranging from 3 to 6 mm. Even if some researchers reported some pitting when operated as reversible electrodes [17], the on-field experience and other works [18] confirm the possibility of adopting HSCI electrodes both as cathode and as anode. Anyway, in case of corrosion, the bars in pond electrodes can be changed very easily.

Usually, they are installed as solid rods characterized by diameters ranging from 56 mm to 122 mm and lengths ranging from 1.5 m to 2.1 m.

2. Graphite electrodes

As discussed for the sea electrodes, they can operate as reversible electrodes if properly impregnated with hot wax, linseed oil or resin, in order to avoid the disintegration of the structure. The typical rods are characterized by diameters ranging from 76 mm to 100 mm and lengths ranging from 1.5 m to 2.0 m.

3. Magnetite electrodes

They can work in reversible operation, even if a significant limitation in terms of current density should be applied. According to [19,20], the maximum value during anodic operation is 100 A/m^2, while during cathodic operation, the value should be reduced to 10 A/m^2 [17]. One of the main drawbacks is related to the sensitivity of magnetite to temperature variations, which could lead to cracks due to the inherent high brittleness of the material.

2.3. Shore Electrodes

Shore electrodes are installed on beaches/coasts, at a distance lower than 1 km from the waterline, guaranteeing access to them while avoiding contact with the seawater. However, their active parts are buried into the beach in order to make them in direct or indirect contact with the underlying seeping seawater, which guarantees a good conductivity. The electrodes are buried into boreholes which are usually backfilled with porous rocks (shingle) or coke. Usually, these electrodes consist of graphite bars or Silicon–Chromium–Iron (SiCrFe) bars. The possible drawbacks are related to changes in the underlying seawater according to tide level and seasons, which lead to high differences in terms of conductivity of the medium of the electrode site. In order to keep the water level constant, it could be necessary to install a pumping system which guarantees a flow rate of at least 0.2 L/s [21,22]. If the water flow is not enough, the electrode can be corroded more rapidly, and the soil could increase its temperature over the limits. Particular care must be given to electrode-feeding cables (since the environment is very unfavorable, if the copper of feeding cable is reached, it will be damaged very quickly).

2.4. Electrodes Comparison

The main reasons for the installation of shore electrodes are either the site located in a cold sea, with the shore installation more protected by damages due to the frozen sea, or, even in warmer climates, the protection from sea waves, also in shallow shores. Of course, such a type of electrode is sort of a hybrid of a marine and a ground electrode, and this means a more complex maintenance and the necessity of monitoring the level of the underground waters, to be sure that the active parts are working well. Sometimes, it is even necessary to provide sea water recirculation plants. The release of chemical by-products into the sea as well as the electric field in the accessible areas are normally very low, while fields close to the dispersing medium can be high, due to the electrodes' limited size.

The pond electrodes present the advantages of having the active parts directly inside the seawater, leading to a better electrical behavior; furthermore, their maintenance is very easy. It is necessary to check the circulation of water inside the pond, to ensure that chemical by-products can disperse quickly. Due to their limited size, the electric fields inside a pond can be high (some tens of V/m), as the pond is not accessible by living beings. The only limiting issue could be the presence of potentially impacted infrastructures very close to the electrode site. In this case, to enforce a sufficient distance, an offshore sea electrode might have to be chosen.

The offshore sea electrodes might solve the above-mentioned issues, at the expense of much larger dimensions: as they cannot be "fenced", the only possibility is to limit the fields with an increase in size. As an example, if we must disperse 1000 A, considering that the electrical conductivity of seawater is 5 S/m and the maximum allowed electric field is assumed to be 1 V/m, the minimum theoretic dispersing surface will be 200 m^2, which will have to be further increased to take into account the geometrical non uniformity and redundancy. The chemical by-products are directly dispersed into the open water, but due to the free water circulation (limiting the water pH), the large size of the electrodes, and the resulting low current density, the production of chlorine is reduced.

3. Existing Installations

This section aims at providing a general overview of the existing HVDC plants with reversible marine electrodes. As a consequence, in the following, HVDC plants with both earth electrodes, with metallic return or with unidirectional power flow, are omitted.

The following subsections describe the places where conversion stations are located, the total length of the HVDC connection, the installed power, the rated voltage and the year.

