On the Measurement of Fields produced by Sea Return Electrodes for HVDC Transmission

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Abstract—**The use of HVDC transmission is spreading worldwide, for a number of reasons. When return electrodes are used, their compliance with international technical standards and environmental limitations has to be assessed after commissioning, before regular operations can start. While the measurements of the fields produced by ground return electrodes is basically derived by the techniques developed over the years for industrial grounding plants, when sea electrodes are used things are more complex, the instruments and measurement techniques are less common. In this paper, we try to summarize the issues and to describe the relevant techniques than can be used.**

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

I. Introduction

When a new High Voltage Direct Current (HVDC) transmission link is commissioned, one of the most important issue is to assess that all operational parameters are compliant with all the applicable standards [1], with the environmental prescriptions [2], and with any other parameter contractually requested by the plant Owner through its addition to the technical specification document. One of the most controversial and misunderstood components is the couple of return electrodes that, according to the type of HVDC system can be of different types and can be of completely different constructive types. Among the electrical parameters that must be measured when dealing with ground electrodes, we can cite the GPR (Ground Potential Rise), as well as the touch/step voltages. The techniques that can be used are similar to that developed for ordinary grounding plants, with some modifications, as normal grounding plant are operated on a limited-time basis in AC, while HVDC return electrodes are operated over much longer times, and in DC. Therefore, some precautions must be taken, for example reference measurement electrodes should be used to prevent electrode polarization and so to minimize measurement errors, but approximatively the concepts are similar. A substantially different situation occurs when dealing with marine electrodes: the limits to comply with are not expressed in terms of voltages, but in terms of electric fields (often called "gradient" in technical standards [1]). Furthermore, in the case of ground electrodes all parameters are measured on the soil surface, while for marine electrodes measures have to be performed also below sea level, all around the electrode. Another issue is that good electrical properties of seawater depends on it being an electrolyte, i.e. an ionic conductor characterized by an electrical conductivity much larger than that of the best soil. Unfortunately, this imply that, in DC, polarization might occur. We will examine the problems and possible solutions to provide reliable measurements of electrical field in seawater [3].

II. The Electric Field

From a mathematical standpoint, the electric field is a vector field that can be defined as the result of application of gradient operator to the scalar electric potential (voltage) field. The first is measured in V/m, while the second is measured in V. In line of principle, then, we could measure the potential in several sampling points, recording in each point its value and the coordinates (see for example Fig. 1). As the relationship between them is:

$$\vec{E} = -\nabla V \qquad (1)$$

afterwards, during a phase of post-processing, it is possible to perform a numerical differentiation, leading to the electric field

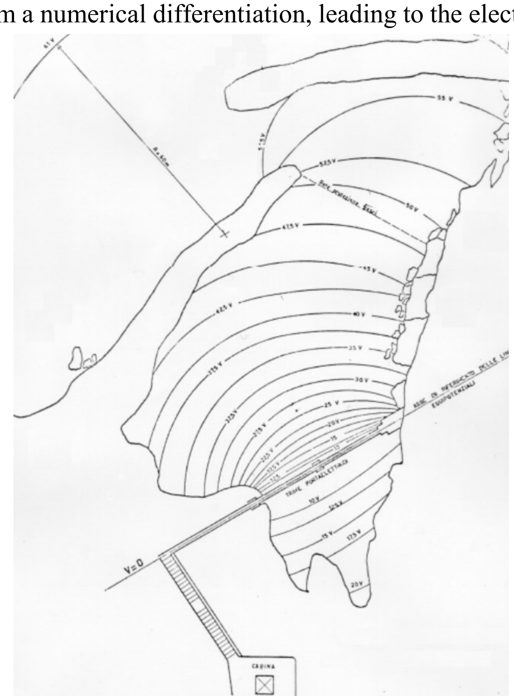

Fig. 1. Measured electric scalar potential field (w.r.t. electrode).

map. Even though extremely logical and linear, this approach suffers a significant drawback: as all measurements are affected by an error, it is notorious that errors are hugely magnified by the application of gradient operator. As seawater has a high electrical conductivity, normally the expected values are below some V/m (the technical standard [1] states that the limit should be 2 V/m), so the risk to obtain a result very similar to numerical noise is high, unless very careful measurements were performed (unlikely, when working immersed in seawater). For these reasons, it is much better to use three orthogonally oriented electric field probes, i.e. measurement instruments able to provide directly the local value of electric field.

