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Offshore Windmills and the Effects of Electromagnetic Fields on Fish

With the large scale developments of offshore windpower the number of underwater electric cables is increasing with various technologies applied. A wind farm is associated with different types of cables used for intraturbine, array-to-transformer, and transformer-to-shore transmissions. As the electric currents in submarine cables induce electromagnetic fields there is a concern of how they may influence fishes. Studies have shown that there are fish species that are magneto-sensitive using geomagnetic field information for the purpose of orientation. This implies that if the geomagnetic field is locally altered it could influence spatial patterns in fish. There are also physiological aspects to consider, especially for species that are less inclined to move as the exposure could be persistent in a particular area. Even though studies have shown that magnetic fields could affect fish, there is at present limited evidence that fish are influenced by the electromagnetic fields that underwater cables from windmills generate. Studies on European eel in the Baltic Sea have indicated some minor effects. In this article we give an overview on the type of submarine cables that are used for electric transmissions in the sea. We also describe the character of the magnetic fields they induce. The effects of magnetic fields on fish are reviewed and how this may relate to the cables used for offshore wind power is discussed.

INTRODUCTION

Offshore windmills are constructed at an increasing rate around the world. Within the near future thousands of windmills will be in use only in Northern Europe. Evidently, there are environmental issues to consider (1). For example, during the construction phase sedimentation and underwater noise could influence fish and other marine organisms (2). Noise may also have an impact when a windmill is in operation (3, 4). Another factor is that the submerged part of the power plant locally changes the marine habitat causing a reef effect, i.e., the hard structure may function as an artificial reef providing habitats for fish and sessile organisms (5–7).

The marine environment may also be affected by the submarine cables that are present within wind parks as well as those leading electricity to land. As magnetic fields are induced by the electric currents marine organisms could be influenced (8–10). The character of the magnetic field varies depending on the electric currents and types of cables used and if the cables are laid on the sea bottom or buried.

Studies have shown that some fish species are magneto-sensitive and that magnetic fields could affect their orientation (11–18); a cable placed on the bottom could disrupt the geomagnetic patterns affecting migrating fish. Further, magnetic fields could influence fishes in terms of physiology, reproduction, and survival (19–22).

In this article we describe the type of submarine cables that are used for electric transmissions in the sea. We also give an overview of the character of the magnetic fields that are induced by the electric currents. The effects of magnetic fields on fish are reviewed and how this may relate to offshore windpower is discussed with preliminary results being presented.

MAGNETIC FIELDS

A magnetic field is characterised by magnetic flux density (B) measured in Tesla (T) (1T = 10 000 Gauss). The magnetic field is induced by electric currents (charges in motion) and characterized as either alternating (AC) or static (DC). In the DC case the magnetic field exists without an accompanying electrical field, while for the AC case both fields coexist simultaneously. For the DC case the magnetic fields are only influenced by magnetic materials, such as magnetic ore, cast iron, or the armoring of a cable. The Earth's magnetic field is an example of the DC variety. This field has a flux of about 60 μT at the poles where the field is vertical and 30 μT at the equator where the field lines are horizontal. There is also a naturally occurring low-frequency AC magnetic field generated by ocean motion and disturbances of the ionosphere.

The DC and AC magnetic fields interact with matter in different ways. The latter induces electric currents in conductive matter, whereas both interact with magnetic material, such as magnetite-based compasses in organisms. The ocean is electrically characterized as a conductive medium. The ability of AC magnetic fields to penetrate or propagate in saline water is characterized by the skin depth. A 50 Hz magnetic field has a penetration depth of about 35 m in Atlantic water, while 1 MHz has a penetration depth of only 0.25 m. The calculation of the magnetic field can be analytically solved for a magnetic line-source placed in an infinite conductive medium. In reality a cable is either buried or laid on the sea bottom, i.e., on the interface between two layers of different conductivities. This fact makes the calculation of the fields more cumbersome which complicates environmental assessments. For an accurate estimation of the fields, numerical models are employed where realistically described environments and cables are part of the analysis (8). Hence, to assess the environmental effect of the magnetic fields it is essential to have detailed information on the characteristics of the cable and the geological properties of the stratum, as well as the conductivity of the water column.

SUBMARINE CABLES

Anthropogenic magnetic fields in oceans are the result of electronic structures. In near-coast environments the sources are found both on land and in the sea. Even though land-based devices, such as power lines structures, emit magnetic fields, it is still the submarine cables that potentially give rise to the largest impact in the oceans as the cables traverses long distances. This could influence migratory fish; with no way around such fishes has to pass over the cable (see below). Moreover, the number of cables is increasing and in some areas fishes are more or less constantly exposed to human-induced magnetic fields.

