Electromagnetic Fields emitted by High Voltage Alternating Current Offshore Wind Power Cables and interactions with marine organisms

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***Abstract*— The demand for renewable energy has lead to a large scale deployment of offshore wind farms, particularly in Northern Europe. The extent of the electrical cabling in the marine environment is unprecedented, and this has lead to questions about whether there are any interactions between the electricity produced and the surrounding environment. A summary of the electric and magnetic fields generated by such cables is presented based on a research project using an analytical method to set up the problem which was then quantified numerically using the finite-element method. An industry standard 132 kV XLPE three-phase submarine cable buried at a depth of 1 m was modelled as an example. The results showed that a cable with perfect shielding does not generate an electric field (E field) outside the cable directly. However, a time-varying magnetic field (H field) is generated by the alternating current in the cable, which in turn generates an induced E field in the local environment. The results are considered in terms of environmental impact assessment relevant for the power delivery community.**

***Index Terms*— Offshore wind farm cables, subsea cables, high voltage AC cables, electromagnetic field, EMF.**

I. INTRODUCTION

Energy from renewable sources has become a priority for many countries worldwide as a response to calls for reduced production of greenhouse gases, lowered dependency on fossil fuels and increased energy security. Offshore wind facilities are currently the leading technology with wave and tidal energy devices going through extensive research and development. Whilst this growth in obtaining energy from renewable sources is globally important there are questions arising about how the industrial expansion may positively and/or negatively impact the environment locally [1, 2]. Environmental and development legislation requires the potential environmental impacts to be properly understood, assessed and mitigated against, if deemed negative. In this context, one specific question raised is whether there are any environmental consequences of transmitting electricity via the extensive network of cables between devices and onwards to onshore electrical grid systems. It has been reported that some marine organisms may be sensitive to subsea cables, more precisely, to the electromagnetic field (EMF) generated by the cables, as they may have wider ecological implications for marine life and the environment [3-8]. Some species of fish, such as skates, rays and sharks (collectively known as the Elasmobranchs), use electric and/or magnetic fields as their primary mode of locating food, finding mates and navigating. Migratory fish, such as the Atlantic salmon or the European eel, respond to magnetic fields in the environment [4] (e.g. the earth's geomagnetic field). The field intensities they can detect are within the range of EMF levels associated with a cable [5-8]. Other organisms such as cetaceans (whales and dolphins) are sensitive to changes in the geomagnetic field of 30 ~ 60 nT (for reference, the Earth's geomagnetic field strength is approximately 50 μT), and probably employ much finer levels of discrimination. Many species are of key importance to our coastal ecosystems, however their numbers are dramatically decreasing due to over-fishing and habitat degradation. With the development of offshore windfarms there is the potential for these organisms to be affected through further deterioration of their habitats or interference with their sensory environment, or positively via habitat enhancement and the protection the offshore wind farm developments may afford them. Either way there is a fundamental need from the power industry and the regulators (including their consultees) to understand whether the EMF generated by wind farm cables may interact with marine species. We were commissioned to conduct an in-depth study into this issue by COWRIE (Collaborative Offshore Wind Research into the Environment) steering group, which represented the offshore wind farm industry, UK government and statutory conservation agencies.)

It is well-known that emissions from electricity cables onshore and overhead may have implications for human health and interference with electrical appliances [9-11]. However, very little study effort has been directed towards underwater cables. Furthermore, the cables used for onshore and overhead electricity transmissions are normally different from that for offshore windfarms. The type of transmission (AC or DC), the cable materials, the power transmission characteristics and the conductivity of the surrounding water will all have some influence on the EMF emitted [11-13]. To date, no studies have considered fully the cables in the sea although anecdotal reports suggest that there are circumstances where the cables and marine fauna do interact [13]. The objective of this paper was to summarise an investigation of the EMF generated by an integrated off-shore windfarm cable using both theoretical/analytical and numerical methods. The detailed outputs are publically available (http://mhk.pnnl.gov/wiki/images/9/99/COWRIE_EMF_Offshore_Cables.pdf [6]