III. The Electric Field Probes

In line of principle two approaches can be used to measure the value of electric field: namely the voltmetric and amperometric one [4]; basically the first one is based on measuring the voltage difference V between two electrodes 1 and 2, located at limited distance, and dividing this value by the distance d (Fig. 2); in fact:

$$V_{12} = \int_1^2 \vec{E} \cdot \mathrm{d}\,\vec{l} \tag{2}$$

$$E_m = V_{12}/d \tag{3}$$

where E_m is the component of the electric field in the direction of the line connecting the electrodes. Of course, the scheme is valid only if the current i, drained by the voltmeter, is small enough to avoid to significantly altering the field under measurement. In other terms, i <<< I, but this condition can be easily satisfied as the internal impedance of modern voltmeters is very high. Of course, if electrodes distance is high, the measure tends to be less accurate, becoming an "averaged" value; on the contrary, if electrode distance is very small the measure converges to the gradient, but the sensitivity decreases and measurement noise rises.

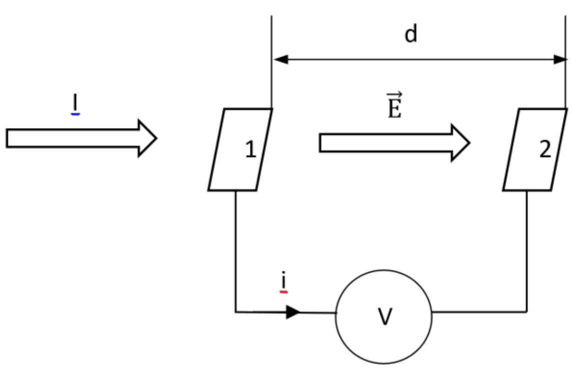

Fig. 2. Voltmetric measurement scheme.

The second approach is more indirect, and it is based on the measurement of the current I flowing through an insulating pipe, having diameter much smaller than its length, with two electrodes on either sides of a high resistivity barrier inside it. The average current density through the pipe J_p is thus determined, dividing the current by the cross section S of the pipe; eventually the electric field is determined, dividing the current density by the electrical conductivity of seawater σ.

$$J_p = I/S \tag{4}$$

$$E_m = J_p/\sigma \tag{5}$$

where E_m is the component of the electric field along the axis of the pipe. In Fig. 3, below, dashed pattern represents insulating material, while 1 and 2 are the electrodes.

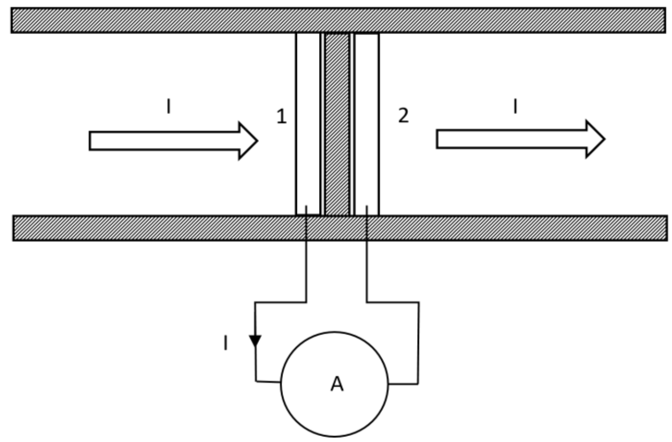

Fig. 3. Amperometric measurement scheme (cross section).

In this case particular care should be taken, as: the impedance of the ammeter must be as low as possible; furthermore, to avoid as far as possible the alteration of the field under measurement, the total resistance (electrodes + external circuit + ammeter) should be similar to the resistance of the seawater. This

Temp. [°C]	Salinity [g/kg]				
	20	25	30	35	40
	Electrical conductivity [S/m]				
0	1.745	2.137	2.523	2.906	3.285
5	2.015	2.466	2.909	3.346	3.778
10	2.3	2.811	3.313	3.808	4.297
15	2.595	3.17	3.735	4.29	4.837
20	2.901	3.542	4.171	4.788	5.397
25	3.217	3.926	4.621	5.302	5.974