Submarine electric cables can be divided into following categories: telecommunication cables, different configurations of high voltage, direct current cables (high voltage direct current [HVDC]), alternating current three-phase power cables, and low-voltage cables (Table 1). The HVDC-technique is commonly employed in submarine cables with three different technologies applied. The first makes use of a single conductor, where the return current is fed through the water, i.e., mono-polar transmission. In the second, two high-voltage cables are used in parallel, but with opposite polarity. In this case electrodes and a

Table 1. Examples of transmissions and employed cables. A wind farm is associated with a whole scale of different types of cables, such as intraturbine, array-to-transformer, and transformer-to-shore. The trend is that the new farms are designed to produce more power, which in turn requires new types of solutions and special cables. Both cables and the transmission technique are usually adopted from the high-power domain. It can be noted that transmission cables of HVDC technique are included in the table, although this type are not used for marine windmill farms. It is highly probable that they will be employed in future wind farm projects, especially in offshore establishments.

Land/sea locality	Type of transmission technique	Total power generated	Cable type	Use of cable	Site
Land	HVDC	170 MW	2 × 1-core	Windmill farm	Näs/Gotland/Sweden
Land	HVDC	7 MW	2 × 1-core	Windmill farm/test site	Tjæreborg/Denmark
Sea	3-phase	20 kW	1 × 3-core	Inter-turbine connection	Used in wind farms
Sea	3-phase	160 MW	1 × 3-core	Windmill farm	Nystedt/Denmark
Sea	HVDC	260 MW	2 × 1-core	High-power transmission	Gotland/Sweden
Sea	HVDC	600 MW	2 × 1-core	High-power transmission	Sweden/Poland
Sea	HVDC	700 MW	1 × 2-cores	High-power transmission	Norway/Netherlands
Sea	HVDC	330 MW	2 × 1-core	High-power transmission	Connecticut-Long Island
Sea	HVDC	500 MW	1 × 1-core	High-power transmission	Sweden-Finland

water return path are used to even out any unbalance between the two HVDC links and as a backup if one cable fails. This system is called bi-polar transmission. The third type is a variation of the first type, but without electrodes and with one or several metallic, low voltage conductors as a return path. The choice is a matter of cost, safety, and environmental considerations.

An example of the first type of submarine cable is the FenoScan power transmission cable which is a mono-polar HVDC cable located between Sweden and Finland in the Baltic Sea. At full power the current is 1600 amps, with the return current fed through the Baltic Sea (Table 1). The magnetic field generated is strong enough to influence ships' compasses. An example of the second type includes the Gotland cable, laid between the Swedish mainland and the island of Gotland. The SwePol Link cable, connecting Sweden and Poland, is of the third type. The Gotland cable was initially a mono-polar type, but to increase the transmission capacity a second cable was added, making it a bi-polar system. However, in case of cable damages, the system can be reconfigured to operate in mono-polar mode. The flux of magnetic fields is mainly dictated by the conductor separation distance and current. For the SwePol Link this distance does not exceed 25 m (9). In direct proximity (distance to cable is shorter than distance between cables), the magnetic fields are comparatively strong, while further away the resulting fields from the two cables tend to cancel each other out.

A new cable is in operation between Norway and the Netherlands (commonly abbreviated NorNed). This cable has a length of 580 km, making it the longest submarine high-power cable to date. A single two-core cable is used, thus the short distance between the core-conductors will result in an emitted magnetic flux that is lower than for the two other types. From an environmental point of view this kind of cable geometry is preferred. However, zero emissions would be the ultimate situation which could be possible in designs to come.

In this context it should be emphasized that there is a multitude of low-voltage signal cables traversing the near-coastal regions. Even the nonelectric optic cables are in some cases fitted with permanent magnetic material to facilitate localization and recovery from the sea bottom. It is not only the magnetic flux density of the individual cable that could inflict an environmental problem but also the quantity of cables. Their numbers and locations are not well documented and their effects on the environment are rarely investigated.

WINDMILLS AND CABLES

The above techniques relate to DC power transmission. It is most likely that DC transmission will be used more frequently, especially for coastal wind farms, in the future. For short-distance transmissions three-phase techniques are more common (AC power transmission). Cables used are either three single-core conductors or one three-core conductor. In terms of offshore-based windpower the three-core cables are applied for interturbine use, while both three-core and three separate cables are used for connecting the farm to the shore. Unlike the HVDC systems the three separate cables are often laid in close proximity to each other, thereby decreasing the resulting magnetic fields. Inside the farm the voltage is in the order of 20–30 kV. The transmitted voltage to land is transformed to about 130 kV and the total current is of the order 1000 amps, depending on the size of the farm. Thus, magnetic fields related to the cable are generated inside the farm and along the route from the farm to the shore. Compared to HVDC the magnetic field fluxes are lower. The main reason for this difference is that windmill farms utilize three-phase transmission, while HVDC techniques are of the DC variety. It should be underlined that the DC and AC techniques cannot be treated on the same footing in terms of environmental considerations. Fishes will most likely perceive static and alternating magnetic fields in different ways.