Please note that no installations are found in South America and Africa.

It is important to state that the authors of this paper do not know the effective time of the anodic and cathodic operations of such electrodes. A bidirectional electrode is usually expected to work, yearly, as anode for more or less 50% of its operation time and as cathode for the other 50%; however, this hardly happens in reality, and consequently although an electrode is defined as bidirectional, it sometimes works mostly as the anode or, alternatively, as the cathode. Unfortunately, the term bidirectional does not have a clear definition. Most of the electrodes are sometimes defined as bidirectional even if they work in reverse condition during emergency only and/or for some hour per year only.

3.1. HVDC Plants with Marine Reversbile Electrodes in Europe

3.1.1. Fenno-Skan 1 and Fenno-Skan 2

Fenno-Skan 1 and Fenno-Skan 2 are HVDC links connecting Finland and Sweden, installed in 1989 and 2011, respectively. The Finnish conversion station is in Rauma (61°09′07″ N, 21°37′32″ E), while the Swedish stations are in Dannebo (60°24′14″ N, 18°08′10″ E–Fenno-Skan 1) and Finnböle (60°25′30″ N, 17°3′42″ E–Fenno-Skan 2). The connections' length is, respectively, 233 and 303 km.

Fenno-Skan 1 has a rated voltage of 400 kV and a rated power of 550 MW, while Fenno-Skan 2 nominal values are 500 kV and 800 MW. The two plants share the same electrodes [23–25].

- Finnish electrode

It is a marine electrode, located in Laitakari (60°59′47″ N, 21°22′4″ E), and its rated current is 1700 A. It is made of 40 MMO titanium sub-electrodes with the dimension of 16.5 × 1.22 m. They are placed in the seabed, forming an arc configuration, which has good mechanical properties and is suitable for possible future developments [26,27].

The electrode is covered by a 0.2 m layer of gravel in order to increase its mechanical protection, inhibit access to it and reduce the field value in the surrounding area which could be accessible to fishes. It substituted a previous copper electrode, originally used when Fenno-Skan was a monopolar link.

The net surface of the electrode is 800 m^2.

- Swedish electrode

It is a marine electrode, located on the sea in front of the Rödhäll (60°22′0″ N, 26°42′0″ E) natural reserve, and its rated current is 1700 A. It is made of 40 MMO titanium sub-electrodes. Each of them has a dimension of 1.6 × 1.22 m, and their configuration consists of a 290 m straight line and two half circles, each of them characterized by a 90 m diameter. The electrode is covered by a 0.2 shingle layer [26,27].

The total surface is 32,500 m^2, while the net surface of the electrode is 800 m^2.

3.1.2. Skagerrak 1, 2, 3 and 4

The Skagerrak HVDC link is a connection between Denmark and Norway which was updated throughout the years (Skagerrak 1 and 2 began the operations in 1977, Skagerrak 3 in 1993, and Skagerrak 4 in 2015) [9,25,28]. The length of the connection is 244 km between the conversion stations located in Tjele (56°28′44″ N, 9°34′1″ E–Denmark) and Kristiansand (58°15′36″ N, 7°53′55″ E–Norway). The rated power is now 1632 MW, while the rated voltage was changed according to the new installations (the rated voltage of the first and second links is 250 kV, the rated voltage of the third link is 350 kV, while the last is characterized by a 500 kV rated voltage). The four plants share the same electrodes.

- Danish electrode

According to [26], the electrode is a shore installation located in Lovns Bredning (56°39′00.0″ N, 9°15′00.0″ E), characterized by a rated current of 2300 A. It consists of 60 graphite rods sub-electrodes, each of them characterized by a diameter of 0.1 m and a length of 1.2 m. Each rod is embedded horizontally in a coke lens which has a diameter of 2.5 m and a height of 0.6 m. The coke lens is encased in an impregnated concrete tube element. Due to the insulation layer, an area of only 5 m^2 in the bottom side of the coke is in effective contact with the soil, since this part is 0.6/0.7 m below the seawater level and about 2 m below the ground surface.

The configuration consists of three straight lines parallel to the coast at distances of 20, 30 and 40 m. Each line is 150 m in length, leading to a total length of 450 m. Each line consists of 20 sub-electrodes, characterized by a mutual distance of 8/11 m.