Table 1. Seawater electrical conductivity vs main parameters.

is in any case a limitation since the conductivity of seawater is temperature/salinity dependent (see Tab. 1). Furthermore, the measure itself is temperature dependent, considering that the field is determined, as pointed above, dividing the current density by the electrical conductivity. One significant advantage of this method is that a direct current measurement in a high conductivity media may result in higher sensitivity and smaller noise. On the other hand, the higher is the current under measurement, the larger is the polarization effect. Thus the amperometric scheme could be more error-prone than the voltmetric one. Normally the measurement of electric field in seawater is very uncommon, and such kind of probes were developed for two main applications: geophysical studies (magnetotelluric measurements), or military applications (anti-submarine warfare) in which the field conditions (both for E and J) are quite different from those encountered around HVDC electrodes. Consequently, the applicability of the probes available on the market must be carefully verified.

Two substantial differences are expected: one is the much higher field value that the probes are likely to measure; as aforementioned, its magnitude can be up to some V/m, while the sensitivity of geophysical and military probes can arrive to nV/m, so it may be necessary to check that the internal amplifier does not reach saturation, et cetera. Another –more insidious– difference is due to the electrodes polarization. Polarization is a well-known electrochemical phenomenon occurring when a conducting electrode is placed into an electrolyte; of course, this problem is marginal when the physical quantity to measure is time-varying, but sensitive in DC. This may lead to unacceptable errors, that could affect both voltmetric and amperometric probes. To be noticed that datasheets of most probes on the market specify a minimum frequency value for the field being measured and furthermore, highlight that noise increases as frequency decreases.

IV. How to Manage Polarization Issues

One "electrochemical" technique is based on the use of reference electrodes; such electrodes are manufactured in such a way to show a very stable potential and are often used, for example, to measure the potential around DC-fed railways or tramways. More complex, but still possible, is their submarine use. Even more complex is their use to build an electric field probe, since two electrodes should be used, and their potential should be the same (within very tight limits), otherwise the measure becomes affected by a systematic error. As for example, if a couple of Copper-Copper Sulfate electrodes (E=+0.314V w.r.t. standard Hydrogen electrode) are used the distance between such electrodes is set to 0.1m and the electric field is 0.1V/m, the expected voltage to measure is 10mV. If one electrode has a potential of +0.314V and the other one just +0.313V, a systematic error of 1mV (corresponding to 10% is automatically added). Such error might even increase at lower field values. This problem is gradually becoming less serious due to the improvements in reference electrode manufacturing technology.

Another remarkably interesting method to reduce polarization effects patented [5] by a US hi-tech company producing instrumentation for military applications, is based on a completely different "physical" approach: a very thin insulating layer (preferably made of metallic oxide) is interposed between the electrode and seawater. Is this way the coupling electrode-seawater is capacitive and this practically removes the electrochemical phenomena that could affect measurement precision.

V. Innovative Measurement Probes

Even though the idea for the solution of polarization reported in the above-mentioned patent [5] gives good results, the Authors propose an improvement of the amperometric scheme (Fig. 4), not subject to polarization problems: basically the approach is similar to that described in Fig. 3. In this scheme the current is not directly measured through an ammeter, but through its magnetic effect. In other terms, the internal canal of the insulating pipe is completely free of obstacles and the electric current is not reduced by the high resistive barrier.

Around the pipe, a toroidal high sensitivity magnetic field ammeter is positioned and the electrical current I *inside* the pipe can be evaluated according to well-known Maxwell equation:

$$I = \oint \vec{H} \cdot \mathrm{d}\,\vec{l} \tag{6}$$

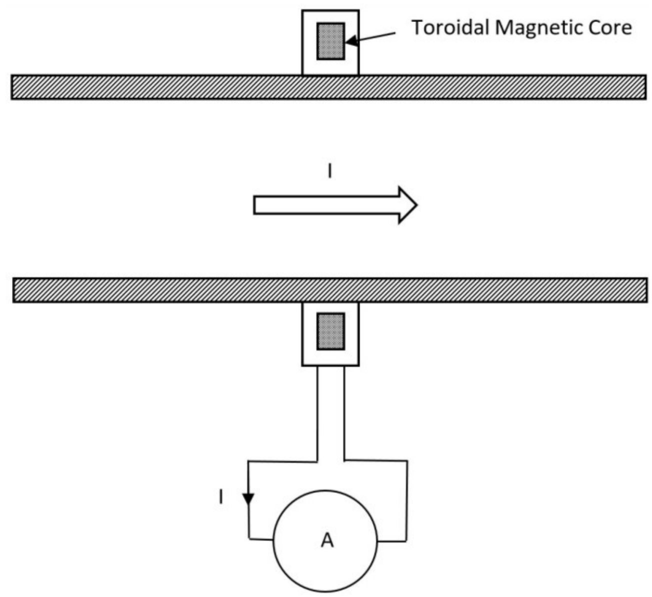

Fig. 4. Magnetic measurement scheme (cross section).

The current I flowing outside the pipe has no magnetic effect on the toroidal core, and then does not influence the measurement. With this approach, two problems are simultaneously solved: any calibration of the external circuit is not needed anymore and the polarization is automatically removed since no interface between electrodes and electrolyte exists. In such a case the only remaining issue would be the measurement of conductivity that, for a fixed salinity, can be achieved through the local measurement of seawater temperature.

VI. Measurement Error Analysis

Particular care should be taken to keep measurement errors under reasonable limits. One interesting feature of voltmetric measurement scheme is that it is possible to show that the estimated measurement according to (3) *always overestimates* the real value of the field in the midpoint of the two electrodes (Figs 5 and 6). This fact is true, assuming that the magnitude of electric field along the distance d is described by a convex function (like d^{-1} in cylindrical coordinates, or d^{-2} in spherical coordinates).

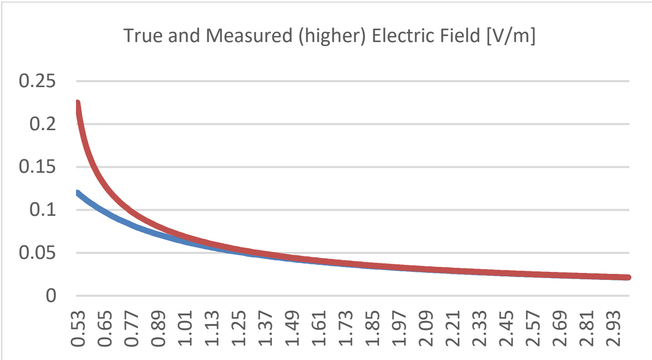

Fig. 5. Example of true/measured fields in cylindrical coordinates

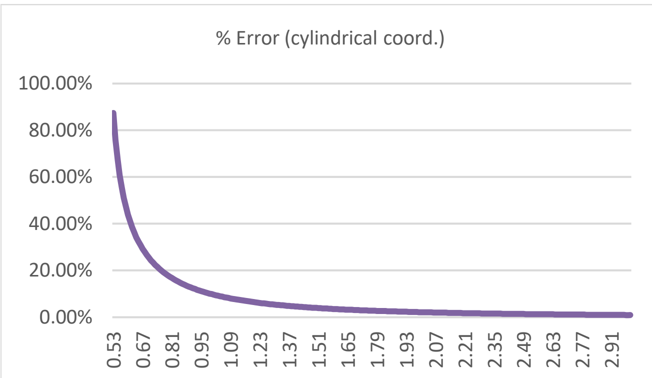

Fig. 6. Example of relative errors in cylindrical coordinates

This condition holds, as the distance from the electrode is not minimal. Of course, the magnitude of the error tends to be much higher for measurement points very close to the electrode, but it quickly reduces to some percent at reasonable distance. For reasonable distance between measurement points, let us say 1m, the voltmetric scheme is therefore able to provide technically meaningful measurements. This is an advantage of this method, as the two aforementioned methods (amperometric and magnetic) are based on an indirect measurement: the E field is assessed from a current measurement through the electrical conductivity of the surrounding medium as per (5). Therefore the errors may have either signs. The proposed magnetic probe in line of principle should be able to measure the current density with great precision, so the only issue is to determine the conductivity with adequate precision (not simple, as it depends on the salinity and on the temperature, see Tab. 1). The amperometric method presents more problems because the electrical conductivity plays also a role in the measurement: in fact the calibration of the probe relies on both the resistance of measurement circuit (that must be as far as possible equal to that of the seawater within the cylinder and between the electrodes) and the high resistivity barrier. Consequently, many parameters are involved, and the variability of seawater conductivity may affect the error in different ways. An accurate calibration turns to be expensive, time consuming, and not easy to perform in field immediately before the measurements (for example, probe heating due to sunrays onboard support vessel would make calibration very problematic).

