# Appendix 4:

# Impact of Electric and Magnetic Fields from Submarine Cables on Marine Organisms – the Current State of Knowledge

# IMPACT OF ELECTRIC AND MAGNETIC FIELDS FROM SUBMARINE CABLES ON MARINE ORGANISMS

## THE CURRENT STATE OF KNOWLEDGE

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# IMPACT OF ELECTRIC AND MAGNETIC FIELDS FROM SUB-SEA CABLES ON MARINE ORGANISMS
# - THE CURRENT STATE OF KNOWLEDGE

## SUMMARY

One environmental concern regarding offshore renewable energy is the potential effects of electric and magnetic fields on the marine environment. The importance of this issue has been identified in several studies and in some countries it is mandatory to describe the potential impact from EMF in an Environmental Impact Assessment (EIA) to meet the statutory requirements of the permit process.

There are marine organisms that are able to detect the natural geomagnetic field for navigational purposes (such as whales, turtles, and fish) and others (mainly fishes as sharks and rays) that can also respond to the biological electric fields emitted by all organisms. This enables them to find prey, mates and possible potential predators. One concern is that when more anthropogenic sources of magnetic and electric fields are present in the marine environment there is a potential that those organisms will be affected.

The aim of this study was to provide an up to date knowledge base concerning environmental effects in the marine environment due to EMF and underwater cables from wave power farms and off shore wind power farms. A better knowledge base will aid permit processes, contacts with authorities, the general public and other stakeholders. The aim was also to identify potential ongoing R&D projects and practical studies, summarise gaps in knowledge and provide recommendations on potential future actions that can be taken to fill these.

Within the study, modelling of the magnetic field was performed for five different AC power cables (10 – 145 kV, 100 – 500 A), as well as induced electric fields. The modelling results showed that:

- The maximum strength of the magnetic field produced by the cable is from 2 – 35 μT, depending on the cable setup and current load.
- The magnetic fields produced by the generating units (wave energy converters) are negligible compared to the fields from the cables.

- An induced electric field of 0.3 – 4 mV/m depending on cable setup and current load will be generated by an AC cable.
- The field strengths decrease rapidly with the distance from the cable. For example, a maximum of 35 μT immediately above the cable will be reduced to 2.2 μT at a distance of 2 meters from the cable.

The main conclusion of the literature study was that the current amount of information on the subject is very limited. Still, no research results were found that suggested that present sub-sea power cables posed as a threat to marine environment due to EMF. Although limited amounts of research have been conducted within the field a few other important conclusions can be drawn.

- Electric and magnetic fields within the magnitude of what is to be expected from marine renewable energy lies within the detection range for some electroreceptive marine organisms and within the assumed detection range for magnetoreceptive marine organisms.
- Behavioural effects have been shown in experiments both for species that use the magnetic field for navigational purposes (eel) and for species using electric fields for detecting prey (elasmobranchs). However the noticed effects have been considered to be small or the results have not been possible to use for evaluation of potential negative or positive environmental impacts.
- Comparing the thresholds identified in the literature study with the modelling results shows that magneto- and electro-receptive species may encounter detectable EM fields emitted by a power transmission cable in a range of a up to a few hundred meters, depending on the species and the cable characteristics.
- Within the project no research results were found that suggested that present sub-sea power cables posed as a threat to marine environment due to EMF.
- There is no information available from research on effects on marine mammals, and also no information suggesting that EMF from marine installations is an issue.
- There is not a sufficient amount of information to evaluate differences between AC and DC transmission regarding environmental effects from EMF.
- There are currently studies undertaken in the U.S., aiming to identify detection thresholds for a number of species from alternating (AC) fields.

In environmental impact assessment and consent processes, EMF-related impacts are treated differently in different countries in Northern Europe. While the environmental authorities in the U.K. and the Netherlands in many cases demand both analysis of potential impacts and monitoring programs during the operation phase, countries like Germany and Norway consider the EMF-related impacts to be negligible. This gives another indication that the mechanisms and impacts of electric and magnetic fields are not fully understood.

Based on the results in this study the main strategy within Vattenfall for EMF and sub sea installations is suggested to be to follow research performed externally within the field, and follow the development on what authorities and interest groups find important regarding EMF impacts. When an environmental statement for a planned wave or energy project is prepared, EMF should be properly analysed but the findings of this study does not motivate for Vattenfall to conduct further research, field surveys or studies on the subject.

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## 1 INTRODUCTION

As offshore wind power is built more extensively, and as wave power is developed, one concern regarding environmental impact is the potential impact of electric and magnetic fields (EMF) from cables and other underwater installations on the marine environment. Different from the case of EMF from land-based transmission (where the focus has been human health related), the main concern regarding EMF from underwater installations is in the context of potential impacts on marine life. The concerns have been if aquatic animals are avoiding or being attracted to sources of EMF and if EMF can cause disturbances in migration behaviour. This has previously been debated regarding the construction of transmission cables in the Baltic Sea.

The importance of this issue in the context of marine renewables has been identified in several studies which have led to the establishment of a number of research projects, investigating the potential or actual impact on marine organisms via field studies or theoretical evaluations. When the environmental impact from wave power and offshore wind power is discussed, EMF is almost always an issue that is brought to light and it is a mandatory part of the environmental impact assessment to describe potential impacts from EMF. Additionally the concern has several times been directly raised to Vattenfall in discussions with e.g. fishing organisations. A common concern is the impact on the migration behaviour on certain types of fish.

For Vattenfall it is of value to have knowledge of the results of research conducted within the field. It is important for future contacts with authorities, the public and other stakeholders and for future permit processes to be able to provide solid facts on the issue.

This report summarizes the current knowledge base regarding sub-sea power cables and their potential impact on the marine environment with focus on EMF, as well as what requirements environmental authorities in selected countries put in terms of impact assessment and monitoring. The outcome of the project will be a better knowledge base concerning environmental effects due to EMF, in the context of underwater cables from wave power farms and off shore wind power farms (i.e. marine renewables). A better knowledge base will aid permit processes, contacts with authorities, the general public and other stakeholders. The aim is also to identify potential ongoing R&D projects and practical studies, summarise gaps in knowledge and provide recommendations on potential future actions that can be taken to fill these.

## 2 METHOD

The information used in the study was mainly gathered by literature search in the database *Aquatic Sciences and Fisheries Abstracts* (which is database with references to articles, books, reports, conference material, patents and research related to water) and through direct contact with researchers and people with knowledge within the field, as well as correspondence with environmental agencies in the U.K., Holland, Germany, Norway and Ireland. If information was missing a broader search using Google was conducted.

The study includes impacts in the submarine environment from the types of cables used in wave and offshore wind projects, as well as the generating units and transformers. HVDC cables have only been included where information from studies conducted on direct current provide valuable input. Impacts on landfall areas are not included.

Modelling of magnetic fields and induced electric fields have been carried out for 5 different cable settings. The methods are described in Section 4.

Main contacts:
- Andrew Gill: Cranfield University involved in the COWRIE EMF studies
- Erland Lettevall: Swedish Board of Fisheries, has got knowledge on marine mammals
- Kerstin Jansbo: Swedish Environmental Protection Agency, responsible for Vindval (research program environmental effects of wind farms)
- Håkan Westerberg: Swedish Board of Fisheries, involved in several studies on the effects of EMF on eel
- Erik Sparrevik: Marine Biologist at Vattenfall Power Consultant
- Rutger Rosenberg: Professor at the institution of Marine Ecology at the University of Gothenburg
- Magnus Wahlberg: Ph. D., Assistance Professor University of Southern Denmark, and Chief biologist, Fjord and Bælt.
- Maria Boethling: Federal Maritime and Hydrographic Agency, Germany
- Sander de Jong: Advisor, Rijkswaterstaat Noordzee, Holland.
- Linn Silje Undem: Norwegian Water Resources and Energy Directorate
- Andrew Sutherland: Marine Renewables Licensing Advisor, Marine Scottland.
- Ross Hodson: Offshore Renewables Consents Manager, Marine Management Organisation, England

# 3 TECHNICAL BACKGROUND

This chapter gives a short technical overview of EMF in the marine environment. The purpose is not to be an exhaustive description of EMF linked to specific installations, but to give an overview to provide context for the biological mechanisms discussed later on.

## 3.1 Explanation of EMF

The chapter includes calculations of EMF levels for magnetic and induced electric fields from cables similar to the types of cables used in offshore energy installations.

EMF is an abbreviation for **E**lectro**m**agnetic **F**ield or **E**lectric and **M**agnetic **F**ields, depending on frequency range. In the case of frequencies below 400 kHz, the term electric and magnetic field is generally used[1]. The electric and magnetic fields can be observed separately from each other but they are interdependent[2].

EMF is generated every time electricity is generated, transported or used, implying that all electric equipment as well as power cables gives raise to EMF. The “primary” electric field (E-field) depends on the voltage and the magnetic field (B-field) on the current. Furthermore, the existence of a time varying magnetic field will cause an induced electric field, denoted iE. The quantity unit for electric field strength is volt per meter [V/m] and for the magnetic flux density tesla, [T]. The magnetic field can also be expressed as magnetic field intensity (H-field), which is measured in amperes per meter and differentiated from the B-field by the magnetic permeability of the medium.[3]. Increasing voltage will give stronger electric field and increasing current will give stronger magnetic field. The field from an AC system will be changing at the same frequency as the current while a field from a DC system will be stable.

**Table 1. Components of the electric and magnet field.**

| Field | Denotation | Unit | Proportional to |
|---|---|---|---|
| Electric | E-field | Volt / meter (V/m) | V |
| Magnetic | Flux density (B-field) | Tesla (T) | I |
| Magnetic | Intensity (H-field) | Ampere / meter (A/m) | I |

The field strength of a power cable is also affected by other parameters than the current and voltage levels, such as the design of the cable (e.g. distances between the phase conductors and the twisting of the conductors) and the distance between the observer and the electrical structure. The fields decrease with increasing distance from the emitting source and only occur in the proximity of the cable, further explained below..

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[1] The term electromagnetic field is used for the high frequency range, roughly above 400 – 500 kHz and electric and magnetic fields below this frequency. In the ELF-range (Extrem Low Frequency), the frequency is between 5 Hz to 2000 Hz. The ELF-range is often called the power frequency range and consists of the fundamental frequency and its harmonics.

[2] For the very low frequencies associated with power systems (~50 Hz), presentation as a composed electromagnetic wave does not make sence due to its extreme wavelength.

[3] There are several alternative names for magnetic field density (B-field) and magnetic field intensity (H-field). The two are indistinguishable outside of the cable (they only differ in units and magnitude). This report will use the B-field measured in Tesla.

## 3.2 EMF of submarine cables

When using the term EMF in consideration of submarine power cables one refers to three components associated with the power transmission. Firstly there is an electric field that with an insulated conductor and earthed metallic screen is shielded within the cable, secondly there is a magnetic field outside of the cable and thirdly there is an induced electric field (iE-field). The iE field is either caused by the changes in field strength of the AC magnetic field, movement of conductors such as water or marine organisms through the magnetic field or as a result of the natural variations in the geomagnetic field.

A simplified overview of the co-existence of the fields generated by an AC-cable is illustrated in Figure 1.[4]

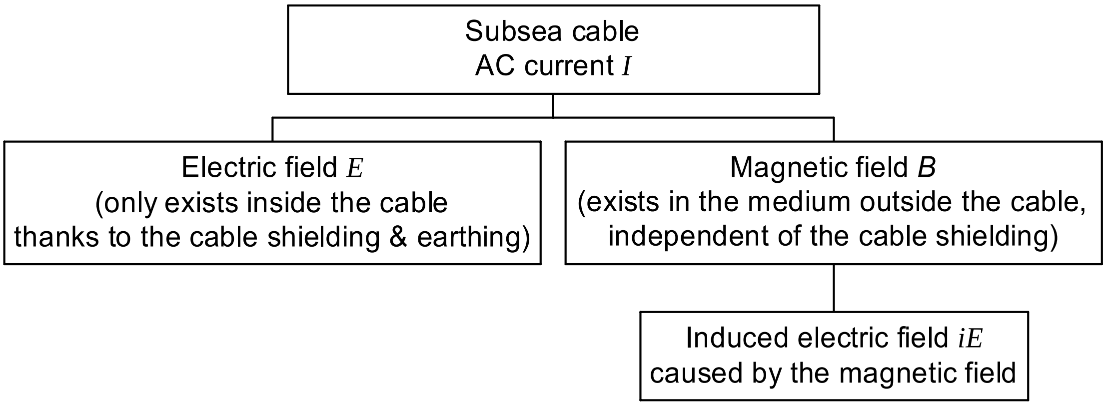

**Figure 1. The electromagnetic field components in the presence of a sub-sea cable carrying a current (after Gill et al. 2009).**

## 3.3 Design and EMF of submarine cables and other installations

### Cable design

Submarine electric cables can be divided into the following categories:

- Telecommunication cables
- High voltage direct current cables (HVDC)[5]
- Alternating current (AC) power cables[6]

The latter category consists normally of three-phase cables and can be divided into: high voltage cables (HV, exceeding 36 kV), medium voltage (MV) and low-voltage (LV, up to 1000 V).

There are several factors that may affect the choice and design of sub sea cables.

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[4] The iE field is also produced through magnetic rotation of a 3 phase AC cable.

[5] The HVDC-technique is commonly deployed in submarine cables with three different technologies applied, 1) single conductor, where the return current is fed through the ground, i.e. mono-polar transmission, 2) two high voltage cables used in parallel but with opposite polarity (bi-polar transmission), 3) A variation of the first type but with one or several metallic low voltage conductors as return path.

[6] The cables used are either three single core conductors or one three-core conductor

1. The utility connection voltage to the regional distribution network or to national transmission system. Gill et al. (2005) stated that for many Round 2 wind power farms in England and Wales AC transmission systems with 3-core 132 kV may be the most cost-effective solution, and that cables within the wind power arrays will be 33 kV.
2. The cable technology used, e.g. different kinds of insulation types and conductor sizes.
3. Distance from shore to array may influence the choice of cable used. The use of HVDC shore link transmission only becomes cost effective where a project is at significant distance from the coastline and where large amounts of power need to be transferred. Developments on the HVDC technology are however continuously decreasing the costs and HVDC-cables may therefore be used in the future.

**Table 2. Compilation of AC and DC cable system properties.**

| **AC** | **DC** |
|---|---|
| Simple to connect to existing transmission net | Needs conversion stations before connection to existing transmission net |
| Restrictions on cable length | Transmission over hundreds of kilometres |

The technology that is used today in offshore wind power installations consists of three phase AC transmission systems that are more suitable for short distance transmissions than systems using DC. In the future it is likely that DC transmissions will be used more frequently (Öhman et al. 2007). Unlike the HVDC systems the three separate conductors of a three-phase AC cable is often laid in close proximity to each other, this reduces the resulting magnetic field (Öhman et al. 2007) but does not eliminate it.

Besides the main transmission cables there might be other installations in an offshore wave power or wind power farm that will produce EMF. First there are smaller cables within the farm that collect the power from all the units to one or several collection points and secondly there might be other installations that could result in EMF such as transformation stations and generators. No information about EMF from other submarine installations in the context of marine renewable energy where found during the literature survey.

# 4 ELECTRIC AND MAGNETIC FIELDS FROM SUBMARINE POWER CABLES AND WAVE ENERGY CONVERTER UNITS

This section described the electric and magnetic fields associated with submarine power cables for offshore wave/wind power, and the wave energy converter units. As stated above the considered cables for marine energy installations of wind and wave power farms are presently AC-cables, not HVDC. It has also been stated that the fields of interest are the magnetic field and the induced electrical field, as the design of cables ensures that in a shielded cable the electric field stays within the cable.

According to the previous research as well as calculations carried out for this study (see below) the levels of the magnetic field of sub sea cables are generally in the range of approximately 0,6-23 μT at a distance of approximately 0,5 metres from the cable. The nature and strength of the fields produced is dependent on the current and design of the transmission system.

In the volume around an insulated and shielded cable the EMF field components exists according to Table 3. As HVDC-cables are currently not being used for marine renewables, fields from DC-cables are not further analysed here. The fields from AC cables are further described in the sections below.

**Table 3. Field components in the space around a shielded and insulated cable.**

| | AC | DC |
|---|---|---|
| **Magnetic field** | Exists everywhere in the volume around the electric conductor, independent of electrical properties of the medium and insulation of cable. | Exists everywhere in the volume around the electric conductor, independent of electrical properties of the medium and insulation of the cable. |
| **Electric field** | No primary electric field exists outside a shielded cable, but the magnetic field will cause an induced electric field denoted “iE”. | No primary electric field exists outside a shielded cable. Normally no induced electric field “iE” will exist, except if the cable and/or the medium (seawater) is moving. |

This section describes modeling results of the fields produced by an AC cable. In situ measurements on existing cables are associated with difficulties and reliable results are not available. More information on field measurements can be found in Appendix 1.

In the following B denotes the magnetic flux density, measured in T (Tesla) and E the electric field measured in V/m (Volt per meter). The relation between the magnetic flux density B and the magnetizing force H measured in A/m (Ampere per meter) is $B = \mu H$ where $\mu$ is the magnetic permeability.

### 4.1 Magnetic fields from AC-cables

In order to get a an impression of the level of the magnetic field from a number of standardised sub sea power cables a calculation has been carried out by Vattenfall Research and Development AB.

The investigated cables used in the modelling are:

- A 10kV cable - which corresponds to the transmission cable to be used at a wave power site in Mayo, Ireland
- Three different 36 kV cables which corresponds to internal cables of larger wind/wave power farms (between the turbines/devices to a sea base platform) or transmission cables for smaller farms
- A 145 kV cable - which corresponds to transmission cables of larger wind/wave power farms from the platform to land

In all cases a base case where the current is set to 100 A have been used. The results can easily be converted to stronger currents (see below).