II. THE CABLE AND ELECTROMAGNETIC ANALYTICAL ANALYSIS

Offshore wind farms can be connected to the grid either using a high voltage alternating current (HVAC) or high voltage direct current (HVDC) transmission scheme depending on the rating of the windfarm and the distance to shore [14-16]. For HVAC transmission, a three-phase system is generally employed since it is currently regarded as the most economical and efficient. The three circuit conductors carry three alternating currents (of the same frequency; 50Hz in Europe) which reach their instantaneous peak values at different times. Taking one conductor as the reference, the other two currents are delayed in time by one-third and two-thirds of one cycle of the electrical current. This delay between "phases" has the effect of giving constant power transfer over each cycle of the current, thus it has been adopted by the offshore wind industry. Typically, the three phased cables for off-shore windfarm application are integrated and packaged into one cable which is different from the three-phase power transmission over the land where three separate cables are often used. Within this compact cable, there are three separate cores, each of which is shielded by an insulation screen as shown in Fig. 1. The use of insulation screens enables the confinement of the electric field within the cable and reduces the hazard of shock, both achieved by the screens being well earthed [12, 13]. However, the magnetic field cannot be effectively shielded in this way. As a result, there may be EMFs generated outside the cable, radiating into the surrounding seabed and sea water.

As it can be seen from Fig. 1, shielding materials are employed in the cable which leads to the field around such a cable being complex and requiring electromagnetic (EM) analysis. Here we consider the elements that affect the EMF. The typical EM properties of the cable materials are summarised in Table 1, the material properties outside the cable are also included. They are the permittivity ε, conductivity σ, and permeability μ.

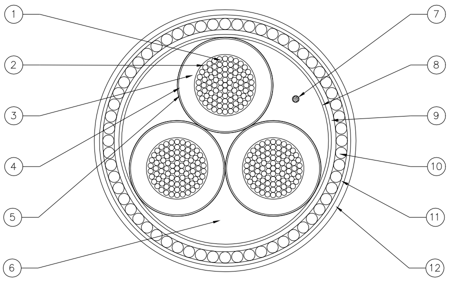

Fig. 1. Typical cross-sectional representation of an HVAC wind farm power cable (not to scale). 1 = conductor, 2 = conductor screen, 3 = insulation, 4 = insulation screen, 5 = core screen, 6 = cores laid up with fillers, 7 = fibre optic package, 8 = binder tape, 9 = armour bedding, 10 = armour, 11 = inner serving, 12 = outer serving.

The cable consists of a triangular symmetrical arrangement of three single-core sub-cables, where the sub-cables are placed at the corners of an equilateral triangle. Every core in the three-phase cable, comprising phases 1, 2 and 3 with 120° phase shift from each other, can be regarded as a return line of the other two. In each core, the lead sheath serves as conducting screen to confine the E field radial inside each sub-cable. Outer steel armouring provides stronger mechanical strength and added protection to the cable. Inside each core is filled with XLPE (a form of polyethylene with cross-links), which has good electrical and thermal performance, and it should increase the breakdown voltage and ability to store electric energy.

With these materials, there are two major factors affecting the EMF around the cable: one is the attenuation due to the conducting materials and the other is the conducting screen/earth.

TABLE 1 EM PROPERTIES OF THE MATERIALS OF THE WINDFARM CABLE AND SURROUNDING ENVIRONMENT.

	ε_r	σ (s/m)	μ_r
Conductor (Copper)	1.0	5.8e+7	1.0
XLPE (dielectric)	2.5	0.0	1.0
Sheath (Lead)	1.0	5.0e+6	1.0
Armour (Steel wire)	1.0	1.1e+6	300
Seawater	81	5.0	1.0
Sea sand	25	1.0	1.0

A. *Field Attenuation*

The EMF generated by three conducting sub-cables may pass the sheath and even the armour. Since both the sheath and armour are good conducting materials and the amplitude of the electric/magnetic field can be expressed as a function of the propagation distance in the lossy/conducting medium [17] and the attenuation factor, which is inversely related to the skin depth of the shielding material. The higher the frequency, conductivity and permeability, the smaller the skin depth (i.e. better shielding effectiveness). Also, the larger the distance, the smaller the field amplitude. Thus the shielding material should be very conductive and highly permeable.

B. *Earthing*

In addition to the attenuation introduced by the sheath and armour on the EMF, earthing the cable is another way to change the field strength significantly. The function of earth is to set the absolute electric potential of a conducting material to be zero – the same as the Earth. Earthing the sheath should reduce any leaked fields further down to zero (earth). Thus we should expect very little electric fields leaking to the outside of the cable.