The total surface is 15,000 m^2.

- Norwegian electrode

According to [26], this electrode is a marine installation located in Grosøysøyla (58°10′2″ N, 8°15′56″ E), characterized by a rated current of 2300 A. It consists of 61 graphite sub-electrodes. Each sub-electrode consists of a graphite rod characterized by a 0.1 m diameter and a 1.2 m length. The graphite rod is placed inside a wooden encasement with a diameter of 1 m and a height of 3 m, placed vertically at the seabed. The first two meters of the encasement are filled with coke (grain size, 20–60 mm), and the upper meter consists of two cylindrical concrete blocks to exert pressure on the coke pile.

The total surface is 25,000 m^2.

3.1.3. Konti-Skan 1 and 2

Konti-Skan is a link between Denmark and Sweden by means of a 147 km submarine located connecting the Danish conversion station in Vester (57°03′46″ N, 10°05′24″ E) and the Sweden ones located in Stenkullen (57°48′15″ N, 12°19′13″ E–Konti-Skan 1) and Lindome (57°36′24″ N, 12°6′40″ E–Konti-Skan 2) [25,29,30]. The original connection was installed in 1965 (Konti-Skan 1) and used as a monopolar system. After some updates in 2006, Konti-Skan 1 is now installed with a rated power of 350 MW on a 250 kV bipolar system. Konti-Skan 2 is a bipolar system installed in 1988 and characterized by a rated power of 300 MW on a 285 kV system. Both HVDC links share the same electrodes.

- Danish electrode

The electrode was changed throughout the years due to a switch from a monopolar to a bipolar system. Nowadays, the electrode is installed in Sørå (57°10′35″ N, 10°26′59″ E) and is characterized by a rated current of 1000 A. It is a shore electrode made of 24 graphite sub-electrodes, each of them characterized by a diameter of 0.1 m and a length of 1.2 m [26]. Each sub-electrode is impregnated in oil and placed inside trenches filled with coke (grain size, 20–60 mm). Each trench is 3.5 m long, and the trenches are at a mutual distance of 3–5 m. The 24 sub-electrodes are placed in a straight-line configuration situated parallel to the coast at a distance of 20 m from the coastline. The land surface is marshy and elevated about 0.4 m above the normal sea level.

The total surface is 6000 m^2.

- Swedish electrode

The electrode was initially a copper cathode, but it was changed due to a switch from a monopolar to a bipolar system. Nowadays, it is a marine electrode located in Risö (58°05′00.0″ N, 11°27′00.0″ E) and characterized by a rated current of 1000 A. It consists of 30 sub-electrodes occupying a total area of 100 × 300 m. Each of them is placed on the seabed and consists of a graphite rod characterized by a diameter of 0.1 m and a length of 1.2 m, embedded in coke and encased in a woven polyethylene sack [26]. The thickness of coke is 0.5/1 m all around the graphite rod, and each sub-electrode is covered with concrete in order to provide mechanical protection. The mutual distance between the sub-electrodes is 5 m.

The electrode is a few hundred meters from a small island (uninhabited), where a central cabin is placed. The distance from the mainland coast is 2–3 km.

The total surface is 30,000 m^2.

3.1.4. Gotland II and III

The Gotland link is a connection between the Swedish mainland and the Gotland Island. It is characterized by a length of 98 km, a rated power of 260 MW and a rated voltage of 150 kV. The mainland conversion station is connected in Västervik (57°43′41″ N, 16°38′51″ E), while the island conversion station is located in Ygne (57°35′13″ N, 18°11′44″ E). Gotland I (now out of service) was the first commercial HVDC plant in the world and went into service in 1954. The connection was later updated in 1983 (Gotland II) and 1987 (Gotland III) [25,31,32].

- Mainland electrode

The electrode was strongly modified throughout the years. According to [26], it is a pond electrode characterized by a rated current of 915 A installed in Almvik (57°34′32″ N, 16°41′49″ E), in the Östra Eknö Bredning region. The configuration consists of two circular pools separated from the sea by means of a rock barrier, where 2 × 48 magnetite Fe_3O_4 sub-electrodes are installed, hanging in the water (depth = 2 m) by means of a wooden support structure. Each sub-electrode has a 6 cm diameter and a length of 72 cm. The distance between each sub-electrode is 1.5 m.