The magnetic flux density is calculated along a line at the sea bottom perpendicular to the cable direction. It is assumed that the cable is buried 0,5 metres within the sea bottom. When burying the cable the minimum distance to animals in the sea water is increased. However, the fact that there is a sediment layer that separates the cable from the animals does not have any influence on the size of the field. In the calculation no transposition of phase conductors or steel armour are modelled. Close to the cable the result is not affected very much but further away the field will be lower than calculated.

The calculation from each conductor is based on the the Biot- Savarts law:

$$B = \mu_0 H = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \cdot 10^{-7} I}{2\pi r} = \frac{2 \cdot 10^{-7} I}{r} = \frac{0{,}2I}{r}[\mu T]$$

where $\mu_0$ is the magnetic permeability for vacuum and *r* the distance from each one of the conductors in the cable. The contributions from each conductor in a cable are added according to Figure 8 in section 4.3.1.

The model is a cross section of the three phase conductors where the length of the cables is very long. All calculation are done with the load current 100 A. The calculation results are shown in Figure 2.

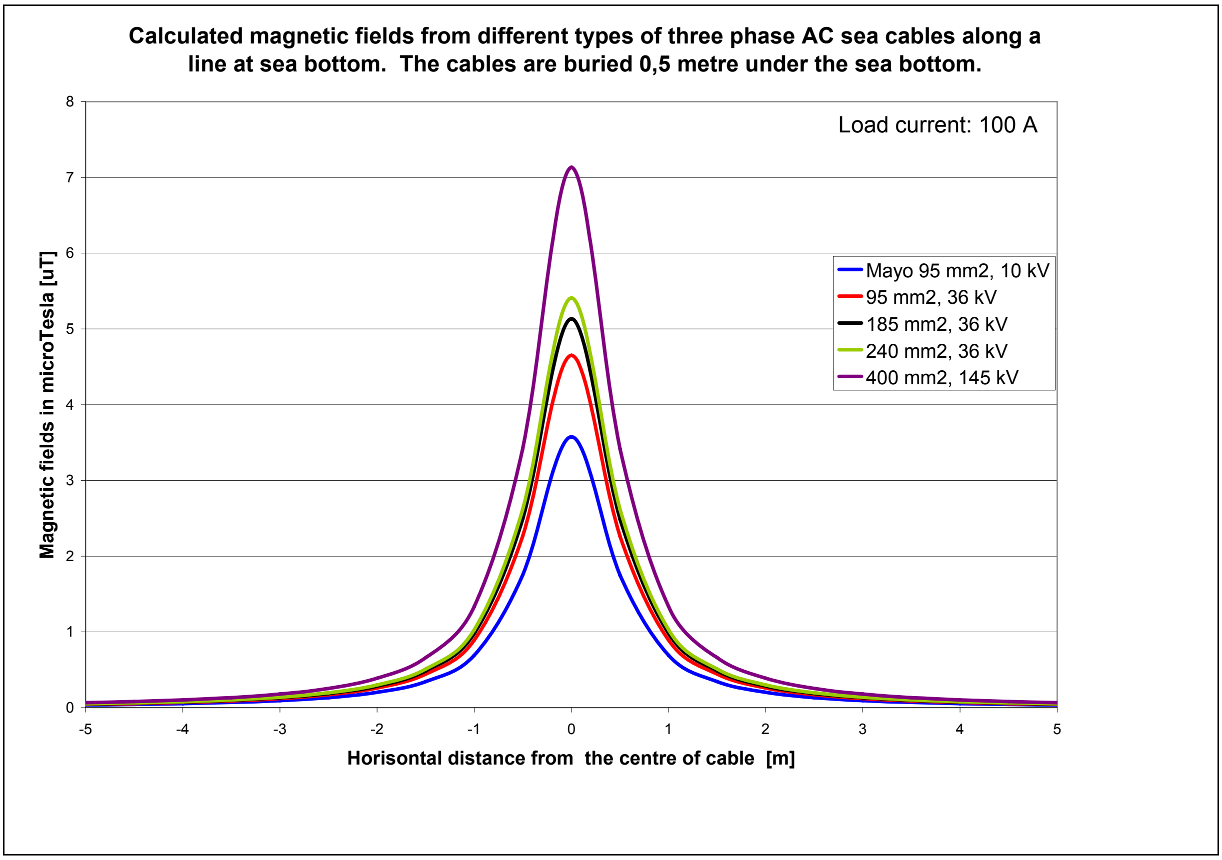

**Figure 2. Calculated magnetic fields from five different types of sub-sea power cables,**

The highest calculated B-field level was from the 145 kV, 400 mm$^2$ cable: 7.1 μT, and the lowest from the Mayo 10kV, 95 mm$^2$ cable: 3.2 μT. The magnetic field levels are rapidly decreasing with distance and at about one metre the magnetic field is lower than 1 μT in most of the cases. At a distance of approximately 10 - 13 m the magnetic field is smaller than 10 nT for all cables. If the load current is increased to 500 A the corresponding distance increases to approximately 30 m. The detection threshold values for magnetoreceptive organisms range from 10 nT to 50 nT (see Chapter 5.2), which would mean that if organisms can respond to this emission they would not be able to do so at a distance of more than 13 m from the cable, with 100 A load current or 30 m with 500 A load current. .

Figure 2 also shows that a larger conductor cross sectional area and higher voltage give slightly higher magnetic fields due to the greater distance between the conductor centres.

The magnetic field is proportional to the current, meaning that an increase of the current by five times would lead to an increase of the magnetic field strength by the same. It is also roughly inversely proportional to the distance from the cable, according to the Biot-Savart law.

To exemplify, a comparison can be made with a higher current in the 145 kV cable, with 500 A at 2 metre distance instead of 100 A at distance of 0.5 m. The current of 100 A in a three phase cable at a distance of 0.5 meter from the centre of the cable gives a calculated magnetic field of 7 μT. If the current instead had been 500 A the magnetic field at the same distance would be 5 * 7 μT, which is 35 μT. But the magnetic field 7 μT was calculated at a distance of 0.5 metre. Two metres is a four times further than 0.5 metres. The reduction of the magnetic field from a three phase cables is proportional to 1/distance$^2$. Accordingly at a distance of 2 metre the calculated magnetic field is then 2.2 μT, see the formula below:

$$B_{500} = \frac{B_{100} \cdot 5}{r^2} = \frac{7 \cdot 5}{4^2} = 2.2\ \mu T$$

If the twisting of the phase conductors is taken into account the reduction of the field with distance from the source will be even more rapid than 1/distance$^2$.

**Table 4. Maximum magnetic field above three different cable types carrying 100, 300 and 500 Ampere and buried 0.5 m.**

| Distance between the three conductors | 100 A | 300 A | 500 A |
|---|---|---|---|
| 35 mm (10 kV cable) | 3.6 μT | 11 μT | 18 μT |
| 49.34 mm (36 kV cable) | 5.1 μT | 15 μT | 26 μT |
| 66.96 mm (145 kV cable) | 7.1 μT | 21 μT | 35 μT |

## 4.2 Magnetic fields from wave energy converter units

The purpose of this section is to assess magnetic field levels outside different parts of sea generation systems, such as machinery, enclosures for generators, transformers and cables. Although presentation of figures is complicated due to the large number of cases it makes sence to assess the level of the emitted magnetic field and compare it with the emissions from connecting cables.

Outside cables and equipment housed inside steel housing there will be no electric fields. However, electric fields appear, indirectly, in animals/fishes when they pass through the magnetic field from the various parts of the plant, including interconnecting cables. It is only the current, not the voltage, that will cause a magnetic field and the field is proportional to the current amplitude.

Three sea generation systems have been theoretically studied from known data presented on each producers website: Two point absorber systems (Seabased and Wave Bob), and one attenuator system (Pelamis).

### 4.2.1 Seabased 50 kW

One of the point absorbers is “Seabased 50 kW”. Each WEC (**W**ave **E**nergy **C**onverter) consists of a floating buoy mechanically connected to a linear generator standing at the sea bottom. The vertical movement of the buoy is transferred into a relative motion between the moving part and stator in the generator and thus producing a three- phase electric power. Each WEC unit has a rated power of 50 kW. The WEC is then connected to a LVMS, **L**ow **V**oltage **M**arine **S**ubstation, also called “hub”. The substation is also located at the bottom of the sea. Several LVMS units may then be connected to a MVMS (**M**edium **V**oltage **M**arine **S**ubstation) unit where the energy at medium voltage is concentrated and transformed to a higher voltage (Seabased, 2010).

The WEC machinery, generator and transformer, is housed in a closed 12 mm steel cone. The thick steel walls will catch and conduct the magnetic field lines due to the high permeability (“magnetic conductivity of steel”), keeping most of the field inside the metal walls. A damping effect in the order of 10 – 100 times is assumed. In addition, distances between conductors and their return paths are small compared with other distances within the generating station. Small extension and short distances between equipment carrying current inside the cone means lower fields. If the conductors are short, they can be considered as point sources of the magnetic field and the decrease will follow the formula $B \sim 1/r^3$, where r is the distances from the conductors. The efficient shielding together with low current amplitude will give a low magnetic field outside the cone.

In case of power outages, the energy will be dumped into special dump loads consisting of two three-phase, resistive units per WEC, taking about 30 A in each circuit. The two loads are located outside the WEC, the length is only about 1 metre and there is a short distance between the conductors. They can be considered as point sources of the magnetic field and the decrease will follow the formula $B \sim 1/r^3$.

The LVMS is placed in a cylinder made of 16 mm steel with almost no air gap between the two halves of the cylinder. The overall design is similar to the WEC design and therefore the magnetic field will be low, related to the emission from connecting cables.

Next generation of the LVMS has a rated power of 2 MW, maximum 40 WEC units at 50 kW and 10 kV, corresponding to a current of 115 A at the high voltage side (Seabased, 2010). The equipment is earthed via a four metre long contact wire between the cable shielding and the water. This earthing is performed with respect to personal safety and the function of the relay protection system will have no effect on the magnetic field inside or outside the steel casing; the earthing of electric fields is for personal safety and the function of the relay protection system for the substation. From the substation a three-phase cable will transmit the power to land or to a MVMS hub. The switching frequency is 3.6 kHz, which corresponds to the 72:nd harmonic. The amplitude of the 72:nd harmonic is predicted to stay below 6.9 $\mu$T which is the action value for this frequency.

The design of the MVMS hub is similar to the LVMS and the only differences are that the voltage level is higher, implying lower current. Hence the magnetic field will be lower because it is proportional to the current. The resulting field depends on the ratio of the transformer and the number of connected LVMS.

### 4.2.2 WaveBob 1.5 MW

The other point absorber system is WaveBob. In the centre a heavy bottle-like, rigid construction, 50 – 100 metres tall, is hanging in the water. Above there is a floating torus with a diameter of 20 metres following the wave motions. The relative motion between the two parts will be transformed into mechanical energy (Wavebob, 2010)..

In the machine house, inside the torus and below deck, there will be a linear generator or a hydraulic system and a transformer, converters. and other electrical equipment. Accordingly, all these electrical devices are enclosed in the steel casing and no electric field will appear outside the casing while the magnetic field will be effectively attenuated. Therefore the field outside the device will be effectively shielded. A three-phase cable is hanging from the side of the machine house down to the bottom of the sea. Each point absorber will have a rated power of 1.2 MW to 1.5 MW. Since the type of generating system and distribution system are not decided yet the amplitudes of the field producing currents are still unknown. For example, if the voltage of the distribution system is 10 kV and the rated power of the generator is 1.5 MW the maximum current will be less than 90 A out from each WaveBob (Wavebob, 2010).

### 4.2.3 Pelamis P2

The Pelamis P2 WEC is a 150 metre long free-floating cylindrical semi-submerged device divided into five cylindrical tube sections, joined by four universal joints. Its diameter is 3.5 metres and the weight 750 tonnes including ballast. The machine house is located in the first section and between the other sections the movements will push a high-pressure fluid through hydraulic motors via smoothing accumulators and drive electrical generators to produce electricity. All five sections have steel casings of significant thickness. Due to the steel construction the magnetic field will be enclosed with shielding material and the magnetic field outside the steel casing is very low. The five section cylindrical semi-submerged unit has a rated capacity of 750 kW, at a voltage of 6.6 kV or 10 kV. A unit of 10 kV and 750 kW corresponds to a current of 43 A (Pelamis, 2010).

### 4.2.4 Conclusion

The magnetic fields outside the generation systems will be low, related to the emission from connecting cables, due to:

- Short distances between different equipment inside the steel housing
- Distances between equipment and the wall of enclosure
- The steel enclosure will reduce the magnetic field by a factor 10 to 100
- The extension of each generation system is short and therefore reducing the magnetic field with the distance according to$1/r^3$ and is lower than from three phase AC sea cable.

## 4.3 Induced electric fields

According to Faraday’s law of induction, the change in density or field strength of a magnetic field will cause an induced electromotive force in an electrically conducting medium. This electromotive force in turn, causes an electric field. In the following this induced electric field is sometimes denoted iE. Due to the electric isolation and shielding of a cable no primary electric field exists in the seawater outside a cable. The following considerations therefore apply to the induced electric field only, and the prefix “i” is omitted.

In a marine environment induced electric fields can exist due to the following reasons:

1) A sub-sea cable carrying an AC-current.
2) Moving water (e.g. tidal water) in the presence of the geomagnetic field.
3) Moving water (e.g. tidal water) crossing a cable carrying a DC-current.
4) Geomagnetic field variations, inducing electric and magnetic field.

1 and 3 are anthropogenic sources and 2 and 4 are natural sources that could give raise to the induction of electric fields. In the following these effects will be discussed.

### 4.3.1 Sub-sea cable carrying AC-current

The induced electric field depends on the distance from the cable, the electrical conductivity of the medium, the separation between the conductors and the load current in the cable. The full technical explanation with equations and calculations are provided in Appendix 3.

Assuming the current is 100 A, the distance between the conductors is 7 cm and the conductivity of the seawater is 3.5 S/m[7] the induced electric field from a three conductor cable is presented in Figure 4. As seen, the electric field decreases almost linearly in a double-logarithmic diagram up to approximately 40 m from the cable, which corresponds to one skin-depth[8] in the seawater. The induced electric field is proportional to the load current which implies that a load current of e.g. 500 A would result in an induced electric field of 1.9 mV/m at a distance of 1 meter.

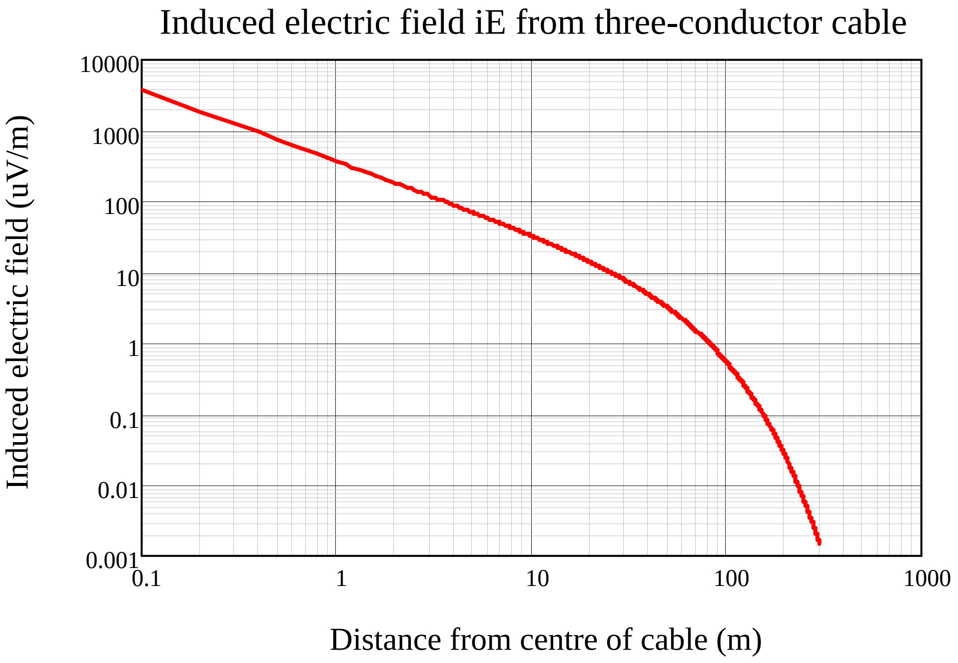

**Figure 3. The induced electric field in μV/m from a three-conductor cable, as a function of the distance from the cable. The current is 100 A, the separation between the conductors is 7 cm and the conductivity of the seawater is assumed to be 3.5 S/m, corresponding to a skin-depth of 38 m.**

Figure 4 shows the magnetic flux density, calculated as a function of the distance from the cable, using the same conditions as for Figure 3.

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[7] The electrical conductivity of seawater depends on temperature and salinity, and ranges from approximately 1.7 S/m to 5 S/m. The mean conductivity of the oceans is 3.27 S/m (National Physical Laboratory 2008, http://www.kayelaby.npl.co.uk/general_physics/2_7/2_7_9.html). The conductivity of the North Sea is around 3.5 S/m.

[8] The skin-depth is defined as the distance at which the amplitude of a plane-wave field has decreased to 1/e = 37% of the original amplitude. In this case the field is not a plane-wave field, and the decrease of the field (Figure 4 and 5) is caused by geometrical reasons up to approximately 30-40 m from the cable. The additional decrease from approximately 40 m is caused by the skin effect.

