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Steel reinforced concrete electrodes for HVDC submarine cables

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ABSTRACT

In HVDC submarine cable connections, electrodes design is paramount for technical and economic feasibility. The cathode is designed as simple as possible, if bidirectional operations are not required since reduction reactions does not produce corrosion of the material. The situation is completed reversed for the anodes submersed in seawater: in this case, the corrosion mechanism provokes removal of surface material.

For this reason, in order to ensure a sufficiently high lifespan, the anode is usually made of different and more expensive materials, like titanium rods or meshes, coated with layers of a noble metal oxide, such as platinum, or a mixture of several of them. Sometimes the seawater anodes are also immersed in materials based on transition elements such as rare earths.

In the present paper, an innovative prototype of seawater anodes, based on steel reinforced concrete, is presented. Moreover, its experimental comparison in seawater at corrosive phenomena is reported, comprising simple steel or titanium bars and titanium meshes protected by special multi metal oxides (MMO). These experiments have shown important reduction of the corrosion phenomena in the case of the prototype of anode made by steel concrete.

1. Introduction

The seawater return circuit is fundamental in HVDC transmission systems of the submarine cables [1–5], being relatively simple and allowing important cost reductions. In fact, seawater has a very high conductivity of approximately 5 S/m due to its high concentration of ions and, hence, it is possible to obtain a low resistance return path. Nevertheless, important differences arise when considering the two opposite electrodes, where the electrons are or injected (cathode) or extracted (anode) into seawater. Conventionally, it is assumed that the anode is the electrode in which current is injected into the ground or in seawater. The much higher conductivity of the seawater in respect to return through earth makes the electrodes considerably smaller, even if the electric field decays more rapidly than in earth. On the other hand, seawater greatly enhances corrosive processes and electrodes in this environment are subjected to higher stresses. Sea and shore electrodes could be bidirectional but they are often designed as unidirectional with the possibility of withstanding current reversal for a short period of time. This choice originates from the asymmetry of the electrochemical reactions that take place at the positive and negative electrodes. Designers take advantage of the less severe condition at the cathode by making it in a more economical way, adopting different features and materials. On the contrary, submarine anodes are much more complex because of the need to protect these components from the corrosive phenomena. For this reason, normally submarine anodes are made of very expensive materials, like titanium rods or meshes, coated with layers of a noble metal oxide, containing also platinum, iridium, plutonium, rhodium or ruthenium.

The present paper presents an innovative prototype of anode, based on steel reinforced concrete. The role of current feeder is carried out by steel while concrete acts as a protective layer, able to create an alkaline environment near the surface of the feeder. Downsized and accelerated experimental tests presented in this paper have shown important reduction of corrosive phenomena for this kind of innovative anodes. In fact, concrete is strongly alkaline (pH $\geq$ 12) and the experiments presented here have shown as these steel-concrete anodes are capable to resist at the corrosive phenomena much better than other traditional anodes, often used, made of other more expensive materials, like titanium rods or meshes coated with layers of a noble metal oxides.

2. Introduction HVDC submarine cables electrode

HVDC electrodes submarine cables are normally designed in compliance with the following specifications [6–8]:

- continuously current of 20% greater of the nominal capacity;
- lifetime expectation of about 20 years or more;
- reversible functionality (cathode/anode) for a limited period;

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- free chlorine emission in the proximity of the anode not greater of 0,2 mg/L [9];
- electrode total voltage drop, at the nominal current of the system, not greater than 12 V;
- electrical field on the electrode surface not greater than 0,5 V/m, in the worst condition.

It is well known that the reduction reactions, which take place at the cathode, do not produce corrosion of the material. For this reason, cathode's design is kept as simple as possible, if bidirectional operations are not required. Usually sea and shore cathodes of HVDC links, which do not require a bidirectional return circuit, are made of copper wires, or more rarely of carbon/graphite, simply laid on the sea floor. The wire may be placed in several configurations such as ring, star and linear shape. Generally, the copper wire forming the cathode is obtained directly from the electrode cable line, which connects the electrode with the converter station, simply by peeling of the insulation. The main design constraints of sea and shore cathodes consists in limiting the current density on the cathode's surface in order to achieve a maximum electrical field not greater than 2 V/m. This precaution assures the safety for the human activities, such as swimming and diving, in proximity of the cathode's area. Sea life is not considerably affected by cathode's electrical field. In fact, it is proven that fishes are repelled from the cathode due to electrostatic phenomena. Another important design consideration is making sure that the dispersed currents that do not flow directly into the cathode would not pose threats to metallic structure on the beach. Hence, the current density on the beach must be limited to approximately 1 $\mu A/cm^2$. Several studies and previous experiences [2–4] have demonstrated that the cathode must be at minimum 1,5 km from the beach in order to respect such prescription. In designing a cathode's structure, one must think of the necessary maintenance operations that must be carried out regularly to remove the deposit on the cathode's surface. In addition, being placed at a certain distance from the beach, cathode's structure must be protected from mechanical stresses, for example the ones deriving from trawling fishing.