The total surface is around 6000 m^2.

- Gotland Island electrode

The electrode was strongly modified throughout the years. According to [26], it is a pond electrode characterized by a rated current of 915 A installed in Gravfält (57°30′52″ N, 18°6′35″ E), in the west coast of Gotland island. The configuration consists of one circular pool separated from the sea by means of a rock barrier, where 48 magnetite sub-electrodes are installed, hanging in the water (depth = 2 m) by means of a wooden support structure. The characteristics of each sub-electrode, as well as the distance between them, are the same as in the main land electrode.

The total surface is around 5625 m^2.

3.2. HVDC Plants with Marine Reversbile Electrodes in Oceania

HVDC Inter-Island 2–3

This HDVC link connects the North and the South islands of New Zealand by means of a 611 km cable connection [33,34]. The conversion stations are in Benmore (44°33′55″ S, 170°11′24″ E) and Haywards (41.151446° S, 174.981691° E), and the rated voltage of the system is 350 kV, while the rated power is 1200 MW. The link was initially installed in 1992 (HVDC Inter-Island 2) with 600 MW of rated power, and the upgrade to the current power was achieved in 2013.

- South Island electrode

The electrode is installed in land configuration in Bog Roy (44.574° S, 170.099° E), 7.6 km from the Benmore conversion station. Since it is a land electrode, its configuration is out of the scope of this paper, and its description is therefore omitted.

- North Island electrode

In the North island, a shore electrode is installed close to Te Hikowhenua (41°12′28″ S, 174°43′11″ E), characterized by a rated current of 2400 A. Its configuration consists of 42 FeSiCr sub-electrodes, each of them with a diameter of 0.121 m and a length of 2.13 m [21,26,35]. The sub-electrodes are installed in vertical perforated concrete pipes characterized by a diameter of 0.6 m and a height of 2.4 m. The base of the concrete pipe is 5 m below the beach surface, and the pipes are placed in a common trench, backfilled with selected round stones. The mutual distance between the sub-electrodes is 18.9 m.

The total surface of the electrode is 20,000 m^2.

3.3. HVDC Plants with Marine Reversbile Electrodes in Asia

Haneam-Cheju

This HVDC link connects the South Korean peninsula with the Jeju island [36]. The submarine cable has a length of 101 km, and the HVDC system has a rated voltage of 180 kV and a rated power of 300 MW. It went into service in 1996, and the conversion stations are located in Haenam (34°22′03″ N, 126°35′34″ E–peninsula) and Jeju (33°32′06″ N, 126°35′44″ E–island).

- Peninsula electrode

It is installed as a pond electrode characterized by a rated current of 850 A. To the best of author's knowledge, the location is unknown. Its configuration consists of 20 FeSiCr sub-electrodes substituting previous electrodes made of graphite. The sub-electrodes were installed by suspending them vertically into the water [26].

The total surface is 6044 m^2.

- Island electrode

The configuration of the electrode located in Cheju island is identical to that of the electrode installed in the South Korean peninsula [26].

3.4. HVDC Plants with Marine Reversbile Electrodes in North America

3.4.1. Pacific DC Intertie

This link is a land connection between the substations located in Celilo (45°43′20.83″ N, 120°41′23.86″ W–Oregon, USA) and Sylmar (34°18′20.9808″ N, 118°27′25.9164″ W–California, USA). The overhead line length is 1362 km, and the rated voltage is 500 kV. The total installed power is 3100 MW [37,38]. Due to its proximity to the Pacific Ocean, the electrode located in California was installed as a sea electrode.

- Oregon electrode

A land electrode was installed 10.6 km far from the Celilo conversion station. Since it is a land electrode, its configuration is out of the scope of this paper, and its description is therefore omitted.

- California electrode

It was installed as a sea electrode characterized by a rated current of 3100 A, was renewed in 2018, and is currently located two miles offshore the Saint Monica coastline. It consists of 144 FeSiCr bars located in 36 concrete boxes laid on the seabed. The former electrode was similar but closer to the coastline and characterized by 48 bars located in 24 concrete boxes [26].