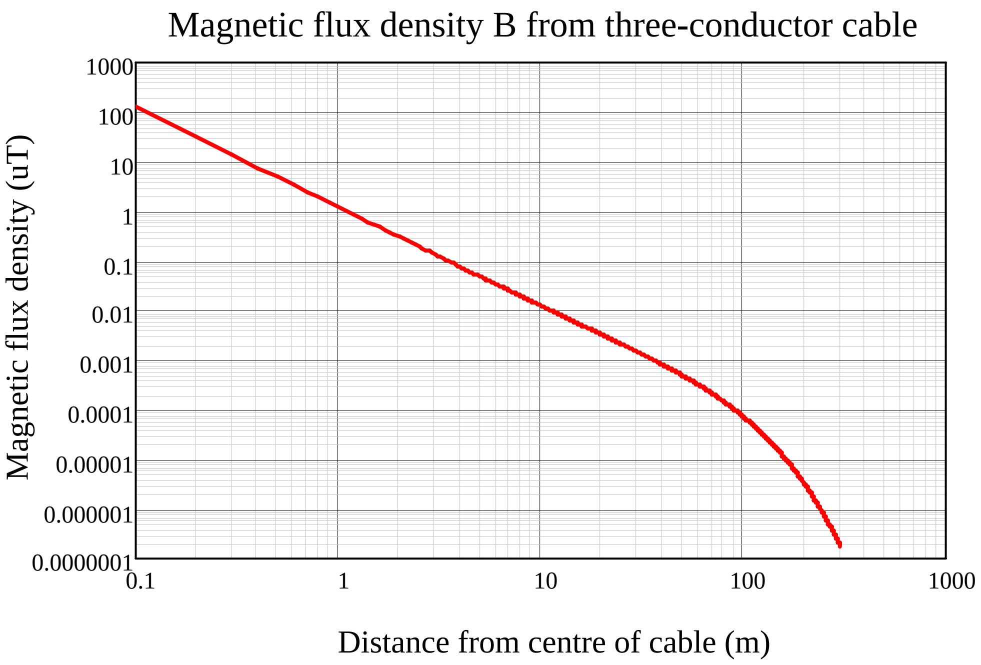

**Figure 4. The magnetic flux density in µT from a three-conductor cable, as a function of the distance from the cable. The current is 100 A, the separation between the conductors is 7 cm and the conductivity of the seawater is assumed to be 3.5 S/m, corresponding to a skin-depth of 38 m.**

Figure 5 shows the induced electric field along a profile on the sea-bottom perpendicular to the cable, assuming the cable is buried 0.5 m, the current is 100 A and the conductivity is 3.5 S/m. As seen, the maximum induced electric field at sea bottom amounts to 0.8 mV/m = 800 µV/m. The induced electric field only depends upon the load current (and the geometrical parameters), and is independent of the voltage. If the current is increased to e.g. 500 A the corresponding maximum induced electric filed will thus be 4 mV/m.

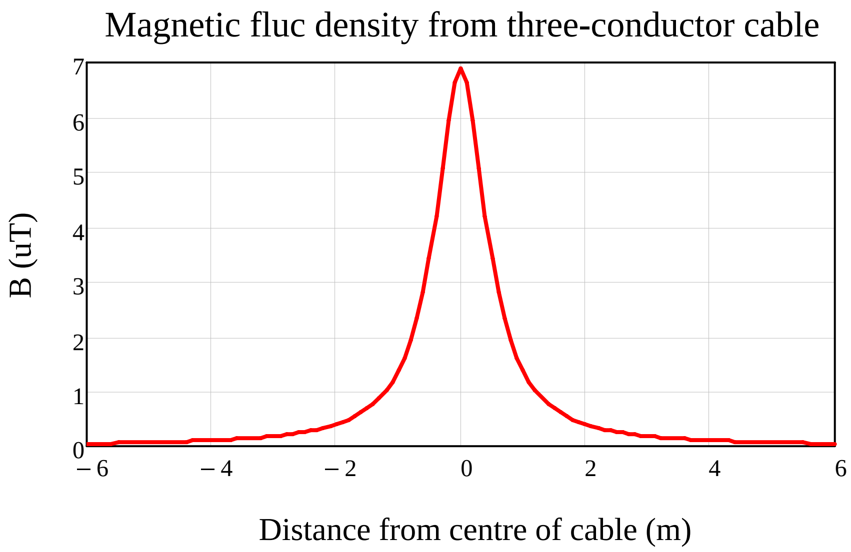

Figure 6 shows the magnetic flux density, calculated for the same conditions as for Figure 5. The maximum flux density amounts to 6.9 μT and the field is elliptical polarized.

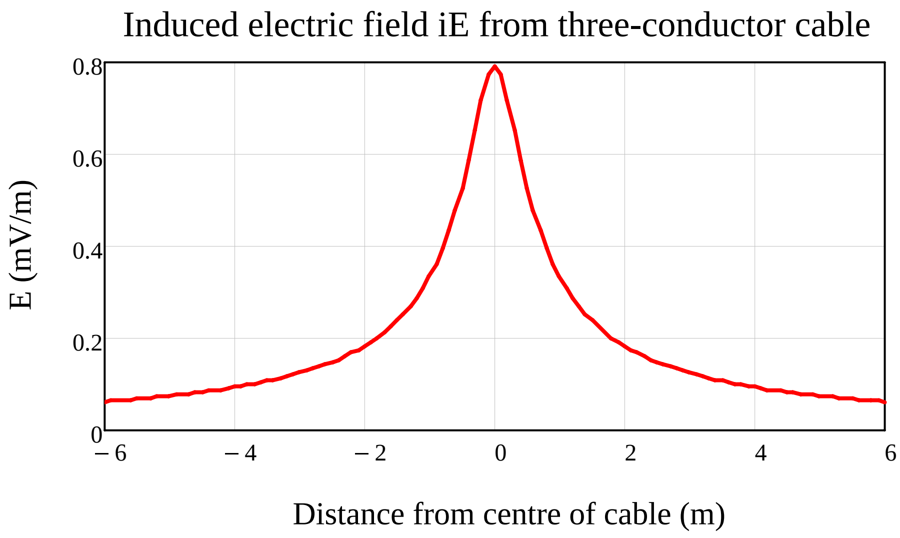

**Figure 5. The induced electric field calculated along a profile on the sea bottom perpendicular to a three-conductor cable buried 0.5 m. The current is 100 A, the separation between the conductors in the cable is 0.07 m (7 cm) and the conductivity of the seawater is 3.5 S/m. The maximum electric field amounts to 0.8 mV/m.**

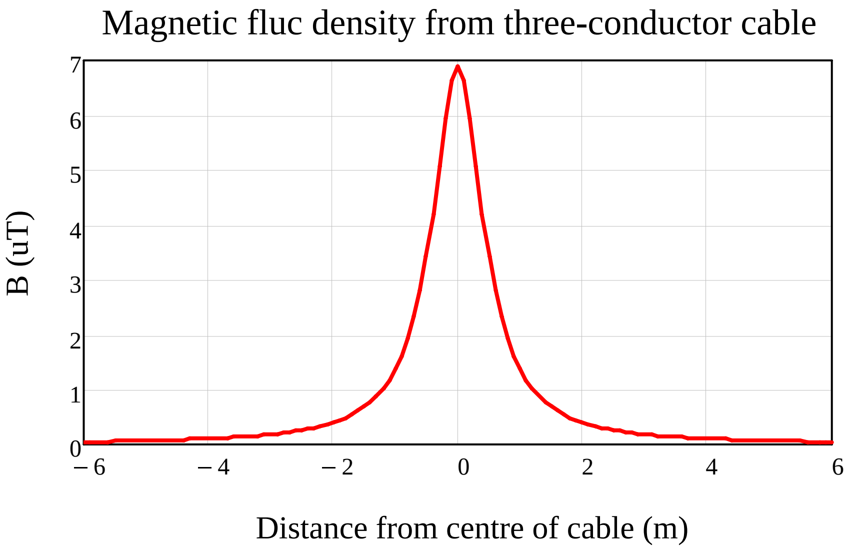

**Figure 6. The amplitude of the magnetic flux density in μT calculated along a profile on the sea bottom perpendicular to a three-conductor cable buried 0.5 m. The current is 100 A, the separation between the conductors in the cable is (7 cm) and the conductivity of the seawater is 3.5 S/m. The maximum flux density amounts to 6.9 μT. The magnetic field is elliptical polarized.**

The induced electric and magnetic fields depends strongly on the distance between the conductors in the cable. Furthermore, the field components depend linearly on the current in the cable. Table 5 summarizes the maximum induced electric field above a cable buried 0.5 m and carrying 100, 300 and 500 A. The field values are calculated for three typical cable geometries, with conductor separation of 35 mm, 49 mm and 67 mm.

**Table 5. Maximum induced electric field above three different cable types carrying 100, 300 and 500 Amp and buried 0.5 m. The seawater conductivity is 3.5 S/m.**

| **Distance between the three conductors** | **100 A** | **300 A** | **500 A** |
|---|---|---|---|
| 35 mm (10 kV cable) | 0.40 mV/m | 1.2 mV/m | 2.0 mV/m |
| 49 mm (36 kV cable) | 0.57 mV/m | 1.7 mV/m | 2.8 mV/m |
| 67 mm (145 kV cable) | 0.79 mV/m | 2.4 mV/m | 3.9 mV/m |

The following should be noted:

- The induced electric field as well as the magnetic flux density depends very little upon the electrical conductivity in the surrounding medium, as long as the fields are considered within one skin depth in the seawater. A conductivity of 3.5 S/m corresponds to a skin depth of ca 40 m.

- In the calculations no attention has been paid to the shielding, which typically consists of steel wires and copper tape.
- The distance between the conductors in a cable is a very important parameter in the calculations of the magnetic field as well as the induced electric field. Increasing the separation causes the “net” amplitude (Figure 2) to increase.

### 4.3.2 Moving water (e.g. tidal water) in the presence of the geomagnetic field

Streaming water in the presence of a static magnetic field will generate a DC (static) electric field. A simple expression for the voltage difference between the two sides of a uniform channel with semi-elliptical cross section can be found in Baines and Bell (1987) as:

$$U = \frac{vB_zL}{1+\sigma_b L/(2\sigma_w d)} \text{ (V)}$$

where $B_z$ is the vertical component of the geomagnetic field (Tesla), $L$ and $d$ are the width and maximum depth of the channel (meter) and $\sigma_w$ and $\sigma_b$ are the conductivities (S/m) of seawater and seafloor respectively. The velocity of the water is denoted $v$.

Pankratov et. al. (1998) estimated the induced voltage in the Bering Strait to be

$U = 239 \pm 11$ mV/(km$^2$× m/s)

The result can be interpreted as follows: if the water velocity is 1 m/s and the cross-sectional area of the strait is 1 km$^2$, then the induced voltage will be 239 mV. The result can also be scaled to other geometries. If e.g. the water depth is 100 m the DC electric field becomes:

E = 23.9 µV/m, assuming the water velocity is 1 m/s.

Although this estimate only is valid for the Bering Strait, it indicates the order of magnitude of the induced electric field caused by moving water in the presence of the geomagnetic field.

Similarly, Nolasco et. al. (2002) have reported motion induced voltages in the range 20-40 µV/m measured in an estuarine system with tidal currents. Kuvshinov et al (2006) reports lunar semidiurnal tide effects causing electric fields up to 100 µV/m in some coastal regions.

This means that when water mass move through the geomagnetic fields (for example tidal streams), an electric field is induced in the order of 10 – 100 µV/m.

### 4.3.3 Moving water (e.g. tidal water) crossing a cable carrying a DC-current.

In the case of streaming water crossing a DC cable in perpendicular direction, a DC electric field will occur. However, since the static magnetic field caused by the cable is very small (typically a few µT) compared to the geomagnetic field (typically about 50 µT), and furthermore limited to some tens of metres away from the cable, this contribution will be small compared to the field caused by the geomagnetic field (see 4.3.2).

### 4.3.4 Geomagnetic field fluctuations, inducing electric and magnetic field.

Due to eruptions of charged particles from the sun, large electric current systems are generated in the Earth ionosphere. These currents, in turn, cause variations of the geomagnetic field. The variations are normally considered as disturbances in the geomagnetic field, but are also used for e.g. geophysical investigations (“Magnetotellurics”). Figure 7 illustrates the magnetic disturbances observed on a typical day and during a “magnetic storm”.

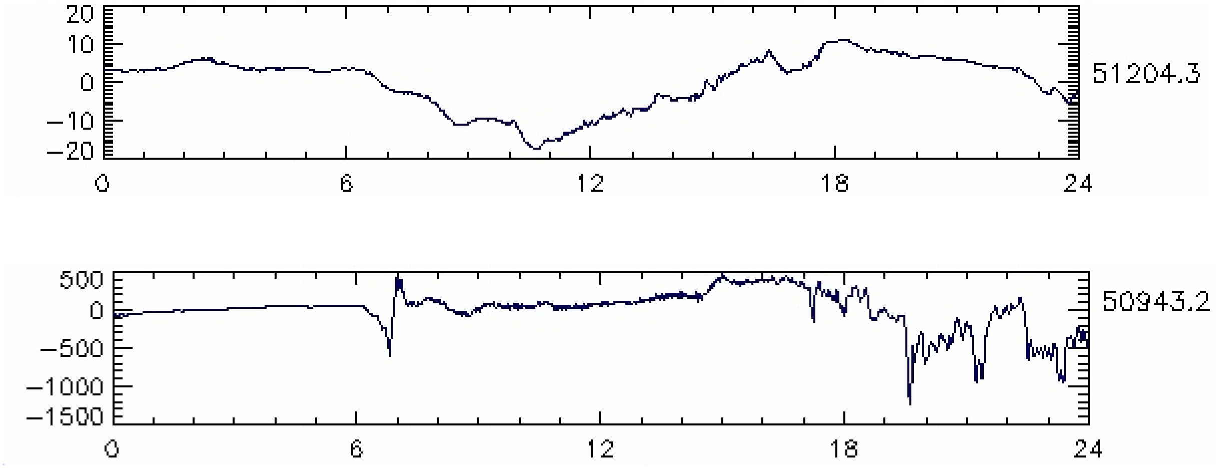

**Figure 7. Examples of geomagnetic field variations, measured in nT, observed at the magnetic observatory in Uppsala, Sweden. The upper diagram shows the daily variations on a typical day (20 June 2010) and lower diagram shows the variations occurring on a day with strong disturbances (29 October 2003). Note the different scales in the two diagrams. As seen, the “magnetic storm” starts around 6:15 and after a calm day it continues during the evening/night with variations of hundreds of nT within minutes. The results presented rely on the data collected at Geological Survey of Sweden (SGU). We thank SGU, for supporting its operation and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org).**

The fluctuations in the magnetic field causes induced “eddy” currents in the ground and in oceans. Typical observed telluric fields are in the order of magnitude 10 μV/m (Parasnis, 1997), and extreme values can be of the order 1 mV/m.

Padilha (1999) reports magnetic field amplitudes of 2 nT in the frequency range 0.001 Hz. Assuming an overall crustal resistivity of 30 Ωm this corresponds to electric fields in the range 1 μV/m. Since the frequency is so low, the field can in the present context be considered as a DC-field.

This means that the fluctuations in the geomagnetic field induce an electric field normally in the range of 1 – 10 μV/m, and in the order of 1 mV/m in extreme cases. The induced electric field caused by geomagnetic fluctuations can be considered as a background noise.

### 4.3.5 Summary

The results from the above mentioned calculations and discussions are summarized in Table 6. Fields at 50 Hz can not be immediately compared to DC fields, or fields with very low frequencies, but gives Table 6.an indicative comparison of electric fields induced by cables and naturally occurring electric fields.

The induced electric fields from a cable is significantly larger than what normally exists in the natural environment, but in extreme cases (during a solar storm), variations in the geomagnetic field will induce a field which is in the same order of magnitude as what is induced from a cable.

Further discussion on natural fields, anthropogenic fields and the detection thresholds of marine organisms is provided in Section 6.4.

**Table 6. Summary of typical magnitudes of the induced electric field.**

| | **AC (50 Hz)** | **DC (very low frequencies, < 1 Hz)** |
|---|---|---|
| A sub-sea cable carrying an AC-current. | Up to 3.9 mV/m at a distance of 0.5 m from a cable carrying 500 A (according to 4.3.1). | |
| Mowing water (e.g. tidal water) in the presence of the geomagnetic field. | | Reported values in the range 10-100 μV/m. |
| Mowing water (e.g. tidal water) crossing a cable carrying a DC-current. | | Due to low magnetic field (compared to the geomagnetic field) expected values around 1 μV/m. |
| Geomagnetic field variations, inducing electric and magnetic field. | | Typically 1-10 μV/m. Up to 1 mV/m in extreme cases. |

## 4.4 Mitigation of EMF

As stated in chapter 3.1 and shown in the field measurements previously described the electric field caused by the power transmission is shielded by a metallic screen within an industry standard cable.

The magnetic and the induced electric fields of an AC transmission system may be reduced by reducing the distance between the conductors in the cable, or by reducing the current. However, both measures have technical and economical implications and are therefore limited by those factors.

Cable burial increases the distance between the fish and the source of the magnetic field, and is therefore a potential form of mitigation measure but burying the cable an additional meter only has minor effects on the magnetic field exposure to marine organisms. Again, due to technical and economical constraints this is normally not a feasible mitigation measure.

# 5 BIOLOGICAL MECHANISMS FOR DETECTING ELECTRIC AND MAGNETIC FIELDS

This chapter summarizes the biological mechanisms that are responsible for allowing organisms to detect electric and/or magnetic fields (or mechanisms believed to be responsible for the detection). The chapter is divided into species that are principally electrosensitive and those that are magnetosensitive. The main purpose is to provide information on species found in Northern Europe, but in some cases other species are included as well for reference.