On the other hand, the magnetic field exhibits different characteristics from the E field: earthing the sheath can reduce the electric potential (hence the outside E field) down to zero but not the H field. This is the major difference between the E field and the H field. We can predict that the E field generated outside the cable might be zero (if earthed properly) but the H field will not be zero and its strength is dependent on the material properties and thicknesses of the sheath and armour for a given current/voltage source.

C. *Induced Electric Field*

From the above, one might wrongly conclude that if the cable is properly earthed, there would be no E field generated outside the cable. Since we are dealing with an AC power system, Maxwell's equations for a time-harmonic case clearly shows that the changing magnetic field ***H*** (either against time or position in space) can generate an induced electric field ***E.*** The analysis demonstrates that both the E and H fields are inversely proportional to the distance to the cable. Furthermore, the electric field and magnetic field in sea water have a phase difference of 90^0 and the amplitude of the electric field is much smaller than that of the magnetic field.

The theoretical analysis demonstrated that both the E and H fields can exist around a typical wind power cable even when well shielded. The magnetic field cannot be earthed and can only be attenuated using extremely thick steel armour while the directly emitted electric field may be shielded by a good earthing screen of the cable. But an induced E field is predicted to be generated by the H field outside the cable. It is not possible to obtain accurate results through the analytical approach due to its complexity; a numerical simulation tool was therefore employed.

III. THE CABLE AND ELECTROMAGNETIC NUMERICAL ANALYSIS

To quantify the extent, intensity and geometry of the EM emission associated with a wind farm power cable a computer simulation using geometrical modelling of the cable was used. The cross-section of a three-phase cable is uniform along the axis of the cable; hence a two-dimensional model was sufficient for the simulation of the entire cable.

A. *The Simulation Software*

Maxwell 2D developed by Ansoft [18] was used for the simulation of EM and electrostatic fields in structures with uniform cross-sections. The model solves Maxwell's equations using the finite-element method. It divides the structure into many smaller regions, which are represented as multiple triangles referred to as the finite element mesh. Input data were the structure and specific relevant material characteristics, boundaries conditions describing field behaviours, sources of current or voltage, and the quantities required to compute. The simulator generates field solutions and computes the requested quantities. Two field solvers were used in this project:

a) The AC Conduction Field Solver to analyse conduction currents due to time-varying electric fields in conductors and lossy dielectrics. It can model current distributions, electric field distributions and potential differences, etc. In addition, any quantity that can be derived from the basic EM quantities can be analysed. This solver computes the electric potential, from which the E field and H field can be derived.

b) The Eddy Current Field Solver calculates the eddy currents (induced by changing magnetic fields) using Maxwell's equation. It allows simulation of the effects of time-varying currents in parallel-conductor structures and can model eddy currents, skin effects, and magnetic flux. In addition, any quantity that can be derived from the basic magnetic field quantities can be analysed. This solver computes the current density, rather than the electric field potential. Using Maxwell's 2nd equation, the current density and the electric field strength in a medium can be described with the result being similar to the field predicted using the analytical approach (see [6] for detail).

B. *Modelling of a Real Cable Scenario*

An industry standard 135 kV cable was selected as an example for simulation. The diameter of the cable was set at 18 cm and all the major parameters were inputted. As in the real environment, the cable was simulated as buried in the seabed at a depth of 1 m beneath the seabed level in a water depth of 20 m (Fig. 2). The cross-section of the cable was modelled based on the main characteristics shown in Fig. 1. Cable operation details were inputted into the Maxwell 2D model, set at 50 Hz with r.m.s AC voltage of 135 kV between phases and 700A AC current flowing in each conductor.