3.4.2. Labrador Island Link

The Labrador Island Link connects the mainland of Canada with the Newfoundland island by mean of a 1135 km cable characterized by a rated voltage of 350 kV and a rated power of 900 MW [39]. The conversion stations are located in Muskrat Falls (53°15′1″ N, 60°46′54″ W) and Soldiers Pond (47°19′7″ N, 53°46′51″ W).

- Mainland electrode

It is installed as a pond electrode characterized by a 2320 A rated current. It is installed in L'Anse au Diable (51°33′50″ N, 56°45′11″ W–Labrador, Canada) and consist of a water basin closed by a rock dyke where FeSiCr bars are immersed [40]. The diameter of each bar is 0.122 m, and their length is 2.13 m. The bars are installed linearly along a 125 m line. The active parts of the electrode are directly in contact with the seawater.

- Island electrode

It is installed as a pond electrode in Dowden's Point Conception Bay South (47°28′13″ N, 53°4′60″ W–Terranova, Canada). Its configuration is similar to the other electrodes but it consists of a trapezoidal structure with the major base along the coastline and the minor one along the sea [40].

3.4.3. Maritime Link

This HVDC plant connects Newfoundland Island and the Nova Scotia Island in Canada by means of a 360 km cable characterized by a rated voltage of 200 kV and a rated power of 500 MW. The conversion stations are located in Bottom Brook (47°27′3″ N, 53°45′39″ W–Newfoundland) and Woodbine (46°0′1″ N, 60°17′55″ W–Nova Scotia) [41].

- Newfoundland electrode

It is installed as a pond electrode characterized by 1250 A, located in Indian Head (47°32′32″ N, 54°51′14″ W). Its configuration consists of 45 FeSiCr bars (5 groups, each of them formed by 9 bars) located inside a pond made of rocks [35].

- Nova Scotia electrode

It is installed as a shore electrode located in Big Lorraine (45°55′42″ N, 59°56′3″ W), realized by means of bars installed in vertical wells.

4. Environmental Issues and Interactions with Infrastructures

This section deals with the interactions of electrodes with infrastructures and the surrounding environment.

They can be categorized according to the structure/subject which are affected.

4.1. Impact on Infrastructures

Corrosion and saturation are two of the main issues affecting infrastructures. In particular, uncoated and coated buried metallic objects can be severely affected by corrosion, as shown in [42,43], while transformers with grounded neutrals can saturate when they are close to the electrode location.

4.1.1. Impact on Non-Insulated Metallic Objects

The corrosion risk of non-insulated objects strongly depends on their orientation, their length in the direction of the field and the strength of the field. The most exposed part to the corrosion risk is the one closer to the cathode, since in this area the metallic object behaves as an anode.

According to some studies proposed in [44,45], a current density of 1 $\mu A/cm^2$ is permitted for unprotected iron, corresponding to a rate of corrosion of 11.62 μm per year, removed from the surface. It is important to remind that corrosion of underwater cables can happen also due to natural reasons such as telluric currents, and consequently, this should be taken into account when evaluating the effect of sea electrodes on non-insulated metallic objects. It is commonly accepted that at distances greater than 66 km from the electrode, the impact of telluric currents is predominant.

4.1.2. Impact on Insulated Metallic Objects

Insulated metallic objects can be affected by corrosion as well, since defects always exist in the coating due to imperfect production or damage during installation. As a consequence, the current is picked up in the defects closest to the anode and is discharged in the defect closest to the cathode, leading to faulty spots and usually a very highly localized corrosion. In order to avoid this behavior, insulating joints should be installed with adequate spacing, thus dividing the metallic tube into electrically separate sections, minimizing the current path. Of course, this is a very expensive mitigation technique, especially on a submarine pipeline in operation.

4.1.3. Impact on AC Grids

If a DC current flows into a transformer magnetizing core, it leads to its saturation. The magnitude and damage of this effect depend on the transformer type, since the transformers are able to withstand some level of DC current. The most affected ones are single-phase transformers and three-phase–five-legged transformers, while three-phase–three legged transformers may withstand higher DC currents [46–48]. In particular, on recent transformers, currents of a few Amperes can produce significant saturation.