Although both magnetoreceptive and electroreceptive organisms may be able to detect EMF from cables the potential responses might differ. Electroreception is believed to be closely linked to mechanisms involved in finding prey, locating conspecifics (i.e. other individuals), finding mates and in some instances for navigation while magnetoreception is believed to primarily be linked to navigation and homing.

Based on the differences of the fields generated by AC and DC Öhman et al. (2007) stated that fish most likely will perceive static and alternating magnetic fields in different ways. The field generated from a DC cable will be perceived as a static amendment to the geomagnetic field while the field from an AC cable will alternate.

## 5.1 Electric field detection

### 5.1.1 Biological role of electroreception

Although, most organisms are unable to produce electricity voluntarily, they all emit weak bio-electrical currents as a result of muscle activity, such as respiratory movements, cardiac contractions and locomotion, as well as the electrochemical difference between the animal's internal environment and the surrounding seawater (Gill et al. 2001). The emitted fields consist of both AC[9] and DC[10] fields, of which the AC fields generally are smaller than the DC fields (Kalmijn (1982), Haine et al (2001); Gill et al. 2009).

Induced electric fields can also occur as a result of the organism itself or oceanic waters interacting with geomagnetic flux lines. Some organisms are known to be able to detect these electric fields from detecting prey, conspecifics[11] and potential predators/competitors and the most common use is assumed to be for detecting prey (Gill et al. 2005, Gill et al. 2001). There are also some organisms that are known (or presumed) to use induced electric fields related to the natural geomagnetic field as navigation cues (Montgomery 2000, Klimley 1993).

The reception of electric fields can be divided into passive and active electroreception:

- Passive electroreception is when an organism can detect an emanating electric field from another organism (or another source emitting electric fields). It is the most common type of electroreception.
- Active electroreception is when an electric fish detects distortions in its own electric field caused by conducting and non-conducting objects within the field.

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[9] AC fields are emitted due to heart and muscle activity

[10] DC fields occurs due to the biochemical processes in the body

[11] Conspecific = belonging to the same species

### 5.1.2 Detection mechanisms

Chondrichthyes (or cartilaginous fishes) are the major group of organisms that are known to be electroreceptive. The group can be divided into elasmobranchs[12] and holocephali[13] (commonly know as chimera or rabbit fish) of which elasmobranchs are the most common and the holocophali inhabit deep sea waters, and will not be affected by marine renewables located off-shore. The detection by the elasmobranchs of the electric fields is registered through a series of pores on the surface skin connected with canals filled with a conductive jelly to clusters of ampullae which enable them to detect small voltage gradients in the environment around them[14] (CMACS 2003).

### 5.1.3 Organisms with electroreception

Fish

Gill et al. (2001, 2005, 2009) and Peters et al. (2007) have summarized the information available on fish that are known to be (or assumed to be) electroreceptive. The list of electroreceptive organisms that can passively detect electric field emissions includes: the Chondrichthyes (Elasmobranchs and Holocephali ratfish), the Acipenseridae (sturgeons), the Polyodontidae (paddlefish), the Polypteridae (bichirs), the Dipnoi (lungfish) and also the Siluriforms (catfish). In addition there are a number of species of mainly tropical freshwater fish in the families Gymnotidae, Sternopygidae, Rhamphichthyidae, Hypopomidae, Apteronotidae - all knifefishes, Electrophoridae (electric eel), Mormyridae (elephant-snout fish) and Gymnarchidae (African knifefish) that can also actively emit their own electric field (ie. electrogenic)

Marine mammals

Among the mammals no strictly marine species are known to be electro receptive. Only one semi-aquatic Monotreme (egg-laying mammals that are only found in Australia and New Guinea) has been found to inherit electroreception and it uses the ability to localize benthic invertebrates (Pettigrew et al. 1999, Bullock et al. 1999).

Invertebrates

Looking at invertebrates no literature was found that describes electroreception. Bullock et al. (1999) stated that there was no concerted effort to look for electroreception among inverterbrates but that the possibility existed that such a sense would be present in some species (for example in an mollusc, arthropod, or even an annelid worm).

### 5.1.4 Threshold values for electroreception

Peters et al. (2007) have reinterpreted and summarized research on electric thresholds in electroreceptive aquatic organisms. The study consisted of both limnetic and marine organisms and included detection levels based on studying the behaviour of the organism and detection levels based on electrophysiological recordings of afferent fibres or nerves. The thresholds for the marine animals based on behavioural effects were 0.1 μV/m whereas for freshwater organisms and monotremes the thresholds were generally higher. Table 3 presents the behavioural thresholds for marine organisms presented in the study. It is important to stress that the list of species in table 3 does not represent all species that

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[12] The elasmobranchs consist of sharks, skates and rays.

[13] Holocephali are sometimes known as ratfish, rabbitfish or ghostsharks.

[14] The detection sensory apparatus is called Ampullae of Lorenzini

are believed to be electrosensitive. Furthermore it should be stressed that most of the results are based on either DC or very low frequencies (far below 50 Hz).

**Table 3: Behavioural thresholds for marine organisms from Peters et al. 2007. Species that are likely to be found in northern Europe are presented in bold.**

| **Species** | **Behavioural threshold (μV/m)** |
|---|---|
| **Dogfish (*Scyliorhinus canicula*)** | **2 - 150** |
| **Thornback Ray (*Raja clavata)*** | **1 – 10** |
| Smooth Dogfish (*Mustelus canis)* | 1.8 |
| Round Stingray (*Urobatis halleri)* | 0.5 |
| Nurse Shark (*Ginglymostoma cirratum*) | 0.5 – 2.5 |
| Spotted ratfish (*Hydrolagus colliei*) | 20 |
| Sandbar shark (*Carcharhinus plumbeus*) | 0.1 |
| Scalloped Hammerhead (*Sphyrna lewini*) | 0.1 |
| Bonnethead Shark (*Sphyrna tiburo*) | 0.1 – 4.7 |
| **Sea lamprey (*Petromyzon marinus*)** | **10** |

The threshold values presented in Table 6 shows that the behavioural thresholds lies within results from modelling of EMF from the connection cables. The results from modelling of induced 50 Hz electric fields presented in section 4.3 shows a iE-field of 1 -5 mV/m adjacent the cable and 0,5 μV/m at a distance of approximately 100 m. Even though many of the presented species in Table 6 are not normally present in northern Europe the values should present a possible range of detection for other elasmobranchs.

The sensitivity of European Eel to weak electric DC and AC currents has been investigated by Enger et al. (1975) and Berge (1978). The studies were not behavioural studies but consisted of analysis of electrocardiograms for eels exposed to various electric currents in different directions. The voltage thresholds that were found were approximately 50– 100 mV/m, i.e 50 000 – 100 000 μV/m.

## 5.2 Magnetoreception

Behavioural experiments have demonstrated that diverse animals, including representatives of all five vertebrate classes, can sense the Earths magnetic field and use it as an orientation cue while migrating, homing or moving around their habitat (Lohman et al. 2000). The Earth's geomagnetic field is approximately 25 - 65μT (CMACS 2003, Walker et al. 2002). The navigation of birds are by far the best studied, followed by marine turtles, whilst little is known about other vertebrates and arthropods (Wiltschko el al. 2005).

There are at least two types of information that can potentially be derived by a magnetosensitive animal from the earth's magnetic field.

1. An animal with the ability to orientate its movements with respect to the geomagnetic field is said to have a magnetic compass sense. This is the simplest form of using the magnetic field to maintain a consistent direction such as north or south (Lohmann et al. 2000, 2007). The list of marine animals that is known to possess magnetic compasses includes isopods, sea turtles, spiny lobsters, rays, eel and salmon (Lohmann et al. 2008, Westerberg & Lagenfeldt 2008).

2. It has been hypothesized that some animals possess an additional sense, called a map sense that provides the ability to determine position relative to a destination. The use of magnetic positional information has been demonstrated in several diverse animals including sea turtles, spiny lobsters, newts and birds, suggesting that such systems are phylogenetically widespread and can function over a wide range of spatial scales (Lohman 2007).

The use of the Earth's magnetic field by animals for navigation during migration and homing has been studied intensively but the detection mechanism and the sensory pathway between the detector and the brain that underpin navigation behaviour remain unknown.

### 5.2.1 Detection mechanisms

Hypotheses have been proposed that link the detection of magnetic fields to vision, electroreception, chemical reactions and magnetite particles. However detection by vision seems to be contradicted by the ability of some animals to orientate in total darkness, electrical induction could mediate magnetoreception by species that has the ability of detecting electrical fields. (Walker et al. 1997, Lohmann et al. 2000). Although diverse mechanisms have been proposed, the most recent research has focused on three possibilities: electromagnetic induction, magnetic-field-dependant chemical reactions and magnetite based magnetoreception.

### 5.2.2 Organisms with magnetoreception

Marine animals that navigate over long distances are widely thought to use the Earth's magnetic field for navigation (Walker et al. 2003, Lohman et al. 2004, Wiltschko & Wiltschko 2005).

Fish

Formicki et al. (2002) and Walker et al. (2003) have summarized experiments conducted that investigate magnetic detection in fish. It is stated that detection have been found in numerous fish species such as salmon, rainbow trout, European eel, American eel, and yellowfin tuna. Although several species have been showed to be able to detect magnetic fields, the few attempts to experimentally test the use of the earth's magnetic field in navigation have been inconclusive (e.g. Papi et al. 2000, Yano et al. 1997). Walker et al. (2003) pointed out that the conducted studies had significant issues of scale and experimental control and that this could be one explanation to the inconclusiveness.

Tiger sharks, blue sharks and scalloped hammerhead sharks have been found to swim in straight lines for long periods across open ocean, and the latter orient to seamounts where geomagnetic anomalies exist. (Meyer et al. 2005).

Mammals

Kirschvink et al. (1986) tested the hypothesis that cetaceans (whales, dolphins, and porpoises) use weak anomalies in the geomagnetic field as cues for orientation and navigation by combining stranding data and magnetic data of the U.S. Atlantic Continental Margin. The results show that there is a statistically robust relationship between cetaceans live stranding positions and the residual geomagnetic field along the U.S. Atlantic continental margin. Significant tendencies to strand at locations with low magnetic intensity were found in species from both suborders15 of Cetacea. Many of the stranding positions in the study suggest that total intensity variations of less than 50 nT are enough to influence stranding location.

#### Reptiles

Marine turtles have been the focus of several studies. Lohman et al. (2004) showed that the Green Sea Turtle has a map sense that at least partly is based on geomagnetic cues.

#### Invertebrates

Boles and Lohman (2003) performed an experiment that implied that lobsters are able to use the magnetic field for navigation. The lobsters were exposed to magnetic fields replicating the fields close to their capture position. The lobsters that were exposed to fields present north of the capture site navigated south and vice verse.

Ugolini & Pezzani (1995) showed that isopods may navigate towards the shoreline using the magnetic field, however the use of a solar navigation system seemed to be the primary cues for navigation.

### 5.2.3 Threshold values

Estimated magnetic field thresholds range between 10 nT and 50 nT in homing pigeons, sharks and whales (Walker et al. 2002). Walker et al. (1997) stated that the behavioural threshold for the vertebrate magnetic sense could be no more than a few tens of nanotesla (this would be necessary to form a useful magnetic map). The modelling results and the results from field measurements presented in chapter 4 showed magnetic fields in the range of 0,6 – 50 µT, this gives that there might be a possibility that the emitted magnetic fields from off shore installations may be detected by magnetoreceptive organisms.

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[15] Toothed whales and Baleen whales

# 6 CURRENT STATE OF KNOWLEDGE – EMF AND EFFECTS ON MARINE LIFE

For most magnetoreceptive or electroreceptive species there is little or no information present on how, or if, submarine AC or DC power cables (or other installations) may impact these organisms. The main research that has been conducted so far is related to effects by submarine cables on migrating eels and elasmobranchs. This sections presents a summary of the literature review conducted for this study, as well as a comparison of the thresholds presented in Chapter 5 with the modelling results presented in Chapter 6.

## 6.1 Effects off anthropogenic sources of EMF on electroreceptive organisms

Research conducted on elasmobranchs in various controlled environments exposed to EMF that replicates EMF from sub sea cables show that the emitted EMF may be detected by the fish. The response may be categorized as behavioural changes (the responses varied both between species and between individuals within the same species). However no conclusions can be drawn from the literature whether the behavioural changes of the elasmobranchs are positive, negative or of no impact from an environmental point of view (Gill et al. 2001, Gill et al. 2009). In one case shark attacks on a sub sea transmission cable have been linked to EMF. However the attacks were not replicated in conducted experiments (Marra 1989).

## 6.2 Effects off anthropogenic sources of EMF on magnetoreceptive organisms

Regarding animals using magnetic information from the geomagnetic field as cues for orientation little is known about the effects of anthropogenic sources of EMF in the marine environment. The results of studies conducted on migrating salmon with attached magnets did not show any effects on the swimming behaviour (Westerberg et al. 2007, Yano et al. 1997). Papi et al. 2000 found similar results in a study using migrating turtles attached with magnets. These results provide information that navigation of organisms assumed to navigate using the natural magnetic field may use a variety of types of information in its navigation (and thus making it less probable that emitted EMF from under water installations may pose a threat to the migration).

Results of *in situ* tracking show that migrating eels may be influenced by both AC and DC transmission cables (Westerberg & Langenfelt 2008, Westerberg 2000, Westerberg et al. 2007). The noticed influence may be considered small in all cases consisting of slight changes in their swimming routes and/or speed.

## 6.3 Summary of literature review

The results presented from studies in the main literature within the field that is directly linked to submarine cables and EMF is summarized in Table 7.

**Table 7. Summary of litterature review on EMF and submarine cables**

| Study | Species | Short description | Main results |
|---|---|---|---|
| The potential effects of electromagnetic fields generated by cabling between offshore wind turbines upon Elasmobranch Fishes (Gill et al. 2001) | • Lesser Spotted Dogfish (*S. canicula*) | Laboratory experiments where the dogfish were exposed to different AC dipole (ie. point source) electric fields in a tank. | • The fish avoided electric fields of 1 mV/m.<br>• The same individuals are attracted to 0,01 mV/m. |
| EMF-sensitive fish response to EM emissions from sub-sea electricity cables of the types used by the offshore renewable energy industry (Gill et al. 2009) | • Thornback Ray (*R. clavata)*<br>• Spurdog (*S. acanthias*)<br>• Lesser Spotted Dogfish (*S. canicula*) | Mesocosm study in the ocean consisting of two large cages placed on top of AC power cables (100 A 7 V AC) | • *S. canicula* were more likely to be found close to the energized cable.<br>• *Some R clavata individuals moved more in the vicinity of the cable when energised.*<br>• Differences in behaviour in some individuals within the studies species. |
| Sub-sea power cables and the migration behaviour of the European eel (Westerberg & Lagenfelt 2008) | • European Eel (*A. anguilla*) | Monitoring of migrating eel while passing a 130 kV three phase AC cable between the Swedish mainland and the island Öland | • The eel reduced its swimming speed while crossing the cable.<br>• There was no evidence that the cable was an obstruction to migration. |
| Effects of HVDC cables on eel orientation (Westerberg 2000) | • European Eel (*A. anguilla*) | A two year field study of migrating Silver eels passing the Baltic Cable pole cable. The eels were tracked both with no current through the cable and with 1000 –1300 A DC. | • The eels did cross the cable with the same probability as if it were absent.<br>• In several cases the tracked eels changed their course slightly at the passage of the cable.<br>• It is stated that some effects of magnetic disturbances of HVDC cables on eel migration seems likely, but that the consequences seem to |

| | | | |
|---|---|---|---|
| | | | be small. There is also no indication that a cable constitutes a permanent obstacle for migration. |
| The effects on fish and fishery by the SwePol Link (in Swedish) (Westerberg et al. 2007) | • European Eel (*A anguilla*)<br>• Salmon (*S .salar*) and Sea trout (*S. trutta*) | Three studies linked to EMF were conducted to evaluate the effects on fish and fishery from the construction and operation of SwePol Link (HVDC cable between Sweden and Poland)<br><br>**1) Migration of eels:** the purpose of the study was to evaluate if the cable affected the migration pattern of eels. The cable emitted approximately 200 µT at a distance of 1 m.<br><br>**3) Magnetic field effects on elvers[16]:** The aim of the study was to show if elvers were attracted to or repelled from magnetic fields of 100 µT I a laboratory setting.<br><br>**2) Magnetic field effects on salmon and sea trout:** 23 fishes were attached with devices that emitted magnetic fields that could be turned on from a distance. The magnetic field is stated to be in the same range as the field emitted from the SwePol Link. | • The conclusions from the eel studies were that the cable would not pose a threat to the migration.<br>• The study on salmon and sea trout showed that the fish that were exposed to an artificial magnetic field showed no suppressing effects on swimming behaviour. |
| Shark bite on the SL Submarine Lightwave Cable System: History, Causes, and Resolution (Marra 1989) | Various sharks | The study consists both of field observations and laboratory studies. An undersea lightwave cable system was damaged five times due to shark bite attacks from a deep water shark species. The cable emitted two types of EMF 1) DC 1 µV/m at 0,1 m, 2) AC *6,3* µV/m @ 1 meter | The attacks were found to be caused mainly by deep water sharks. The attacks on the cable were not replicated in the conducted experiments. However different types of sharks were used in the experiments compared to the actual attacks. |

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[16] Elver = young eel

| | | | |
|---|---|---|---|
| | | To investigate the cause of the shark attacks several experimental studies were performed. | |
| Environmental monitoring at Nysted wind power farm – Final Results | • Common eel (*A. anguilla*)<br>• Baltic herring (*C. harengus*<br>• Atlantic cod (*G. morhua*)<br>• Flounder (*P. flesus*) | The study consisted of sampling with nets on two sides of the transport cable (at a distance of 300 m) from the Nysted Offshore wind power farm in denmark during 2001-2004. The study included a mark and recapture program for eel.<br>(There was no way of knowing if the caught fish actually crossed the cable). | • The movements of the eel and the Baltic herring were not affected by the power production.<br>• The Cod might be repelled from the cable at high levels of power production.<br>• Flounder is more likely to pass the cable at periods with low power production.<br>• The large distance between nets and the cable makes it hard to link the effects to EMF. |

In Appendix 2 there is a summary on the reports cited in Table 7 as well as information on studies that are conducted on disturbed magnetic and electric fields that aren't linked to anthropogenic sources of EMF (studies conducted to evaluate natural behaviour). As seen in Table 7 there is a very limited amount of information that is directly linked to anthropogenic EMF and marine organisms. The main conclusions from the studies are that both magnetoreceptive (Eel) and electroreceptive (Elasmobranchs) may detect, and respond to EMF from the cables. However the results showed there appears no obvious negative impact on the organisms, although this is a low confidence conclusion. More specific studies are required.