On the contrary, sea and shore anodes are subject to corrosion and removal of surface material. For this reason, anodes cannot be designed in the same way as cathodes. In order to ensure a sufficiently long lifespan, the anode is usually made of different and more expensive materials. The parameters that characterize anode's performances are current density and wear rate. Current density influences the dimensions of the electrode. On the other hand, a slow rate of corrosion is required to ensure the functionalities of the anode for the longest possible period. A common practice is to build a layered anode in which the bulk structure is composed of a metal able to withstand the dispersing current and with good mechanical characteristics, in terms of resistance and weight, called current feeder. In order to reduce consumption of the anode's core metal, one or more layers are added in the form of coating or drowning into another material that function as interface between the current feeder and sea water. The layers must have the lowest possible wear rate. Beside the material, form factor is another important design decision. There are several possible form factors, but the most common are rods and meshes. Usually, the choice of the geometrical shape is related with the choice of material due to the different casting techniques of the metals.

The most common types of anode used in sea and shore anodes are [6,10]:

- Titanium or niobium mesh or rods coated with platinum or other mixed metal oxides (MMO);
- Iron oxides, like magnetite;
- Carbon/graphite rods;
- Silicon or chromium high alloy steel (SiCrFe) rods.

Platinized titanium rods are used in most of the modern shore anode applications. The structure is composed of several rods suspended on a traversal insulating structure, generally wooden. Only a part of each rod is submerged in sea water. The rods are coated with a 5–20 μm layer of a noble metal oxide, such as platinum, or a mixture of several of them, such as iridium, rhodium or ruthenium. The titanium rods function as current feeder and mechanical support. Titanium has very good mechanical resistances, comparable to that of iron alloys but with significantly less weight. Platinum is used for its lower wear rate in chloride-rich solutions such as seawater. As a matter of facts, the platinum coating acts as a corrosion shield to the titanium feeder. Titanium anodes, not protected, have a very high wear rate in the range of 6–8 kg/A year. Anyway, the great advantage of this type of anodes, when protected, is the possibility of varying the coating recipe to adapt the anode to environment. On the other hand, the main drawback is the very low withstanding capabilities of current reversal. In that case, the hydrogen atoms present in the coating would limit the maximum cathodic current density. MMO (mixed metal oxides) coated titanium anode is often used in mesh form. This shape is generally more suitable for sea electrodes application since it can be laid on the sea floor with simple supporting structures.

This type of seawater anodes (rods of platinized titanium) have demonstrated to work properly even though they present very high costs.

3. Anodic corrosion in seawater

The main criticality of anodes is corrosion by oxidation. Qualitatively, anodic corrosion consists in the dissolution of surface metal ions into the electrolytic solution. From the electrochemical point of view, the anode is fixed at positive potential with respect to the ground by the external system and hence it attracts negative ions, like Cl^- and OH^-, which are naturally present in seawater [11]; the anion that first reacts is Cl^-, due to its much higher standard potential. Chloride atoms are not stable and match with each other resulting in gaseous chloride molecules Cl_2 that tend to rise to the surface in the same way of the hydrogen gas at the cathode. The other anions tend to remain in proximity of the anode forming a negative ionic cloud. The resulting electrons are absorbed by the metallic structure as long as its ions tend to become unstable. These ions are repelled by the imposed external voltage and are attracted by the anion cloud present in proximity of the anode, with the final result of detachment and dissolution of metallic materials into the electrolytic solution.

This whole process produces a removal of material from the anode even if this phenomenon interests mainly the surface layers of the metal. This uniform corrosion does not represent the main danger for the anode since a protection mechanism starts to be triggered by the process itself. In fact, on the surface of the anode, metallic oxides and/or hydroxides are formed creating a thin passive film, which increases the electrical resistance of the surface preventing further corrosion of the metal. The process is called passivation and it can be considered as the most efficient protective layer of metallic surface of the anode. However, this protective film is soluble in acidic solution and may dissolve, primarily if scratched or in presence of discontinuities of the surface. In the disrupted points, the protective film could form once again or localized corrosion of the underneath metal could take place. The factors affecting these outcomes are the solubility of the oxide, anion activity, potential and pH.

Furthermore, the chemical aspects of the occurring phenomena are well described in the Annex J of the IEC TS 62344-2013 [6]. If the electrode is made with not noble elements, such as Al, Zn, Mg, Fe or Ti, it will lose metallic ions which will participate in the anodic chemical process to form substances like chloride and no gas chlorine is expected to be released.

In addition, changes between anodic and cathodic direction of current may be critical for certain materials. Materials like coke or graphite withstand current reversal well, while high silicon iron is