VII. Practical Issues

Basically, two types of HVDC electrodes are directly installed in seawater: pond electrodes (the majority), and real sea electrodes (a few around the world). The main difference between them is that pond electrodes are installed in direct contact with seawater, into natural or artificial ponds, alongshore), while sea electrodes are installed in open sea, not closer than some hundreds meters from the shore. Therefore, the dispersing components of pond electrode are located at the surface of sea, or at most at very low depth (1 – 2m), so they can be reached very easily; completely different situation characterizes sea electrodes. Normally to reduce installation problems (and costs) they are installed not deeper that 30 – 40m, but anyway the correct positioning of electric field probes can be difficult to achieve and check. If location requirements of measurement points need not be extremely accurate, a ROV (Remotely Operated Vehicle) can be used. On the contrary, scuba divers must position the probes manually; it must be remarked that submarine works are slow, expensive, and present some peculiar aspects. Scuba divers are usually not particularly expert about unusual electrical measurements like those here reported and, last but not least, must be trained before the campaign of measurement. Furthermore, and probably the most substantial aspect, is that every measurement must be logged and carefully time-stamped, to correlate the measured value of the electric field at a fixed location with the actual value of the HVDC electrode current (provided from the current transducer installed within the converter station) in the exact moment of the measurement. For this reason, such submarine measurements require a significantly greater coordination effort, if compared with more common measurements. Measurements performed with ROV are obviously preferred for their simplicity in the selection of the sampling points and moreover the higher number of measurements per hour.

VIII. Choosing the Correct Sampling Points

Depending on the electrode type, sampling points must be chosen in a meaningful way. Schematically, real sea electrodes can be of categorized into three main types:

- Copper conductor (cathode);
- Concrete boxes with dispersing parts inside;
- Flat electrodes with dispersing parts parallel to the seabed.

The first type of electrode (Fig. 7) is built by laying a stranded conductor above the seabed (around 1m), using suitable structures. This is to ensure that the dispersing medium is always surrounded by seawater avoiding the contact with seabed mud. The length of such conductor is usually in the order of some hundreds meters giving as a whole a very uniform electric field along its length even though there is strong variation in radial direction, i.e. varying the distance point-conductor. Obviously such longitudinal uniformity is no longer true near the ends of the stranded conductor due to “side effects”. Therefore, for such reason, it is recommended that the measurements shall be performed at different radial distance both at the ends and in between.

Fig. 7. Copper cord electrode on its supports (feeding cable omitted).

Another used configuration for sea electrodes is based on a concrete box (Fig. 8), with a number of holes on its external surface, each one covered by a network barrier, which has the function of inhibiting marine living creatures from entering the box. Inside the box, in fact, the dispersing elements (usually metallic bars) are properly suspended; therefore, the field is much higher there. As the concrete is less conductive than seawater (usually 3 order of magnitudes), the electrode current flows mostly out the holes.

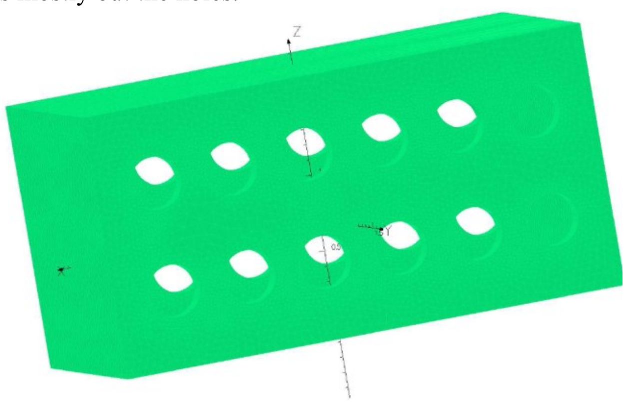

Fig. 8. Geometry of a typical concrete box type electrode.