Estimates of magnetic field strength around cables are mainly concluded from approximate calculations based on an infinite and straight cable in a homogenous environment. An elaborate analysis of magnetic fields generated by windmill cables, was conducted by the University of Liverpool (8). In their case study a three-core cable with a 350 amps current in each conductor, placed in a three-layered medium, was examined. It should be noted that their specific choice of relative permeability was 300, giving rise to a magnetic flux density of 1.6 μT on the cables' outer periphery, while the magnetic flux was higher for an armoring with relative permeability equal to one. The effect of induced magnetic fields due to varying armor and sheeting conductivity was also investigated. Their overall conclusion was that the peak flux of the magnetic fields is most effectively reduced by burying the cable.

In an earlier study performed by Pettersson and Schönborg (23) the effect of core twisting was studied. Their results showed that the magnetic field in proximity to the cable can be substantially reduced by this technique. Still, the geometries and material characteristics (e.g., the permeability) of the cables are different for different types of cables and sometimes unknown, likewise is the status of the environment, especially sedimentary properties. In order to gain more knowledge it is necessary to perform *in situ* studies. Unfortunately, few controlled studies have been hitherto performed.

MAGNETIC FIELD DETECTION IN FISH

There are studies that suggest that fishes could be influenced by magnetic fields as there are species that contain magnetic material which could be used for geomagnetic field detection, assisting them in spatial orientation (16). Small amounts of magnetic material occur in all the major groups of teleost,

The number of offshore windmills is increasing in seas in Northern Europe and elsewhere. Submarine cables associated with windfarms generate electromagnetic fields that could influence fish. Photo: M. C. Öhman.

distributed diffusely in the whole body (24). The European eel (*Anguilla anguilla*) has magnetic material in the skull, vertebral column, and pectoral girdle (25) and the yellowfin tuna (*Thunnus albacares*) has such deposits in the skull (26). Kirschvink et al. and Mann et al. (27, 28) showed that chinook salmon (*Oncorhynchus tshawytscha*) and sockeye salmon (*Oncorhynchus nerka*) respectively, not only contained ferromagnetic material, but also that the material had the right properties to facilitate magnetic detection. The most detailed investigation, combining anatomical, physiological and behavior studies has been made on rainbow trout (*Oncorhynchus mykiss*) by Diebel et al. and Walker et al. (29, 30).

A different mechanism, compared to teleost fishes, is found in elasmobranchs (sharks, rays, and skates) (12). The elasmobranchs can gain spatial information by detecting fields created by movements of ocean currents and by the movements that the fish make themselves through the Earth's magnetic field. They have sensitive electro-receptors usually located on the head, around the mouth, and along the body.

MAGNETIC FIELDS AND FISH BEHAVIOR

Behavioral studies also indicate that fish could be magnetoreceptive. In a study by Formicki et al. (21) a number of species including perch (*Perca fluviatilis*), pike (*Esox lucius*), roach (*Rutilus rutilus*), rudd (*Scardinius erythropthalmus*), bleak (*Alburnus alburnus*), bream (*Abramis brama*), and ruffe (*Gymnocephalus cernuus*) were found to prefer fyke nets on which magnets were mounted. Tanski et al. (31) even showed that embryos were affected in terms of orientation. These studies were conducted on freshwater species that may react differently compared to marine species. However, wind parks are developed in lakes and freshwater species are common in brackish seas such as the Baltic Sea as well as in inshore coastal marine areas.

Migrating fishes would be expected to use magnetic fields for orientation. Indeed, Walker (26) showed that yellowfin tuna (*T. albacares*) were able to discriminate between magnetic fields. Salmonids commonly migrate long distances and contain magnetic material as mentioned above; Formicki et al. (21) showed that the behavior of trout larvae and fry was modified by the presence of magnetic fields. Nevertheless, Yano and coworkers (32) were unable to demonstrate that the orientation of chum salmon (*Oncorhynchus keta*) was altered when the magnetic field was increased by two orders of magnitude in relation to the Earth's geomagnetic field.