## 6.4 Summary of detection thresholds and modelling results

The detection thresholds presented in Chapter 5 provide a possibility to set the modelling results for cable related magnetic and induced electric fields in a context. The identified thresholds for different species are however not based on alternating magnetic fields whereas the fields generated by AC power cables fluctuate with a frequency of 50 Hz. It is not fully understood how organisms respond to AC fields and the response may be weaker compared to non-alternating fields. The following should therefore be considered as indicative only.

The electric fields detection thresholds presented in Section 5.1.4 range from 0,1 μV/m for some sharks to 100 mV/m for European Eel. Based on the identified thresholds, the distance at which the specie may be able to detect the electric field induced by the cables with 100A load rating is presented in Table

**Table 8. Detection thesholds and distances from the cable in which a specie may be able to detect the field. Species that are common in northern Europe are presented in bold.**

| **Species** | **Behavioural threshold (μV/m)** | **Distance of detection (100A load rating)** |
|---|---|---|
| **Dogfish (*Scyliorhinus canicula*)** | **2 - 150** | **1 – 80 m** |
| **Thornback Ray (*Raja clavata)*** | **1 – 10** | **30 – 90 m** |
| Smooth Dogfish (*Mustelus canis)* | 1.8 | 80 m |
| Round Stingray (*Urobatis halleri)* | 0.5 | 120 m |
| Nurse Shark (*Ginglymostoma cirratum*) | 0.5 – 2.5 | 60 – 120 m |
| Spotted ratfish (*Hydrolagus colliei*) | 20 | 15 m |
| Sandbar shark (*Carcharhinus plumbeus*) | 0.1 | 160 m |
| Scalloped Hammerhead (*Sphyrna lewini*) | 0.1 | 160 m |
| Bonnethead Shark (*Sphyrna tiburo*) | 0.1 – 4.7 | 50 – 160 m |
| **Sea lamprey (*Petromyzon marinus*)** | **10** | **30 m** |

For magnetic fields the detection thresholds have been established for for example homing pigeons, sharks and whales in the range of 10 – 50 nT. Based on a threshold of 10 nT, such species would be able to detect the magnetic field from the cable at a distance of 13 m with a load current of 100 A, and 30 m with a load current of 500 A.

The distances provided here gives an indication of from how far organisms can detect the fields generated by the cable, but can not be translated into an area along the cable where the species are negatively affected by the magnetic and electric fields. On top of the previously mentioned insecurities due to the differences between alternating and non-alternating fields, fluctuations in the naturally existing fields are at times significantly stronger than the detection thresholds. All species are expected to encounterchanges in field strength within the environment they inhabit.

### 6.5 Knowledge gaps

The main knowledge gap is the limited amount of research performed within the field. In the following chapters the identified knowledge gaps are listed in greater detail.

Electroreceptive organisms

- Of the few studies conducted, most regarding electroreceptive organisms have been conducted on elasmobranchs and with a setting based on AC transmission (given the fact that it is the most important form of transmission for the off shore energy of today). Based on this one can not draw any conclusions in potential differences between AC and DC transmission.
- There are studies showing that elasmobranchs may react to the type and size of EMF emitted by AC 50Hz cables from offshore windpower and expected to be similar for wave power installations. The results in the studies only show limited responses to the EMF exposure, and the studies are not sufficient in evaluating potential environmental impacts.
- The number of electroreceptive organisms that have been used in experiments must be considered to be small.

Magnetoreceptive organisms

- There are very few studies performed on organisms that are likely to be affected by a disturbed magnetic field. Most of the research is connected to migration behaviour and the results show varying results for different species. Experiments with salmons and turtles showed no response, and experiments with eel show a response to the cable. However it should be stressed that all the effects that have been registered in conducted studies have been considered to be small.
- No information was found on the potential effects of EMF on marine mammals. This focus might increase in the future if wave power expands in areas where cetaceans are more common.

General

- Impact studies conducted so far have been based on a single cable. Further research may be necessary to understand the potential effects of additive and cumulative EMF associated with for example the network within and between wind/wave-power farms.
- No information was found on effects on different life stages of organisms (except for eel) and potential sensitive environmental settings. Embryos and juveniles are likely to have different sensitivities and responses than adult species.
- Even though the conducted studies imply that the effects on both electro- and magnetoreceptive organisms can be considered to be small, it is hard to draw any general conclusions about potential effects on a population level for different species (i.e. will there be consistent behavioural effects for some species due to EMF that may cause changes of significance to a population of individuals).

# 7 EMF IN ENVIRONMENTAL IMPACT ASSESSMENTS

The potential impact from electric and magnetic fields on the submarine environment is not completely understood and new research results and data are slowly being added to the knowledge base. Due to the uncertainties, both the offshore industry and the authorities face challenges in the planning, permitting, construction and operation of offshore power projects. In addition to investigating the potential impact in the planning phase of a project, environmental monitoring may also be carried out during the construction and operation phases in order to determine if and what type of mitigation measures are necessary, as well as for research purposes.

The environmental authorities in different countries place different demands on both the impact assessment process and the monitoring of EMF-related effects from offshore energy production. This section provides a summary of the analysis of impacts and requirements from the responsible authorities in selected countries where construction of submarine cables from offshore energy production facilities is currently taking place.

## 7.1 Germany

The agency responsible for the application procedure and approval for cables and other offshore projects in the German Exclusive Economic Zone (EEZ) is the Federal Maritime and Hydrographic Agency[17]. Within the territorial sea (12 nautical miles) the responsibility rests with the German coastal state, but the practise from BSH provides guidance and advice to the coastal states. The BSH has issued a standard for environmental impact assessment of offshore wind farms, specifying the required scope of the investigations to be carried out (BSH 2007a). The standard briefly identifies electric and magnetic fields as a possible impact during the operation phase, but does not give any further requirement as to what extent EMF must be investigated or modelled.

In a second standard, *Design of Offshore Wind Turbines* (BSH 2007b), limited values for electric and magnetic fields are given but these are based on the potential impact on humans (areas in which people stay for long periods) and not in the submarine environment and are thus irrelevant for the present study.

BSH states that the expected magnetic field produced by a submarine power cable will be well below the geomagnetic field on the surface, and the effect therefore assumed to be negligible. Technical cable design requirements may still be used to minimise electric fields. Since the EMF from the cable systems used in suggested offshore power projects are limited, and the effects are considered negligible, there are no monitoring requirements related to EMF (Boethling, personal communication).

For example, in a EIA for the Veja Mate offshore wind farm, which was approved in 2008, a similar line of argument is followed. It is concluded that the magnetic field emitted from the cable is much weaker than the natural geomagnetic field and therefore the effect is assumed negligible (CSC 2008).

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[17] Bundesamt für Seesciffart und Hydrographie (BSH)

## 7.2 United Kingdom

The agencies and responsibilities for environmental licensing and marine consents in the U.K. have recently undergone changes, with a new structure in operation since April 1st 2010. Applications for offshore wind, wave and tidal project of sizes up to 100 MW are handled by separate agencies in England, Northern Ireland, Scotland and Wales in the respective waters, whereas applications for larger project are decided by the Infrastructure Planning Commission. In a guidance note for environmental impact assessment for offshore wind farms, it is concluded that the effects of electric and magnetic fields on the marine environment are unclear, and may need to be considered to address local concerns (CEFAS 2004).

The Marine Management Organisation, the agency responsible for <100 MW consents in England, does currently not have general guidance on maximum EMF levels nor monitoring requirements, which are determined case by case and largely depends on the abundance of elasmobranchs. Applicants for offshore energy projects are expected to provide information and modelling of the emitted fields. In Scotland, the Marine Scotland Licensing & Operations Team has a similar standpoint, there are no standard procedures or requirements in place at the moment but this may change in the future as ongoing research provides more knowledge on the subject (Sutherland, personal communication)[18].

Irrespective of the responsible agency, the underlying regulations is the same for projects in the marine environment, namely the Food and Environmental Protection Act 1985 (FEPA) and Section 34 of the Coastal Protection Act 1949 (CPA).

Environmental Statements and applications for (environmental) permits[19] in the U.K. typically include a brief description on the current knowledge of the potential effects on the marine environment, and references to studies conducted under the framework of COWRIE (Collaborative Offshore Windfarm Research Into the Environment), an NGO set up to improve the understanding of potential environmental impacts of offshore windfarm development in the U.K waters. Some projects conduct specific EMF modelling while others use data from calculations done for other projects, or in the COWRIE reports. It is acknowledged that the mechanisms and impacts are not entirely understood, but the impacts are considered negligible or not significant in the Environmental Statements.

Post-construction monitoring requirements for a project are described in the FEPA license. The following is for example an extract from the FEPA licence for the Barrow Offshore Wind Farm:

> The Licence Holder must provide the Licensing Authority with information on attenuation of field strengths associated with the cables, shielding and burial described in the Method Statement and related to data from the Rødsand wind farm studies in Denmark and any outputs from the COWRIE tendered studies in the UK. This is to provide reassurance that the cable shielding and burial depth(s), both between the turbines and along the cable route to shore, given the sediment type(s) at the Barrow site are sufficient to ensure that the electromagnetic field generated is negligible. Should this study show that the field strengths associated with the cables are sufficient to have potential detrimental effect on electrosensitive species, further biological monitoring to that described in Section 7 of this Annex may be required to further investigate the effect.

The general conditions for the licence are described but the exact monitoring methods are open for discussions between the project developer and statutory bodies. Similar paragraphs can be found in the FEPA licences for most approved offshore wind projects in the U.K (Gill et al. 2005).

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In the Barrow project, the monitoring of EMF was to be conducted by as part of the COWRIE Research Programme, measurements were planned to be carried out at the Barrow site during spring 2008 (BOWind 2008). The programme was then changed, and measurements were never carried out at Barrow, but instead at two other sites (North Hoyle and Burbo Bank). The results supported pre-construction modelling of both the magnetic and the electric fields, and it was therefore concluded that no revision or amendment to the monitoring program at Barrow was necessary (BOWind 2009).

### 7.3 The Netherlands

The Rijkswaterstaat Nordzee is the responsible agency for offshore-related licensing issues in the Netherlands. Analysis of impacts from EMF is required in the impact assessment process, and was carried out for the two existing offshore projects in the Netherlands, Prinses Amalia and Noordzeewind.

In addition to modelling, Rijkswaterstaat requires post-construction, sub-sea measurements of the fields emitted from a cable, to confirm the levels calculated before construction. Even though such a requirement is described in the permit for the respective wind farm, the measurements cannot currently be carried out due to lack of available technology. It is possible to conduct measurement at the surface but the Rijkswaterstaat requires sub-sea measurements. This part of the monitoring programmes is therefore on hold, awaiting the technical feasibility and methodology to conduct the measurements (de Jong, personal communication).

### 7.4 Ireland

The agency responsible for permits for marine renewable energy projects in Ireland is the Department of the Environment, Heritage and Local Government. Potential EMF-related impacts are recognised but there are no guidelines or general monitoring requirements. Besides cables from offshore wind- and wave-energy project, a large HVDC cable between Ireland and Britain is currently in the impact assessment and licensing phase.

In Environmental Impact Assessments for Irish projects EMF is thoroughly analysed and electroreceptive and magnetoreceptive species in the project are identified. Potential impacts on such species are however considered negligible or insignificant. The planned submarine HVDC cable (EastWest Interconnector), potentially producing stronger magnetic fields, has a similar approach regarding effects from the magnetic field which are not predicted to be significant.

### 7.5 Norway

The Norwegian Water Resources and Energy Directorate is the responsible agency for licensing and permits for marine renewable energy projects, as well as for submarine transmission cables. There are no guidelines or recommendations for EMF in either the impact assessment stage or the post-construction monitoring.

Generally, in applications for permits effects from EMF are considered negligible, largely based on the assumption that the magnetic field levels emitted by the cables are below the geomagnetic field. Where impacts from EMF are evaluated more in detail, it is in relation to human effects from the land sections of the cable and not on the marine environment (Undemm, personal communication).

## 7.6 Sweden

The Swedish Environmental Protection Agency, which is the agency responsible for environmental matters in Sweden, has initiated a program (Vindval) aiming to compile data for impact assessments and permit application processes. Impacts from electric and magnetic fields are not considered significant, but have been the subject of one study, on the migration of eel across an AC cable.

The study was conducted as part of the monitoring program of Lillgrund, the largest offshore wind farm built so far in Sweden. Results from the study are presented in Appendix 2. Monitoring programs for other offshore projects have not included studies or measurements aimed to investigate the effects of electric and magnetic fields.

The potential effects of EMF were investigated in greater detail before and after the construction of the HVDC submarine link between Sweden and Poland, SwedPol. The results of the investigations are available in Appendix 2.

Applications and impact descriptions from other marine renewables projects generally include a description and sometimes modelling of EMF, but the impact is considered negligible or insignificant.

## 7.7 Conclusions on Environmental Impact Assessments

Judged by the review of EMF-related impact assessment and monitoring, the potential effects on submarine organisms caused by EMF are not sufficiently understood. There are large differences in the amount of attention paid to the subject in different countries, ranging from a general dismissal of the issue as negligible (Germany), to a stringent precautionary approach requesting project owners to conduct measurements that are not technically possible (the Netherlands).

Environmental statements in different countries reflect to a large extent the attitude of the respective authority, and the section on EMF varies both in quantity and quality. Some common shortcomings include that induced electric fields are often overseen, the properties of electric and magnetic fields are confused, and the effect of using cable burial as mitigation measure is overrated. There are also discrepancies in the EMF-threshold levels for effects on marine organisms, as well as which species are the most important in this respect.

COWRIE is considered the most comprehensive source of knowledge and is often referred to, in the U.K. and other countries and by project developers and authorities alike. It is probable that as the knowledge base on the potential effects is increased, and necessary mitigation measures better defined, the discrepancies between the requirements in different countries will decrease. The current situation reflects the fact that the current knowledge base is not sufficient to establish the existence and the nature of, or the non-existence of EMF-related impacts from marine renewables on submarine organisms.

# 8 CONCLUSIONS

In the conducted literature study no information was found that suggested that EMF from existing power cables have influenced marine organisms negatively. The only effects that were found were

1. A slight delay or a small deviation in course during the passing of migrating eels over both AC and DC cables,
2. Some fish are more likely to pass the cable at low power transmission rates (however, the cable didn't affect the distribution in the area and there was no way to prove that fish actually crossed the cable) and
3. Shark attacks on a lightwave cable system, however no attacks were reported for other systems.

This means that the effects that have been assessed are related to the behaviour of the organisms, not to other effects such as health or reproduction. The noticed factual effects must be considered as minor or negligible.

The organisms that can be affected are either magnetoreceptive (such as salmon) or electroreceptive (such as elasmobranchs) or both. Species that are not electro- or magnetoreceptive are not believed to be affected. Experimental and behavioural studies (both in natural and experimental settings) show that measured and calculated induced electric and magnetic fields from submarine power cables lie within the range of detection (or expected range of detection) of both electro- and magnetoreceptive marine animals. Based on the same detection thresholds, and modelling conducted in this study, electro- or magnetoreceptive species may be able to detect the fields emitted from a cable. Besides the insecurities in identification of the detection thresholds, the detection range depends on the field strength from the cable. Depending on the sensitivity of the specie and cable characteristics, the detection range varies from zero to several hundreds of meters. However, although an animal may be able to detect the field there is no indication of a negative impact in the current state of knowledge.

The source of EMF is only power transmission cables – the fields emitted from the wave energy converts themselves are insignificant due to shielding in the steel casing of the units.

Very few studies have been conducted on the nature of potential impacts from EMF on marine organisms. The noticed effects of EMF (if any) in the conducted studies could be considered insignificant or small, but it should be stressed that it is hard to draw any general conclusions about potential environmental effects based on such a limited amount of research. To be able to answer whether EMF from underwater installations have negative effects on the marine environment in specific types of settings more research is needed, both in the form of field studies at existing cables, and research evaluating potential sensitive environments and the effects on different life stages of organisms. Effects from both magnetic and electric fields need further understanding, and one of the fields (electric or magnetic) cannot be identified as potentially more harmful than the other. The major knowledge gaps identified in this study is the lack of information on marine mammals and magnetic fields, and the difference in response between fields from AC (alternating) and DC (non-alternating) fields. This is however a research field that we suggest is the responsibility of a wider research community and not for a single energy utility such as Vattenfall.

Regarding potential mitigation measures, cable burial only increases the distance between the cable and the marine organism. The burial itself does not reduce the strength of the magnetic field and thereby not the strength of the induced electric field. The most effective way of reducing the produced EMF is to choose cabling techniques where the magnetic fields from several conductors cancel each other out creating a smaller resulting magnetic field. Other cable design parameters, such as conductivity and permittivity, also affect the emitted fields.