Consequently, an irregular field distribution is to be expected (higher in front of the holes, and lower elsewhere, Fig. 9). As the distance from the box increases, however, field tends to reduce quickly.

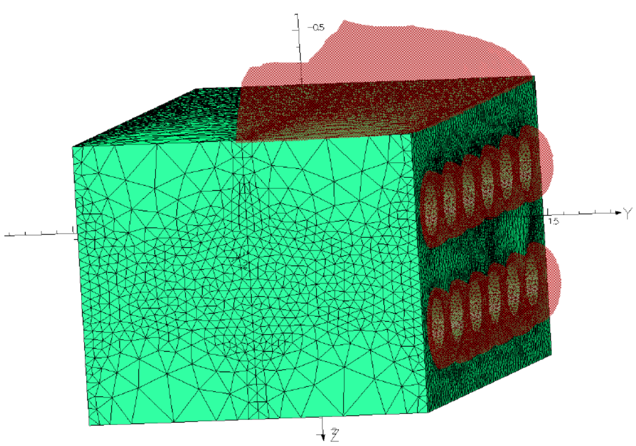

Fig. 9. Example of equipotential surface around box electrode.

Flat electrodes can be made using different technologies, ranging from the use of concrete “lenses”, basically sort of dishes, filled with coke, inside which the dispersing elements (usually graphite bars) are located [6]; another technology uses ready-to-install modules made using as dispersing element a coated titanium mesh, inserted between two protective plastic mattresses [7]. Irrespective of the adopted technology, all these electrodes are characterized to be horizontally laid on or above the seabed. In absence of any specific design countermeasure, the natural behavior is to have higher fields around their external edges, and somewhat smaller in their central area. Sometimes equalization techniques are deployed in such a way to achieve more uniform distribution of fields, by connecting each dispersing element using a cable of different length (and therefore resistance). The measurement can thus be performed above the dispersing elements along a vertical direction, choosing a reasonable number of points, to check whether the field is uniform within the prescribed design limits. Also in this case, fields tend to reduce very quickly as the distance from the electrode increases. In any case a good practice is that measurement points should be carefully selected during the electrode design, in order to have enough points to compare as far as possible the numerical simulation with the infield measurements.

It should clearly be stated that, for all the above-described probes, the value of the measurement provided is to be intended as averaged over probe characteristic dimension. For this reasons, if the measurement shows large variations over distances of the same order of magnitude of the probe, the output measure can be significantly different from the expected one. This is particularly true when getting very close to the HVDC electrode, where the measurement can even loose practical significance. In other terms, larger probes means higher sensitivity, but worse performances when dealing with fields with steep space variations.

IX. An Infield Measurement

Electric field measurements performed on the anodic electrode of the Italy-Montenegro HVDC intertie is here reported. The voltmetric method was selected for its simplicity and smaller error. The measurement electrodes were installed on a ROV and the measurements were performed when the electrode was at its rated current (1200 A). The electrode is made of 12 sub-electrodes (see Fig. 10) installed at 32 m depth on the Adriatic Sea. The electrode is divided into two half-electrodes with 6 sub-electrodes each. Each half-electrode is connected to a 3-core cable in which each core connects two sub-electrodes in

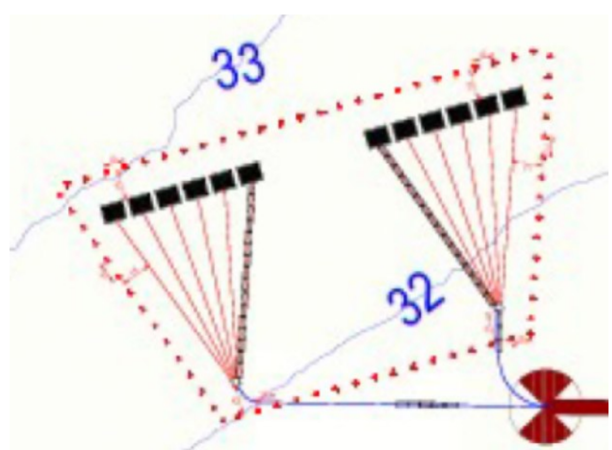

Fig. 10. Sketch of the Italy-Montenegro anode electrode.