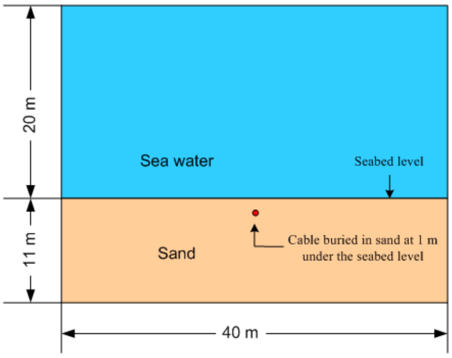

Fig. 2. Scenario of the windfarm cable used in simulation

IV. RESULTS AND DISCUSSION

A. *Simulation Results of AC Conduction Field Solver*

With the time-varying voltage source assigned to each conductor of the three-core cable, the electric field distributions alternately attain the maximum value due to the alternating voltage sources with a 120° phase shift at each core. The metallic sheaths create earthed shields, so that the electric fields are strictly confined in each core and have symmetrically radial distribution within the dielectric XLPE. Consequently, no electric field is leaked from each core, hence no electric field outside the submarine cable (assuming the ideal case that cable sheaths are perfectly earthed). Moreover, as known from Maxwell's equations, alternating electric fields generate magnetic fields, through AC current flow in each conductor. These changing magnetic fields induce electric fields in surrounding medium and eddy currents in conductors. The Eddy Current Field Solver simulated the induced E fields.

B. *Simulation Results of Eddy Current Field Solver*

The operating windfarm cable has alternating currents flowing in each conductor with a 120° phase shift in each core, generating changing magnetic fields around each conductor. Fig. 3 shows the simulated magnetic fields inside the cable at different phases. Note the magnetic fields have a temporal rotation along the axis of the cable.

Whilst the sheaths of the cable provide good shielding to the electric field, they cannot shield the magnetic fields; hence they are expected to exist outside the cable. Fig. 4a shows the simulated magnitude of magnetic flux density outside the cable; with strong magnetic field in close proximity to the cable, dissipating along the radial direction of the cable cross-section. The magnetic fields at the same distance to the cable are identical, due to the non-magnetic properties of both the seawater and the sea sand.

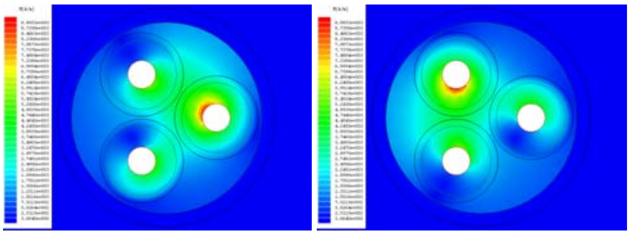
(a) (b)

Fig. 3 The magnetic field strength H inside the cable at different phases: (a) $\theta = 0$ and (b) $\theta = 120^{o}$. The colour scale is from 1 to 10^3 A/m

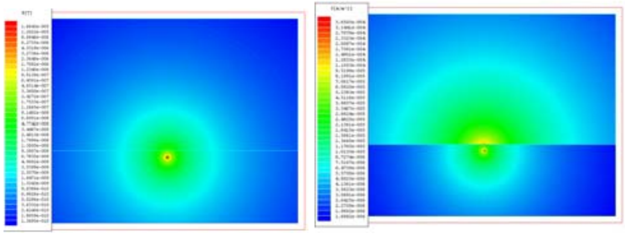
(a) (b)

Fig. 4. (a) The magnitude of the magnetic flux density (B field) outside the cable. The colour scale is from 10^{-10} to 10^{-5} T . (b) The magnitude of the current density outside the cable. The colour scale is from 10^{-6} to 10^{-4} A/m^2

Fig. 9 shows the simulated current density in both the seawater and the sea sand. Since the seawater and the sea sand have different electrical properties (i.e. conductivity), the simulated current density is discontinuous across the boundary between the seawater and the sea sand. Due to the higher conductivity and permittivity of seawater, the current density at an observation point in the seawater is approximately 5 times higher than that in the sea sand, both at the same distance to the cable. These modelled results match closely with the emission predicted using the analytical method earlier [6].

V. CONCLUSIONS

The current state of knowledge regarding the EMF emitted by subsea power cables is currently too limited and variable to make an informed assessment of any possible environmental impact of EMF on organisms that may be sensitive to the EM fields emitted. The results of the EMF research [6] summarised here provide quantitative evidence using analytical and numerical simulation that EMFs will be present within the sea bed and seawater around three-phase HVAC cables. The magnetic fields generated by the AC in the cable and the induced electric fields due to the changing magnetic fields are within the detectable range for EM sensitive species. The findings from this research are not just limited to offshore wind farms they have wider application to other subsea cable deployments (e.g. marine renewable energy; supergrids and interconnector projects).

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