In environmental impact assessment and consent processes, EMF-related impacts are treated differently in different countries in Northern Europe. While the environmental authorities in the U.K. and the Netherlands in many cases demand both analysis of potential impacts and monitoring programs during the operation phase, countries like Germany and Norway consider the EMF-related impacts to be negligible. This gives another indication that the mechanisms and impacts of electric and magnetic fields are not fully understood.

## 9 RECOMMENDATIONS

Pro-active actions such as conducting experimental research on EMF-sensitive organisms should not be the main priority for Vattenfall. The results from the modelling and literature review in this study do not motivate such activities. The main questions that remain to be answered by the research community is if the response to EMF which has been found in the few studies conducted so far, represent a negative impact, and to what degree. In addition, there is extremely known about mammals and their response to EMF, as well as cumulative effects from a large amount of cables in a limited area.

Undertaking field measurements on existing cables is not motivated either, as the questions to be answered are mainly revolving around responses of marine organisms to different fields, not the strength of the fields themselves.

Based on the results in this study the main strategy within Vattenfall for EMF and sub sea installations is suggested to be to follow research performed externally within the field, and follow the development on what authorities and interest groups find important regarding EMF impacts. When an environmental statement for a planned wave or energy project is prepared, EMF should be properly analysed but the findings of this study does not motivate further research or studies on the subject by Vattenfall.

If the issue of EMF was to become of greater significance (due to problems encountered in permit processes or due to new research findings) in the future, this strategy should be revised.

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## APPENDIX 1 – MODELLING AND FIELD MEASUREMENTS OF EMF

Table A1 shows a summary of the results from field measurements and modelling of EMF within the investigated study of AC and DC cables, in addition to the modelling presented in section 4.

Table A1:Results from modelling and measurements of EMF

| Size of EMF | Distance | Type of cable, source |
|---|---|---|
| | *E-field* | |
| The E-field did not reach outside the cable, due to the model assuming perfect grounding of the metallic screen around the conductors | - | Modelling of 3 Phase AC, 132 kV cable with 350 A in each conductor (CMACS 2003). |
| | *B-field* | |
| 1,6 μT | At the skin of the cable. Distance to background level was 20 m. | Modelling of 3 phase AC, 132 kV cable with 350 A in each conductor (CMACS 2003). |
| 30 – 50 μT | < 1 m from the cable, at a distance of 100 m the B-field was in the range of two magnitudes smaller | Modelling of single conductor AC 150 kV cable[1] (Hoffman et al. 2000). |
| 0,6 – 0,7 μT | 2- 4,5 m from the cable | Field measurements of 3 phase AC 36 kV export cables with currents varying between approximately 100 – 350 A (Gill et al. 2009). |
| 1 μT | 0,5 m from the cable | Modelling of a 300 A DC cable with 2 conductors. (results presented from Uppsala university) |
| | *Ie-field* | |
| 91,25 μV/m | At the skin of the cable | Modelling of 3 Phase AC, 132 kV cable with 350 A in each conductor (CMACS 2003) |
| 10 μV/m | 8 m from the cable | Modelling of 3 Phase AC, 132 kV cable with 350 A in each conductor (CMACS 2003) |
| 0,5 μV/m | 295 m from the cable | Field measurements of 3 phase AC 36 kV export cables with currents varying between approximately 100 – 350 A (Gill et al. 2009). |

[1] No data from the actual calculation of the EMF was presented.

The results presented in table A1 shows that the results from modelling and field measurements are within the same range. One exception is the results presented by Hoffman et al (2000) where a single conductor AC cable is modelled and where the calculated magnetic field is found to be higher[20] however three-phase transmission systems is more likely to be used in marine renewables (Öhman et al 2007).

Modelling results AC

To evaluate the size of the EMF emitted from a sub sea power cable from an offshore wind farm, CMACS[21] (2003) performed both a modelling of a AC 132 kV cable with a current of 350 A in each conductor and field measurements for verification of the results. The results showed that strong magnetic fields were present in close proximity to the cable and that the fields rapidly decreased perpendicular to the cable. In the model the cable was buried in 1 m sand, the results showed that the burial gave no additional mitigation (due to the lack of magnetic properties for both sand and seawater) except for putting the cable at some distance from the water. The magnitude of the modelled B-field on the skin of the cable was approximately 1,6 μT (the AC current will give a varying field that is superimposed on existing B-fields). The strength of the field diminished rapidly in a non-linear manner and the background level was reached within 20 m. The iE-field on the skin of the cable was calculated as 91,25 μV/m and at the distance of 8 m from the cable the iE field strength was approximately 10 μV/m.

Hoffman et al. (2000) presented results from an internal study by the Danish Institute for Fisheries Research that modelled EMFs from cables from an offshore wave power farm. The cable was a single conductor 150 kV cable and the magnetic field was 30 – 50 μT at distances less than 1 m from the structures. At a distance of 100 m the magnetic field was two orders of magnitudes smaller than the geomagnetic field.

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[20] Using a three-phase cable the emitted fields from the different phases cancels out each other causing a smaller resultant.

[21] The Centre for Marine and Coastal Studies.

# APPENDIX 2

## Experimental studies and monitoring related to submarine cables and other studies on the impact of disturbed EMF

### The potential effects of electromagnetic fields generated by cabling between offshore wind turbines upon Elasmobranch Fishes (Gill and Taylor. 2001)

The project consisted of two major parts, first a literature review on electroreception in Elasmobranchs including a technical description on offshore wind farm developments and secondly an experimental study of the potential effects of cabling from an offshore wind power installation on electroreception in Elasmobranchs.

In the experimental part of the study the Lesser Spotted Dogfish *S. Canicula*[22] was used, se figure A1.

**Figure A1: The Lesser Spotted Dogfish (UK Divers 2009).**

The central aim of the study was *…to compare and contrast the behavioral response of dogfish when presented with two artificially created electric fields, one simulating the electric field of a prey item and the other the field associated with a power transmission cable of standard specification.*

The experimental design consisted of three 1,5 m diameter black, acrylic tanks with a depth of 0,75 m set up with a flow through system of water (the water temperature was approximately 6-7° C). Between the tanks 24 adult dogfish were distributed (estimated 0,65 m in total length). On the base of the tanks a salt bridge electrode was placed at a random position 0,6 m from the center, the electrode had a thin covering of sand.

The dogfish then encountered three experimental treatments.

1. 8 μA electric current at the electrode (previous studies have demonstrated that dogfish are attracted towards electric fields created by dipoles passing a field of that magnitude which simulate prey).
2. Max predicted electric field from an unburied 150 kV electric cable with a 600 A current (10 μV/cm).
3. Control, using all equipment but without a power connection

To induce the movement of the fish 30 ml of liquid obtained from macerated scallop was introduced into the water during the experiments[23].

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[22] Now named the Small Spotted Catshark

A number of conclusions are being drawn as a consequence of the research:

> 1. There is a dearth of objective and definitive published information relating to the question of whether electric fields produced by underwater cables have any effect on electrosensitive species.
>
> 2. Preliminary research has demonstrated that the benthic shark, Scyliorhinus canicula, avoids DC electric fields at 1000μV/m (or 10μV/cm) which are the maximum predicted to be emitted from 3-core undersea 150kV, 600A cables.
>
> 3. The avoidance response by the dogfish of 1000μV/m (or 10μV/cm) electric fields was highly variable amongst individuals and had a relatively low probability of occurring in the conditions presented in these experiments.
>
> 4. The same species individuals were attracted to a current of 8μA (representing an electric field of field of 0.1μV/cm at 10cm from the source), which is consistent with the predicted bioelectric field emitted by prey species.

However the authors presented a few constraints relating to the project:

- Time: The project was set up to review and undertake a pilot study and to provide recommendations for further work within a three-month period.
- Temperature: The low water temperature gives the dogfish a low metabolism and a low level of activity.
- Species: The dogfish was used in the project due to the availability of elasmobranchs at the time of the project. If the study would have been made at another period other more sensitive species would have been possible to use.
- Measurements of electric fields: In the project there was an ambition to measure the produced electric fields which failed.

### EMF-SENSITIVE FISH RESONSE TO EM EMISSIONS FROM SUB-SEA ELECTRICITY CABLES OF THE TYPES USED BY THE OFFSHORE RENEWABLE ENERGY INDUSTRY (GILL ET AL. 2009)

The project objective was to determine if electromagnetic sensitive fish respond to electromagnetic fields with the characteristics and magnitude of EMF associated with offshore wind farm power cables.

The experiments consisted of:

1. A mesocosm study to investigate effects of EMF on elasmobranchs.
2. Measurement of EMF from two existing wind farms.

Two identical sections of AC electricity cable were lowered into 10 –15 m of water and buried 0,5 –1 m depth. Two identical mesocosms were lowered on top of the cables (the mesocosms were circular with a diameter of approximately 40 m and a height of approximately 5 m).

---

[23] Sharks are well known to use a hierarchical sense response with the sense of smell predominating at a distance and electroreception taking a major role in the final 20 –30 cm of a reaction to a stimulus source.

To generate the EMF most similar to the standard off-shore wind farm cables, a high current, low voltage 3-phase SWA (steel wired armoured) cross linked XLPE cable was used. For further details and technical specifications see Gill et al. 2009. A difference between the experimental design and real circumstances at a wind farm was that the sheeting and design of the cable in the experiment were set so that less current was required to produce the B-field present at a real wind farm (different sheeting and smaller dimension).

The EMF was monitored by in situ pod dataloggers. Tidal information for the local area was downloaded from the UK Hydrographic Office every week.

Between August and December 2007, three[24] repeats of the mesocosm study were conducted. To eliminate the possibility of site-specific effects, the experimental and control mesocosms were switched between trials. Each trial was approximately three weeks long. An equal number of fish where released into both mesocosms. In one mesocosm (called the “live mesocosm”) the fish were exposed to EMF and in the other (the control) no electricity was fed through the cable. In the live mesocosms the fish were exposed to one hour EMF during day and one hour EMF during night. The movement of all fish where recorded by a acoustic tracking system (VRAP)[25], some of the fish were also equipped with small archival tags that recorded pressure (i.e. depth) every 20 seconds and temperature every 5 minutes.

Two species of electrosensitive, elasmobranchs were used in each trial. For trial 1 the benthic Thornback Ray (Raja clavata), the free-swimming Spurdog (Squalus acanthias) were used, see figure A2.

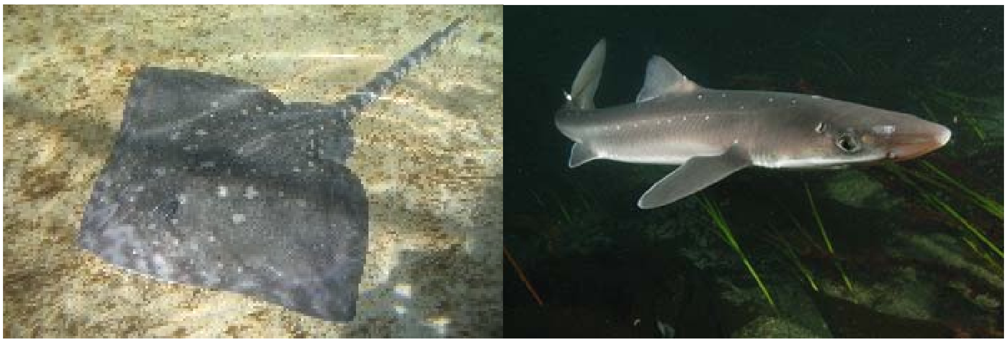

**Figure A2: To the left Thornback Ray (ardtoe marine 2009), to the right the Spurdog (Radio Netherlands 2009) to the right the Spurdog.**

The Spurdogs have a natural tendency to continuously swim which later was judged to reduce the possibility of detecting effects from the cable. Therefore the Spurdog were replaced with the benthic Small-spotted Catshark/Lesser-spotted Dogfish (Scyliorhinus canicula) in trial 2 and 3. At the end of each trial, fish were recovered by hand and the acoustic transmitters and data storage tags recovered for downloading data. Table A1 shows the number of fish in entered into and recovered in each trial.

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[24] The aim was to conduct four trials, however, due to the very tight time constraints, adverse weather and other logistical issues only three repeats were made.

[25] The movements and space use of fish were determined by equipping each individual with an acoustic transmitter. For further information se Gill et al. 2009.

**Table A1: The species and number of fish introduced into the mesocosms for each study trial (after Gill et al. 2009).**

| | Trial | | | | | |
|---|---|---|---|---|---|---|
| | **1** | | **2** | | **3** | |
| **Species** | Fish in | Fish + tags Out | Fish in | Fish + tags Out | Fish in | Fish + tags Out |
| Thornback Ray | 16 | 9 | 9 | 6 | 9 | 7 |
| Spurdog | 16 | 12 | 3** | 3 | n/a | n/a |
| Catshark | n/a | n/a | 12 | 7 | 10* | 8 |
| **Total number** | 32 | 21 | 24 | 16 | 19 | 15 |

*** Fish that were not caught from previous trial.*

** One fish remained from the previous trial.*

The original plan was that the EMF from the cable would be within the range potentially detectable for the fish to a distance of approximately 17 m on each side of the cable. The actual detectable EMF only extended around 2 m of either side of the cable.

The data from the experiments were analysed evaluating frequencies of fish at various positions of the mesocoms. The number of individual fish within the area of 2 m on either side of the cable one hour before, during (one hour) and one hour after the cable was energized were compared.

The results of the study can be summarized as:

- There is evidence that the benthic elasmobranchs species studied did respond to the presence of EMF emitted by a sub-sea cable. However, this response was variable within a species and also during times of cable switch on and off, day and night.
- The noticed responses was not predictable and did not always occur, and when it did occur it was both species dependant and individual specific.
- The Kernel Density Probability Function (KDPF) analysis showed that all the fish species moved throughout the mesocosms regardless of whether there was any EMF present or not. There was a predominance of movement towards the offshore side of the mesocosms.
- Analysis of the overall spatial distribution of fish within the mesocosm was non-random and one species, S. canicula (the Small-spotted Catshark) was more likely to be found within the zone of EMF emission during times when the cable was switched on.
- The fine scale analysis was limited by the tracking technology available which meant the number of fish individuals studied was low. However, there were differences found for some individuals of Rays and Catshark in terms of their rate of movement around the zone of EMF emission when the cable was switched on.
- There appeared to be a response by the Rays of being nearer to the cable when it was turned on; however a similar response was found in the control mesocosm. This highlights the importance of including the control in the study.
- However, for the individually tracked rays there was a greater rate of movement within the zone near to the cable when it was energised.

- Taking the overall and fine scale analyses conducted in the study together suggests that the Catsharks will at times be found more of the time near to the energised cable and they will be moving less than during times when the cable is not switched on. This result is consistent with the area restricted searching that is associated with feeding in benthic catsharks.
- There was no differences in depth related movement during the time that the cable was on or off.
- There did not appear to be any differences in the fish response by day or night or over time.
- Whilst the results clearly showed individual differences to the EMF there were insufficient occurrences of individuals responding consistently over time for any determination of habituation. Further study on more individuals would be required.

### SUB-SEA POWER CABLES AND THE MIGRATION BEHAVIOUR OF THE EUROPEAN EEL (WESTERBERG & LAGENFELT 2008)

The purpose of the study was to investigate if effects from AC fields from two early Soviet studies could be demonstrated[26].

The experiment was carried out on migrating European Eel in the Baltic. Eel was chosen due to its fairly predictable way of migrating in the Baltic sea. Between the Swedish mainland and the island Öland there is a approximately 10 km long sub sea power cable. The cable is a three-phase 130 kV, twisted cable with metal wire sheeting. The cable is buried in the littoral zone but otherwise unburied. The experimental design was to use four transects across the sound using data-logging, ultrasonic receivers. The spacing between transects were approximately 3-4 km and the cable was situated between the middle two transects. Sixty tagged silver eels were released north of the transects with a 4-day interval, se figure A3.

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[26] Soviet studies (Poddubny 1976; Podubny, Malinin & Spector 1979) demonstrated a milling behaviour and delay of salmon and sturgeon passing under overhead AC power lines in a river (Westerberg & Lagenfelt 2008)

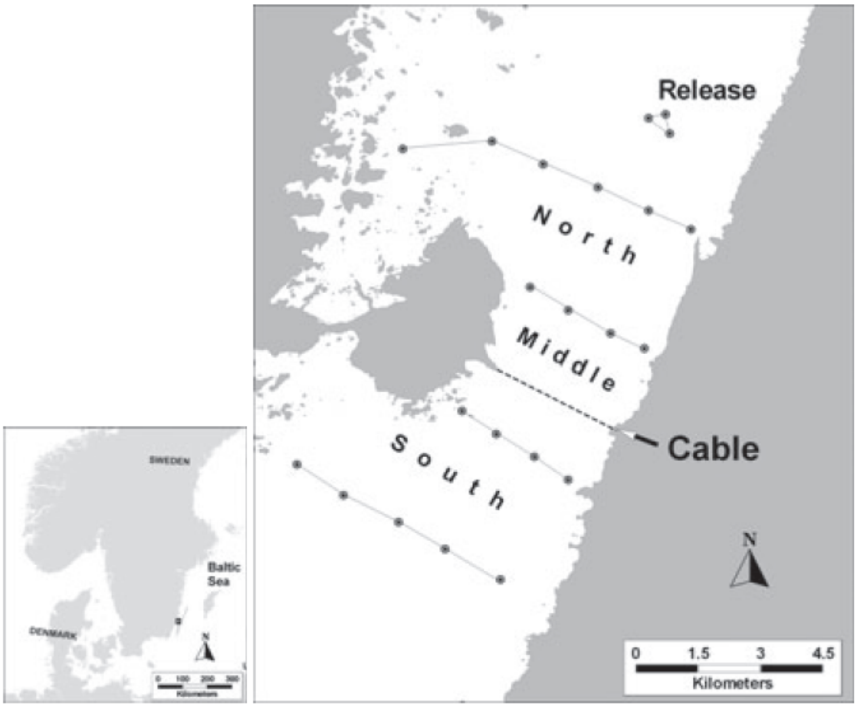

**Figure A3: Overview of the receivers, cable and release point of the fish. (Westerberg and Lagenfelt 2008).**

The mean velocity for the eels were then calculated between the transects. Of the 60 tagged eels, 46 gave a complete record of passage through all four transects. The speed of swimming was adjusted to the measured current approximately 9 km south of the array. The results of the experiments showed that the swimming speed in the middle interval was significantly slower than the speed both in northern and the southern interval.