parallel. Such solution was decided in order to monitor the current sharing among couple of sub-electrodes. Each sub-electrode is made of a coated titanium mesh installed beneath a fiberglass structure as reported in Fig. 11. Such structure due to

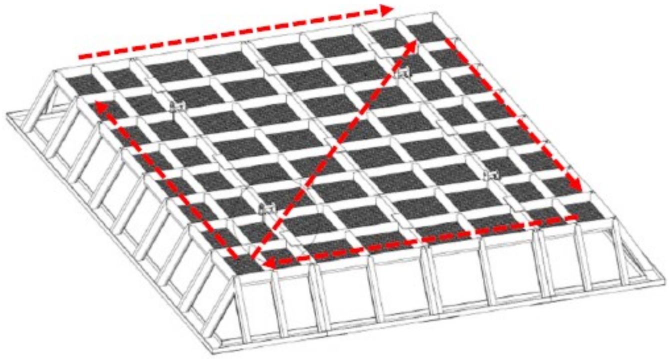

Fig. 11. Sketch of the fiberglass structure supporting the coated titanium mesh (dark area).

its high resistance to mechanical stresses provides a good protection to the coated titanium mesh itself. The sub-electrode structure allows the operation of the coated titanium mesh 1m above the seabed for a better current dispersion and lower current density. Fig. 12 shows the measurement along the edge of three sub-electrodes of the same half-electrode, in particular the two external sub-electrodes and one in the middle.

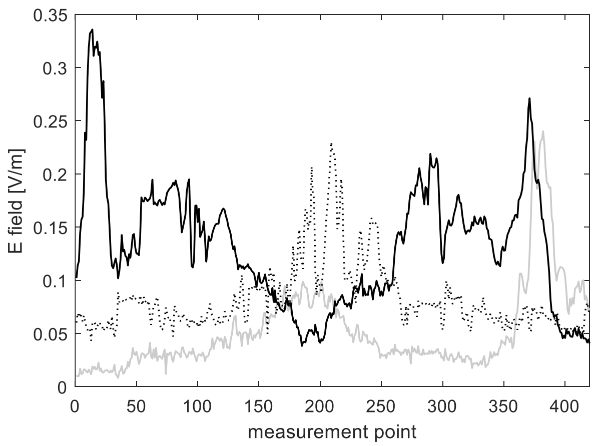

Fig. 12. E field measurement on three different sub-electrodes of a half-electrode: the external sub-electrode farthest from the other half-electrode (solid black line), the external sub-electrode nearest from the other half-electrode (solid gray line) and a sub-electrode in the middle of the half-electrode (dotted line).

As expected, the highest field value is recorded near one of the external sub-electrode, the one that is farthest from the other half-electrode (solid black line in the figure). With the exception of some point, the average field value is in the range of 0.1 V/m. The max field value does not exceed 0.35 V/m on the most external sub-electrode, while slightly exceed 0.25 V/m on the other sub-electrodes.

X. Conclusion

The spreading use of HVDC links, sometimes leads to the need of installation of sea electrodes. They present many advantages with respect to ground electrodes, but also a number of peculiarities. One is the not simple measurement of their performance, in terms of the emitted electric field during operations. Even though many issues are still open, the paper tries to describe the main problems arising during the preparation, the execution and the analysis of measurements around them, requested by Technical Guidelines, but scarcely described in technical literature.

The problem is intrinsically multidisciplinary, and requires the cooperation of instrument manufacturers, plant operations management, measurement experts, scuba divers, et cetera. Quite differently from pond electrodes, where normally fields are higher, and the environment is more “comfortable”, when dealing with real sea electrode things get more complex, measurement time and cost significantly increases, and measurement errors get worse.

Three different E field measurement methods are described with their pros and cons. The voltmetric method, very attractive for its practice, is less exposed to errors than the amperometric method. The magnetic method is innovative – for the first time proposed here from the University of Genoa, simpler than the amperometric method, but more prone to measurement error than the voltmetric method. In any case represents an interesting solution to take into account.

Practical issues on infield measurements are discussed in order to give some hints based on the experience of the Authors. Measurement results from an in service HVDC electrode are also reported and illustrated.

The Authors hope that this contribution may help researchers and engineers working both in the design and in the infield measurements for the design verification of HVDC marine electrodes.

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