4.2. Impact on the Environment

4.2.1. Chemical Products

On the surface of sea anodes, Cl_2 (chlorine) and O_2 (oxygen) are usually produced. Since chlorine is unstable in seawater, hypochlorite, chloride, hypobromite, bromide, chloroform and bromoform can be formed [17]. In particular, the latter two are toxic, and consequently, it is strongly recommended to reduce the amount of chlorine by means of maintaining a low pH value (by increasing the seawater circulation) or increasing the electrode size (reducing the current density). It is important to underline that there are no recognized upper limits not to be exceeded for such chlorine by-products.

According to [7], for a titanium mesh sea electrode in seawater characterized by 0.8% salinity, Cl_2 represents the 30% of the chemical products at the rated current of 1364 A, corresponding to 1.7 A/m^2 (i.e., oxygen production is 70%). When the current decreases to

50% and 20%, the percentages will be 17% and 9%, respectively (i.e., the oxygen production increases to 83 and 91%).

On the other hand, close to cathode, H_2 (hydrogen) is produced. It is usually dissolved in the seawater until it reaches a saturated concentration. If H_2 is not completely dissolved, it will be released in the atmosphere. Some issues can appear, due to the formation of chemical by-products fouling, mainly formed by $Mg(OH)_2$ and other substances such as Na_2O, CaO, MgO, Fe_2O_3 and SiO_2. Furthermore, it is important to underline that due to the high concentration of Mg in seawater, $Mg(OH)_2$ is the main compound responsible for a chalklike layer on the electrode surface in cathodic operation, increasing the electrical resistance and the possibility of temperature hot spots. Such layer is a sort of coating that can reach up to some cm of thickness and thus shall be periodically removed through high-pressure water if this action does not damage the electrode. The anodic operation can lead to the self-cleaning of the electrode from such coating, but investigations are needed to better understand if other factors need to be taken into account.

4.2.2. Electric Field

In principle, the maximum electric field allowed close to humans or fauna should be 1.25 V/m [7]. Please note that, in case of low salinity, the seawater resistivity increases, and consequently, in order to keep the same voltage gradient, the electrode should increase in size. In the case of sea electrodes, if the voltage gradient limit is exceeded, properly countermeasure should be taken, as, for example, the restriction of the accessible area close to the electrode. Usually, sea electrodes are always clearly marked on navigation maps, and diving activities are always prohibited. Special buoys are often used in order to attract the attention of the most absent-minded divers. On the other hand, in the case of pond electrodes, the area surrounding the electrode is interdicted to people, and no fishes are there; thus, no further actions are required. A methodology to properly measure the electric field generated by marine electrodes can be found in [49].

It is important to notice that, in the Skagerrak HVDC link, it has been found that apparently, fishes close to the electrodes showed no reactions, even if the electric field was around 6 V/m [50].

5. Conclusions

Reversible marine electrodes in HVDC connections are becoming more frequent due to the increasing number of HVDC links and to the choice of the sea as a current return path, which represents a better choice with respect to the soil, owing to its higher conductivity. The main sea electrodes configurations were described, focusing on the configuration type (shore, pond or sea electrodes) and on the most adopted materials able to guarantee a correct behavior in anodic and cathodic operation. Secondly, a review of the installed configurations around the world was presented, classifying them in terms of geographical location, rated power, rated voltage and connection length. Finally, the main impacts of the electrodes on the surrounding environment were presented in terms of impacts on infrastructures and in terms of impacts on the flora and fauna. The conclusions are the following: it is normally much better to develop a sea electrode of any kind instead of a ground electrode, due to the much higher conductivity of the surrounding medium. Moreover, the choice between sea/pond/shore electrodes mostly depends on local constraints (sea depth, maintenance inspections, environmental conditions, risk of interference with anchors and trawl nets, possibility of sea freezing, etc.). Many of such factors depend on the adopted technology, which also impacts on the environmental friendliness of the electrode: while the impact of the cathodes is practically negligible, the anodes in salty water originate chlorinated by-products. Today, considering this aspect, the best material seems to be coated titanium, particularly if used under a limited current density, which also leads to very limited electric field values in the immediate vicinity of the electrode. Other materials, such as graphite in combination with coke, can withstand higher current densities, leading to more compact electrodes, at the expense of the production of a somewhat greater quantity of chlorinated by-products. Of course, research about new materials could significantly change things, leading to more compact and environmentally friendly electrodes.

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