However from an environmental point of view, the effect of the cable on eel was considered to be small. There was no evidence that the cable was an obstruction to migration (just 2 out of 60 eels turned back somewhere in the middle interval containing the cable, a figure that can be explained by chance rather than caused by the cable). The delay was about 40 minutes on average and would hardly influence fitness in a 7000-km migration.

Even though the small environmental impact shown the reaction to the presence of an AC electromagnetic field was of general concern. In the study it is stated that other magneto-sensitive fish species (for example Pacific salmon or sharks and rays) may react differently.

## EFFECTS OF HVDC CABLES ON EEL ORIENTATION (WESTERBERG 2000)

The study consisted of a two-year telemetry study at the Baltic Cable pole-cable at the Swedish south coast. Migrating silver eels were tagged with ultrasonic transmitters and tracked from a boat during their passage of the cable. The study consisted of 25 female silver eels and of those 60 % were observed while passing the cable. Four tracks were made without current in the cable; otherwise the current was 1000 –1300 A producing a magnetic field of 5 $\mu$T at a distance of 60 m from the cable.

The conclusions of the study was:

- The eels did cross the cable with the same probability as if it were absent.
- In several cases the tracked eels changed their course slightly at the passage of the cable. However the spatial resolution was in most cases to low to draw any certain conclusions.
- It is stated that some effects of magnetic disturbances of HVDC cables on eel migration seems likely, but that the consequences seem to be small. There is also no indication that a cable constitutes a permanent obstacle for migration.

### THE EFFECTS ON FISH AND FISHERY BY THE SWEPOL LINK (IN SWEDISH) (WESTERBERG ET AL. 2007)

The report is a summary of studies performed to evaluate the effects on fish and fishery from the construction and operation of SwePol Link (A HVDC cable between Sweden and Poland). The studies that were related to EMF consisted of:

<u>Migration of eels.</u>
The purpose of the study was to investigate if the migration pattern of eels are affected by the cable. The tracing of the eels were conducted using acoustic tracking both when the cable was fully operating and turned off. The maximum magnetic field emitted from the SwePol Link is approximately 200 μT at the distance of 1 m. The field study was conducted during the period 2003-2005 and with total 37 eels. Out of the 37 eels 35 gave useful results. The main conclusions from the studies were:
The frequency of registered passages of eel when the cable was energized did not differ significantly from the unenergized cable. The cable was not a definitive threat to the migration.
The eels did not show any systematically reoccurring reactions to the cable that were traceable with the techniques used.

<u>Magnetic field effects on salmon and sea trout.</u>
The study was conducted to evaluate if the cable would affect the orientation behaviour of salmon (Salmo salar) and sea trout (Salmo trutta). In total 23 fishes were attached with a transmitter and a coil that generated a magnetic field that could be turned on from a distance. The results of the study showed the disturbances of magnetic fields with the used strength (approximately the double magnetic field of the earth) didn't have any suppressing effects on the swimming behaviour of salmon and sea trout.

<u>Magnetic field effects on elvers:</u>
The main purpose of the study was to show whether elvers are attracted to or avoiding magnetic fields of 100 μT; this to evaluate if the SwePol Link will work as a migration barrier.

Two Y-shaped labyrinths were constructed out of PVC. In the openings of the channels doors were mounted and under each channels an electromagnetic coil was placed connected to a DC generator. There were two sizes of coil used generating magnetic fields

Cross-section

of 200 μT and 400μT at the center of the coil, se figure A4.

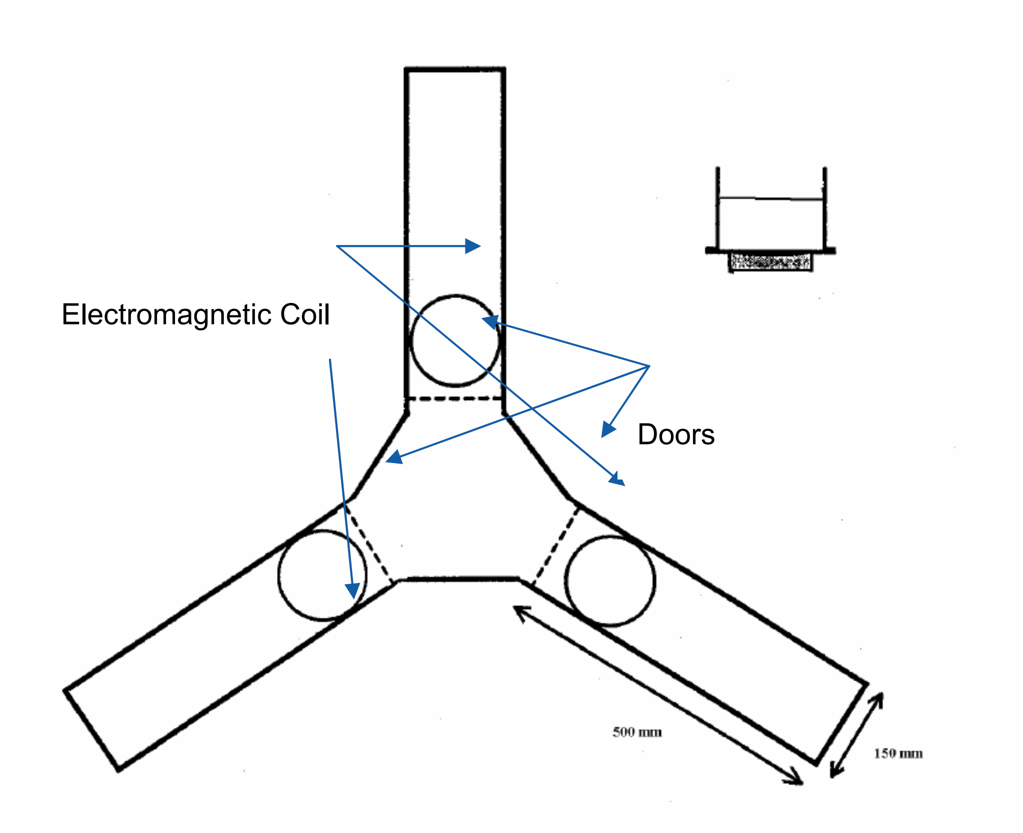

**Figure A4: The Y-shaped labyrinth used in the experiments. Modified from Westerberg et al. 2007.**

In each trial ten eels were placed in the central chamber of the labyrinth with the doors to the channels closed. Then the light was turned off in the experiment hall and the eels were left for acclimatization for 15 minutes. The one random coil was activated and the doors were opened, this setting was left for 15 minutes. The doors then were closed and the eels in each chamber were counted. Totally 260 experiments with a small coil and 200 with the large coil were conducted (out of which approximately 50 % were experimental controls without electricity). Between the experiments the eels were exchanged for new ones and the labyrinth was rotated.

The results of the study were that none of the experiments indicated that the cable may pose as a threat to the migration of the eels. Even though it was uncertain if the eels could detect the magnetic fields it was stated that the potential effects of behaviour is not significant enough to stop the eels from migrating through a magnetic field gradient.

## NYSTED, THE DANISH MONITORING PROGRAMME: FINAL RESULTS (PEDERSEN ET AL 2006)

The building permits for the Danish offshore wind power farms Nysted and Horns Rev included an obligation to carry out comprehensive environmental monitoring programmes including environmental conditions before during and after the two wind farms were established. The Danish Forest and Nature Agency, the Danish Energy Authority, Vattenfall and DONG Energy coordinated the work. During the years 2001-2004 studies were conducted to evaluate potential impacts from EMF from the transmission cable from the Nysted wind power farm and to verify the local migration route of the common eel.

Study site & methodology

The transmission cable from the Nysted wind power farm consist of a 10 km long three-phase 132 kV AC cable. The water dept in the area is 3-8 m.

For the assessment a specially designed setup and fishing gear was developed and used along the cable trace. Initially ordinary pound nets were used simply to monitor the fish fauna on each side of the cable, the final design of fishing gear included two types of pound nets, bi-directional and quadri-directional. One bi-directional and two quadri-directional nets were set up at each side of the cable. This setup made it possible to detect migration direction of the fish and estimate the nuber of fish passing the cable. Figure A5 displays the setup.

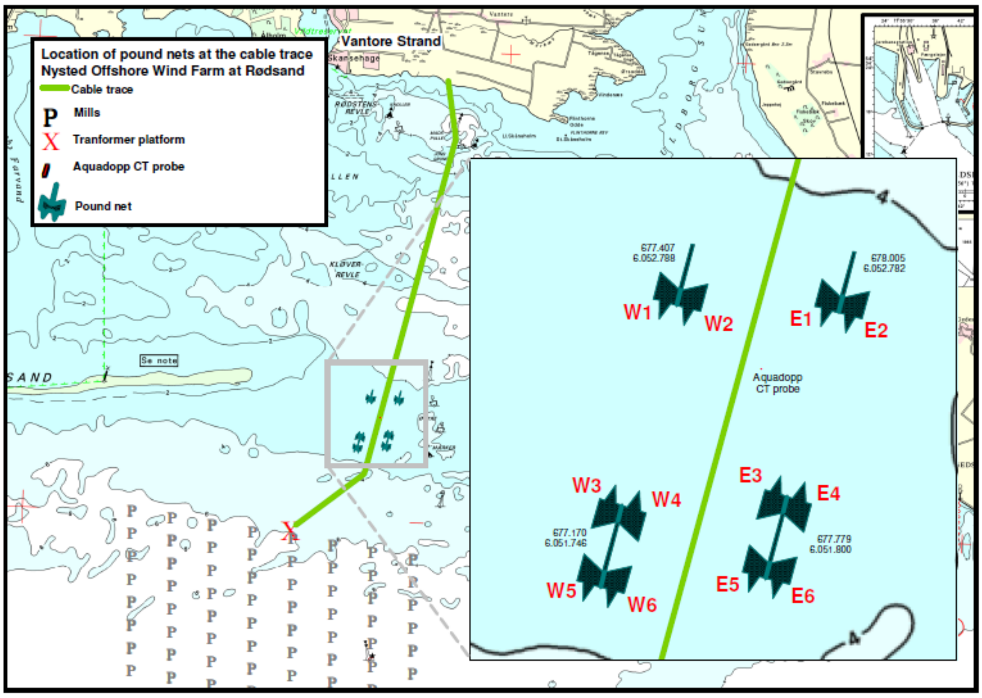

**Figure A5: Map of the planned cable trace south of Nysted, the selected study area and the geographical positions of the four pound nets. Both of the two northerly nets were designed as two-way directional pound nets with double fykes and the two southern nets where designed as four-way directional pound nets with double fykes in each end of the leader (BioConsult 2004).**

A large limitation of the study was the distance between the cable and the nets as the nets were placed 300 meters from the cable. Due to this it is impossible to say if the fish caught in the directional nets actually crossed the power cable.

To investigate the local migration route of the common eel a mark and recapture programme was carries out in 2004. The eels that were caught in the pound nets were marked and released on the same side of the cable as they were caught.

No measurements of the actual EMF were made during the study and the experiment design did not allow the investigators to separate effect from EMF from effects from the physical establishment or presence of the cable trace. To count for the lack of EMF measurements the power production data was used.

<u>Results</u>
Common eel, Baltic herring, Atlantic cod and flounder were found significantly affected by the presence of the power cable (or the cable trace). However for Baltic herring and common eel no correlation with the actual power production was found.

Flounder was found to prefer passing the cable during period with low power production indicating sensitivity to electromagnetic fields. During 2003 Atlantic cod and flounder displayed a significant attraction to the cable, however this was explained by the increased amount of food that the disturbed sea bed from the cable installation provided. In periods with high power production the Atlantic cod was repelled from theese food resources.

The investigations carried out were characterized by a high complexity including many difficulties both in both the sampling phase and the analyse phase. The main conclusions from the investigation are;

- The potential barrier effect that the cable might induce is very local and displays a temporary pattern due to variation in power production.
- No significant differences in fish communities were detected between the two sides of the cable trace either before or after the wind farm was operational, meaning that the composition and structure of the local fish fauna at Nysted is unaffected of the presence of the subsea cable.

Again it should be stressed that it is hard to make any real conclusions of the results of the study due to the rather large distance between the power cable and the nets.

### SHARK BITE ON THE SL SUBMARINE LIGHTWAVE CABLE SYSTEM: HISTORY, CAUSES, AND RESOLUTION (MARRA 1989)

In September 1985 an undersea lightwave cable system was installed linking two of the Canary Island together. During the following three years the cable was damaged five times due to shark bite attacks. It was evaluated that it was highly unlikely that the sharks where attracted to, or prompted to attack the cable due to visual, acoustical and olfactory stimulation emancipating from the cable. Furthermore there was little or no difference between the SL and neighbouring systems (of which shark attacks were no problem) concerning those factors.

However there were two factors differentiating the SL cable from neighbouring systems:

1. The system had a significant induced 50-Hz field (6,3 μV/m @ 1 meter) caused by an AC current induced onto the cable´s power feed system (possibly from a power plant located near the systems earth groundbed). After the third fault this field was eliminated from the system.
2. The DC current in the cable was three times stronger than it´s neighbouring systems causing an approximately three times stronger magnetic field (1 μV/m @ 0,1 m < 1 Hz).

To evaluate if it was the electric fields of the cable that triggered the attacks a series of experiments where conducted (both as experiments in aquaria and in shallow water sea). None of the tests were able to demonstrate a significant correlation between any electromagnetic stimuli to emanate from the cable and shark attacks. However the experiments were conducted using shallow-water sharks (due to the difficulty of keeping deep-water sharks alive and healthy), and all the attacks but two had been identified as belonging to the deep-water shark species *Pseudocarcharias kamoharai* and possibly some closely related species.

## INFLUENCE OF WEAK ELECTRIC AND MAGNETIC FIELDS ON TURNING BEHAVIOUR IN ELVERS OF AMERICAN EEL *ANGUILLA ROSTRATA (MCCLEAVE AND POWER 1978)*

The turning behaviour of elvers of the American eel was studied in an arena in which a horizontal or vertical magnetic field could be manipulated. The main purpose of the study was to determine how the strength and polarity of a weak DC electric field influenced elver orientation and to evaluate if the elver orientation was linked to induced electric fields caused by the elvers own swimming movements through the magnetic field. The results of the study showed that, as the electric current density increased from 10 μA/cm to 102 μA/cm the elvers turned increasingly towards the anode.

## EFFECT OF MODIFED MAGNETIC FELD ON THE OCEAN MIGRATION OF MATURING CHUM SALMON, *ONCORHYNCHUS KETA* (YANO ET AL. 1997)

The aim of the study was to investigate the role of magnetic compass orientation in oceanic migrating chum salmon. Four fish were attached with a tag that generated an artificial magnetic field around the head of the fish. The fish had implanted ultrasonic transmitters that allowed tracking. Initially the fish were tracked for 16 h without any artificial magnetic field then the magnetic field was altered for 16 h. The generator produced an alternating magnetic field intensity of about 0,6 mT, with polarity reversed every 11.25 minutes.

The results of the study showed that there was no observed effects on the horizontal and vertical movements of the salmon.

## OPEN-SEA MIGRATION OF MAGNETICALLY DISTURBED SEA TURTLES (PAPI ET AL. 2000)

In the study seven green turtles were fitted with six powerful static magnets during their migration from their Brazilian feeding grounds to nesting beaches at Ascension Island in the middle of the Atlantic Ocean. The weakest magnetic fields at various parts of the body of the turtles were 1500 – 49 000 nT. The turtles were tracked using satellite. The results shoved no differences between the turtles navigating in the disturbed magnetic field from turtles migrating without magnetic disturbances one year earlier.

## APPENDIX 3

This appendix provides the technical background to to section 4.3.

### INDUCED ELECTRIC FIELD FROM SUB-SEA CABLE CARRYING AC-CURRENT

The induced electric and magnetic field from a single, infinite long line-source (cable) carrying a current $I = I_0 \cdot \exp(i\omega t)$ along the x-axis in an infinite, homogenous medium can be expressed analytically (REA, 1984) as

$$E_x = -\frac{\gamma^2 I}{2\pi\sigma} K_0(\gamma r) \qquad (1)$$

$$H_\varphi = \frac{\gamma I}{2\pi} K_1(\gamma r) \qquad (2)$$

where
$\sigma$ is the electrical conductivity (S/m),
$r$ is the distance from the cable (m),
i is the imaginary unit,
$\gamma = \sqrt{i\omega\mu\sigma}$ (1/m)
$\mu = \mu_0 = 4\pi \cdot 10^{-7}$ (Vs/Am) is the permeability
and $K_0$, $K_1$ are the modified Bessel functions of the second kind, of orders zero and one respectively (Abramowitz and Stegun, 1972). It is furthermore assumed that displacement currents can be neglected, an assumption that is very good in this case since the frequency is low. Cables can be shielded with a conducting material and/or a magnetic permeable material. This of course will affect the magnetic and induced electric field outside the cable. The effect of screening has not been considered in the present calculations.