Eels are well known to migrate to distant spawning areas and have for that reason received special attention in studies on fish behavior and magnetism. Orientations in artificial magnetic fields were first studied by Branover and Vasilyev (11). In a study by Nishi, Kawamura, and Matsumoto (17) it was observed that the Japanese eel (*Anguilla japonica*), which migrates thousands of kilometers to spawn, responded to changes in the magnetic field at 12 663 nT. McCleave, Rommel, and Catchart (33) and Rommel and McCleave (34) got equivocal results for conditioning to magnetic field changes in American eel (*Anguilla rostrata*). Sensitivity to magnetic fields of the European eel (*A. anguilla*) was demonstrated in laboratory experiments performed by Karlsson (35) and Tesch, Wendt, and Karlsson (36).

There are contradictory results of the behavioral response of fishes to magnetic fields. This may be the result of different methods and species used. A detection of stimuli does not necessarily lead to a response in behavior. In addition, magnetoreception could be present but fields are below detection levels. Further, senses that detect magnetic fields are not the only means of spatial orientation; vision, hearing, and olfaction as well as hydrographic and geoelectric information could all be used for spatial orientation (13, 16, 37).

MAGNETIC FIELDS AND FISH PHYSIOLOGY

In addition to fishes' ability to detect magnetic fields as discussed above there are physiological aspects to consider. For example, magnetic exposure was noted to modify hormone levels in brook trout (*Salvelinus fontinalis*) (20). In another study, it slowed down embryonic development of trout (*Salmo trutta*) and rainbow trout (*O. mykiss*) and altered the circulation motion in embryos of trout as well as in larvae of pike (*Esox lucius*) and carp (*Cyprinus carpio*) (38). Krzemieniewski and coworkers noticed in a laboratory experiment that biomass decreased and mortality increased in the European catfish (*Silurus glanis*) when exposed to a constant magnetic field with an intensity ranging from 0.4 to 0.6 T (22). In contradiction, young flounders (*Plathichthys flesus*) that were under the influence of a static magnetic field of 3.7 mT for several weeks were not affected (39).

OFFSHORE WINDPOWER AND FISH

With the large-scale developments of offshore windpower the number of underwater electric cables is increasing. The above mentioned studies indicate that human-induced magnetic fluxes are an environmental issue that should be considered; various fish species sense magnetic fields and consequently fish migration could be altered, and there are physiological aspects to consider especially for nonmigratory species. However, few field studies have examined how fish are affected by cables and the magnetic fields they may generate.

Russian studies (40) have demonstrated a reaction of fish passing under overhead power lines in a river which they assumed to be an effect of magnetism. An early Swedish study of fish behavior around a 100 amps cable in an experimental DC system was made by Höglund and Koczy (41). In a telemetry study by Westerberg and Begout-Anras (42) the migratory patterns of European silver eels were monitored during the traverse of the submerged Baltic Cable in the Southern Baltic Sea. This cable produces a magnetic field of 5 μT at a 60 m distance. Using ultrasonic transmitters the movements of the eels were tracked by boat and a fixed array of hydrophone buoys. The results were consistent with the hypothesis that the eels followed a constant magnetic compass course, with a deviation from a straight course of the same magnitude as was expected from the magnetic anomaly caused by the cable. The spatial resolution of the tracking was too low to draw a firm conclusion about the effect. It was also noticed that depth and ambient water currents need to be considered.

In terms of studies that directly consider offshore windpower Westerberg (43) examined the migratory patterns of European eel in the vicinity of a windmill in the Southern Baltic. Telemetry tracking did not show any altered migratory behavior, at least not 500 m beyond the windmill. Catch statistics at eel pound nets in the area did however indicate an effect of whether the windmill was on or off. If this should be attributed to the effect of acoustic or electromagnetic disturbances was unclear.

In an unpublished study by Westerberg and Lagenfelt, 60 migrating silver eels were tagged with ultrasonic tags and released north of the 130 kV AC cable between the island Öland and the Swedish mainland. The migration speed was measured over approximately 4-km intervals between four transects with moored monitoring receiver buoys. The cable runs across the middle interval. After correcting for advection by the water current it was found that the swimming speed of the eels was significantly lower in the interval with the cable. Even if an effect on migration is demonstrated this impact is small. On average the delay caused by the passage was about 30 minutes.

In conclusion, submerged cables transverse seas and lakes and as a consequence fishes are exposed to magnetic fields. With the increasing numbers of offshore windmills the presence of magnetic fields is increasing. Studies indicate that fishes are influenced by magnetism but that this does not necessary mean that submarine cables will have an impact. As there is paucity in terms of scientific information on how fishes are affected by windmill cables more research is needed; especially field studies that in a direct manner address these issues.

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