Although the situation with a cable on the sea-bottom differs from the assumptions of an infinite medium, the differences are believed to be small since the electrical conductivity of the upper part of the sediments are comparable to the water conductivity.

In a non-conducting medium (e.g. air) the magnetic field (2) simplifies to the well-known expression:

$$H_\varphi = \frac{I}{2\pi r} \qquad (3)$$

In the case of a three-phase cable (i.e. a cable with three conductors) the amplitude of the induced electric field components from the three conductors adds up according to the symbolic phase diagram shown in Figure 8.

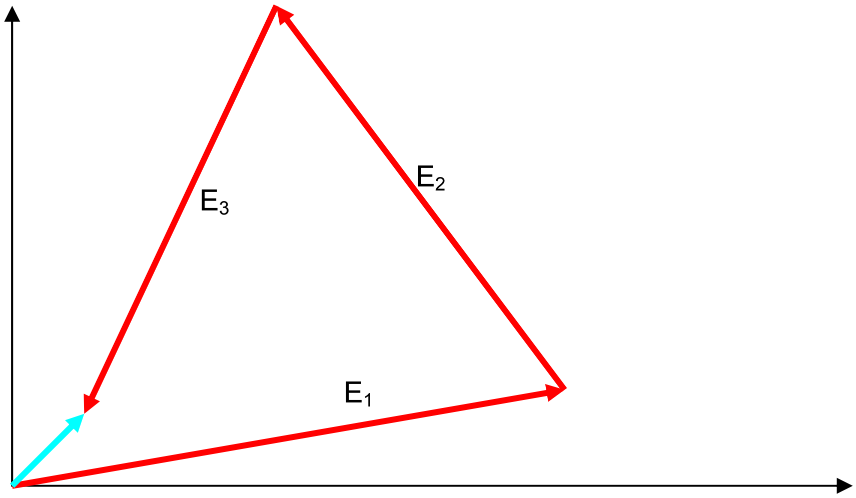

**Figure 8. Symbolic phase diagram (after Parasnis 1997, Figure 6.2) illustrating the addition of the amplitudes of the electric field $E_1$, $E_2$ and $E_3$ from the three conductors with phase differences of 120°. The resulting "net" amplitude at a certain location away from the cable is indicated by blue colour.**

If the three conductors in the cable are denoted 1, 2 and 3, the electric field from conductor *i* is given by

$$E_i = -\frac{\gamma^2 I}{2\pi\sigma} K_0(\gamma r_i)\text{, } i = 1,2,3. \qquad (4)$$

in which $r_i$ is the distance from conductor *i* to the point of calculation, and it is understood that the field is directed along the x-axis (parallel to the cable).

The electric fields from conductor 1 and 2 add up to the resulting field:

$$E_{12} = \sqrt{|E_1^2| + |E_2^2| + 2|E_1||E_2|\cos(120^\circ)} \qquad (5)$$

where the fact that the phase difference between the current in the two conductors are 120° has been used. Combining this field with the field from conductor 3 we arrive at:

$$E = E_{123} = \sqrt{|E_{12}^2| + |E_3^2| + 2|E_{12}||E_3|\cos(240^\circ - \alpha)} \qquad (6)$$

where

$$\alpha = \arctan\left(\frac{\frac{\sqrt{3}}{2}\cdot|E_2|}{|E_1| - \frac{1}{2}|E_2|}\right) \qquad (7)$$

Equation (6) is evaluated numerically[27] and illustrated in Figure 3, assuming the current is 100 A, the distance between the conductors is 7 cm and the conductivity of the seawater is 3.5 S/m[28]. As seen, the electric field decreases almost linearly in a double-logarithmic diagram up to approximately 40 m from the cable, which corresponds to one skin-depth[29] in the seawater. The induced electric field is proportional to the load current according to Eq. 4. This implies that a load current of e.g. 500 A would result in an induced electric field of 1.9 mV/m at a distance of 1 meter.

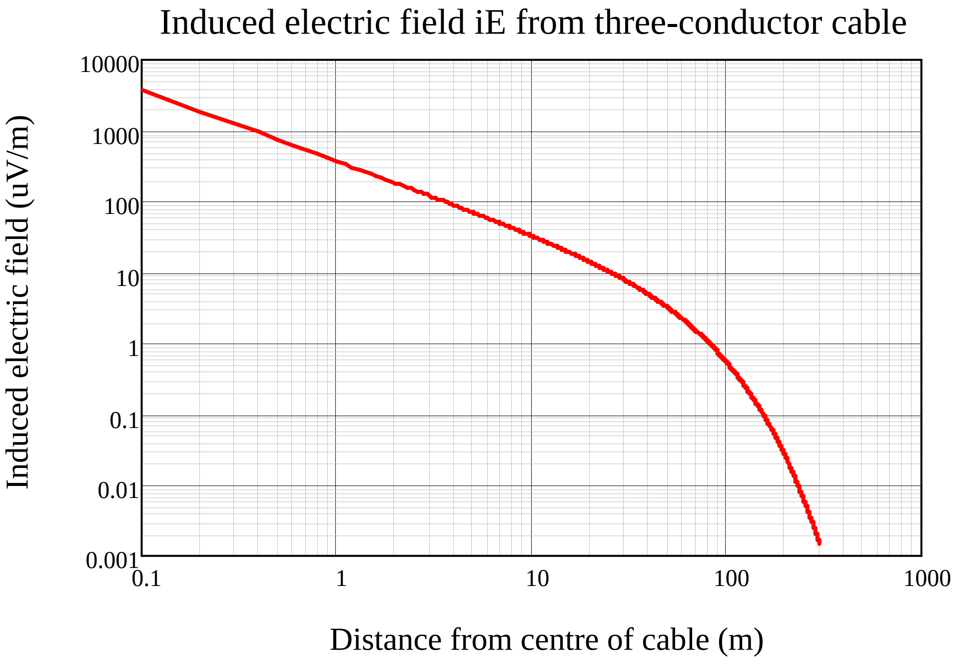

**Figure 9. The induced electric field in µV/m from a three-conductor cable, as a function of the distance from the cable. The current is 100 A, the separation between the conductors is 7 cm and the conductivity of the seawater is assumed to be 3.5 S/m, corresponding to a skin-depth of 38 m.**

Figure 4 shows the magnetic flux density, calculated as a function of the distance from the cable, using the same conditions as for Figure 3, using equation 2 and an expression similar to equation 6. As a rough check of the reliability of the calculations, it is valuable to calculate the far-field “apparent resistivity” (Parasnis 1997, eq. 6.53). At a distance of 100 m from the cable the results are E= 0.54 µV/m and B = 0.072 nT. This results in an apparent resistivity of 0.224 Ωm, which is equivalent to an apparent conductivity of 4.5 S/m. Since the assumed conductivity of the seawater was 3.5 S/m this result indicates that the

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[27] For the evaluations is used Mathcad version 14.0 under Vattenfall Workplace User license.

[28] The electrical conductivity of seawater depends on temperature and salinity, and ranges from approximately 1.7 S/m to 5 S/m. The mean conductivity of the oceans is 3.27 S/m (National Physical Laboratory 2008, http://www.kayelaby.npl.co.uk/general_physics/2_7/2_7_9.html). The conductivity of the North Sea is around 3.5 S/m.

[29] The skin-depth is defined as the distance at which the amplitude of a plane-wave field has decreased to 1/e = 37% of the original amplitude. In this case the field is not a plane-wave field, and the decrease of the field (Figure 4 and 5) is caused by geometrical reasons up to approximately 30-40 m from the cable. The additional decrease from approximately 40 m is caused by the skin effect.

individual calculations of the induced electric field and magnetic flux density are correct. A similar calculation at a distance of 1000 m results in an apparent conductivity of 3.57 S/m.

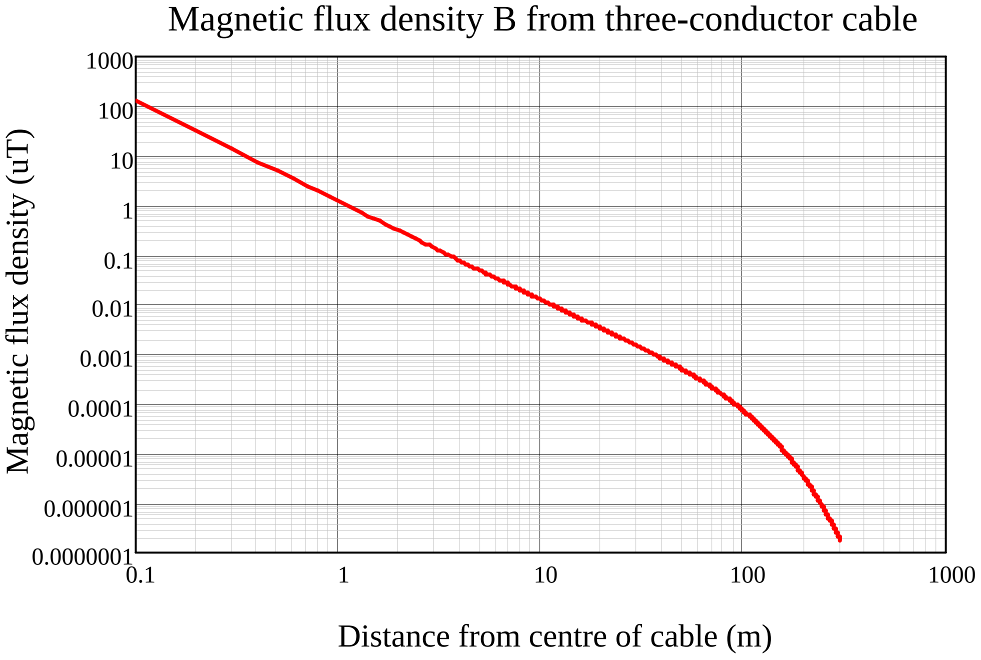

**Figure 10. The magnetic flux density in μT from a three-conductor cable, as a function of the distance from the cable. The current is 100 A, the separation between the conductors is 7 cm and the conductivity of the seawater is assumed to be 3.5 S/m, corresponding to a skin-depth of 38 m.**

Figure 5 shows the induced electric field along a profile on the sea-bottom perpendicular to the cable, assuming the cable is buried 0.5 m, the current is 100 A and the conductivity is 3.5 S/m. As seen, the maximum induced electric field at sea bottom amounts to 0.8 mV/m = 800 μV/m. The induced electric field only depends upon the load current (and the geometrical parameters), and is independent of the voltage. If the current is increased to e.g. 500 A the corresponding maximum induced electric filed will thus be 4 mV/m.

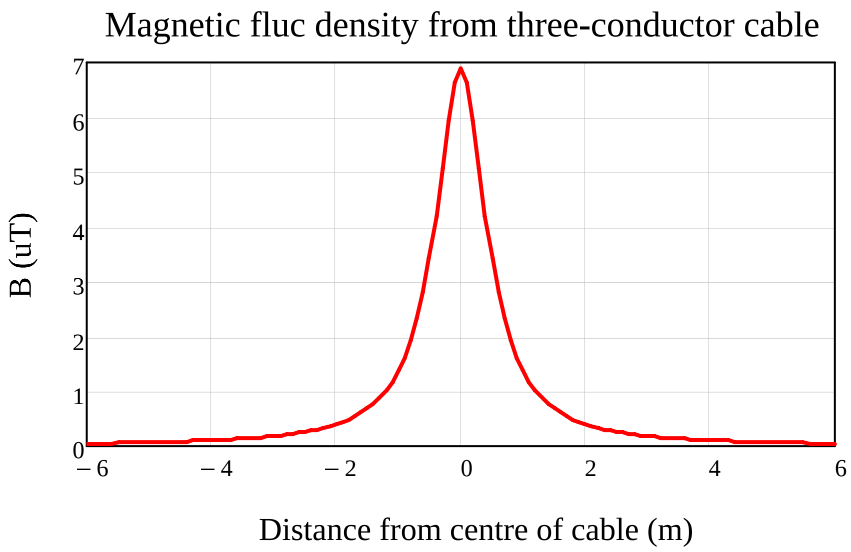

Figure 6 shows the magnetic flux density, calculated for the same conditions as for Figure 5. The maximum flux density amounts to 6.9 μT and the field is elliptical polarized.

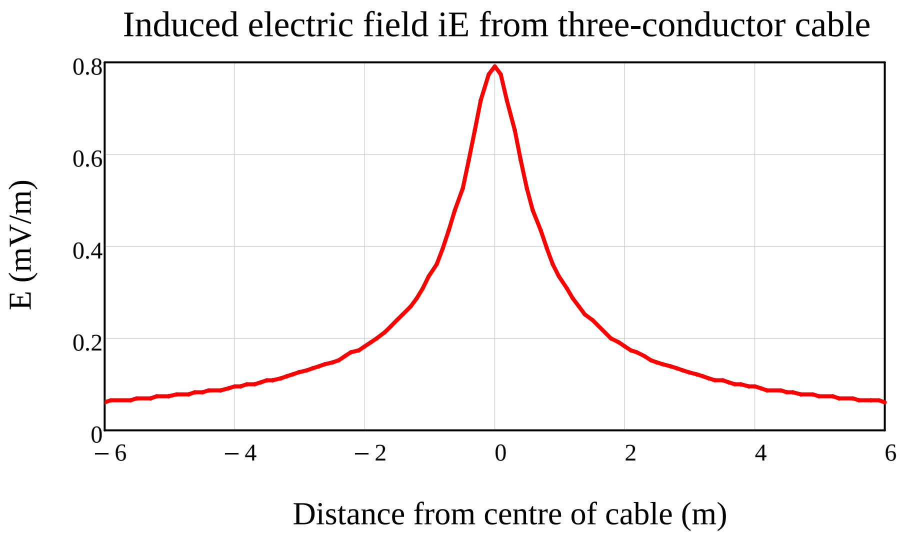

**Figure 11. The induced electric field calculated along a profile on the sea bottom perpendicular to a three-conductor cable buried 0.5 m. The current is 100 A, the separation between the conductors in the cable is 0.07 m (7 cm) and the conductivity of the seawater is 3.5 S/m. The maximum electric field amounts to 0.8 mV/m.**

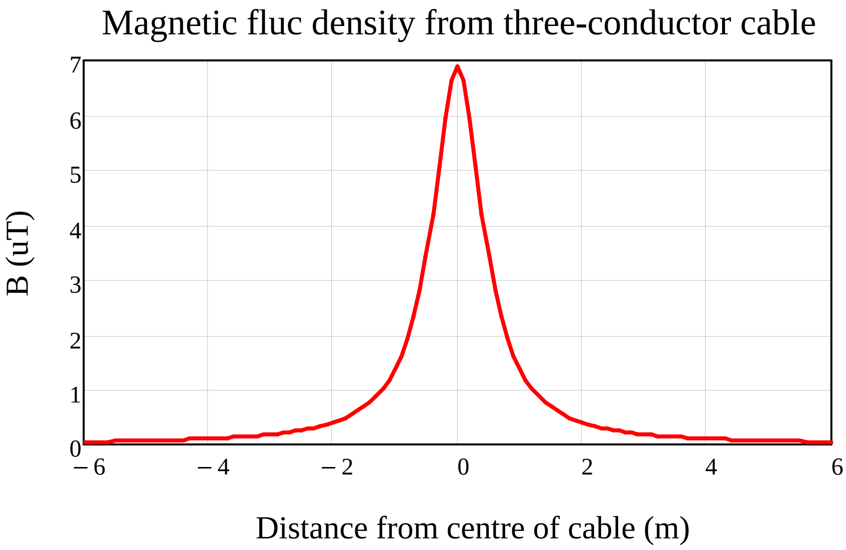

**Figure 12. The amplitude of the magnetic flux density in μT calculated along a profile on the sea bottom perpendicular to a three-conductor cable buried 0.5 m. The current is 100 A, the separation between the conductors in the cable is (7 cm) and the conductivity of the seawater is 3.5 S/m. The maximum flux density amounts to 6.9 μT. The magnetic field is elliptical polarized.**

The induced electric and magnetic fields depends strongly on the distance between the conductors in the cable. Furthermore, the field components depend linearly on the current in the cable. Table 5 summarizes the maximum induced electric field above a cable buried 0.5 m and carrying 100, 300 and 500 A. The field values are calculated for three typical cable geometries, with conductor separation of 35 mm, 49 mm and 67 mm.

**Table 9. Maximum induced electric field above three different cable types carrying 100, 300 and 500 Amp and buried 0.5 m. The seawater conductivity is 3.5 S/m.**

| **Distance between the three conductors** | **100 A** | **300 A** | **500 A** |
|---|---|---|---|
| 35 mm (10 kV cable) | 0.40 mV/m | 1.2 mV/m | 2.0 mV/m |
| 49 mm (36 kV cable) | 0.57 mV/m | 1.7 mV/m | 2.8 mV/m |
| 67 mm (145 kV cable) | 0.79 mV/m | 2.4 mV/m | 3.9 mV/m |

The following should be noted:

- The induced electric field as well as the magnetic flux density depends very little upon the electrical conductivity in the surrounding medium, as long as the fields are considered within one skin depth in the seawater. A conductivity of 3.5 S/m corresponds to a skin depth of ca 40 m.

- In the calculations no attention has been paid to the shielding, which typically consists of steel wires and copper tape. The shielding will certainly affect the primary electric field strongly. However, since the induced electric field is caused by the magnetic field, which is unaffected by the shielding, the attenuation of the induced electric field is believed to be minimal.
- The distance between the conductors in a cable is a very important parameter in the calculations of the magnetic field as well as the induced electric field. Increasing the separation causes the “net” amplitude (Figure 2) to increase.