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Acoustic and Electromagnetic noise induced by wind mills – implications for underwater surveillance systems Pilot study

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Report title

Acoustic and Electromagnetic noise induced by wind mills – implications for underwater surveillance systems. Pilot study

Abstract

Underwater vehicles in combination with Sweden's long coastline and its large number of archipelagoes represent today a threat to the country with regard to surveillance. The prospects of detecting and identifying such types of vehicles are based mainly on underwater acoustic and electromagnetic sensor systems.

Modern underwater vehicles are getting more and more silent and their electromagnetic signatures lower and lower, which leads to the fact that it will also be easier for them to hide. There is also a risk that the underwater acoustic and electromagnetic noise level could mask signatures from underwater targets.

Until today, only a few measurements performed in the water close to off-shore wind power stations are described. The results from these earlier studies have shown that underwater disturbances can occur. The aim of this preliminary study is to find out how strong the hydroacoustic and electromagnetic disturbances generated by a wind power station could be. Also how such disturbances affect the performance of the passive naval surveillance systems used by the Swedish Armed Forces.

We performed a test on August 22-23, 2000, at the wind power park at Bockstigen, Gotland, in order to study the hydroacoustic and electromagnetic fields created by a typical sea-based wind power plant.

The result show that the windmill at Bockstigen generates significant hydroacoustic noise, as well as electromagnetic radiation in the water. The measurements are restricted to operating conditions with low wind force and also limited to uncontrolled background levels. This pilot study ends up with some recommendations for further work to clarify if the disturbance can effekt the performance of naval surveillance systems.

The building of off shore wind power in the Baltic Sea will continue during the coming years. Development of new and more efficient technique in combination with the use of numerical wave propagation models for noise prediction in the water may contribute to facilitate the future planning.

Key words

Bockstigen, ambient noise, off shore wind power, noise power spectra

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Rapportens titel

Akustiska och elektromagnetiska störningar från vindkraftverk - inverkan på uv-spaningssystem. En förstudie

Sammanfattning

Undervattensfarkoster utgör, i kombination med landets långa kustremsa och många skärgårdar ett spaningshot mot vårt land. Detektions- och identifikationsmöjligheterna av dessa typer av farkoster baseras idag huvudsakligen på hydroakustiska och elektromagnetiska sensorsystem placerade i vattnet. Moderna undervattensfarkoster blir allt tystare och ges allt lägre elektromagnetiska signaturer vilket gör att de också lättare kan dölja sig i de bakgrundsstörningar som förekommer i Östersjön. Det finns också en risk att den akustiska och elektromagnetiska nivån i vattnet höjs så mycket att signaturer från undervattensmål maskeras i den höjda bakgrundsnivån.

Det finns idag bara enstaka mätningar som är utförda i vattnet vid havsbaserade vindkraftverk. Resultaten från dessa tidigare undersökningar har visat att undervattensstörningar kan förekomma. Denna förstudie syftar till att utreda hur starka hydroakustiska och elektromagnetiska nivåer ett vindkraftsverk kan alstra och hur dessa påverkar prestandan på Försvarsmaktens marina passiva spaningssystem.

En fältmätning utfördes 22-23 augusti 2000 vid vindkraftparken vid Bockstigen, Gotland för att studera de hydroakustiska och elektromagnetiska fält som skapas av ett typiska havsbaserat vindkraftverk.

Vi visar att vindkraftverket vid Bockstigen alstrar både hydroakustiska och elektromagnetiska störningar i vattnet. Mätningarna är begränsade till ett drifttillstånd i låga vindstyrkor och har bara kunnat jämföras med en okontrollerad bakgrundsnivå. Utifrån denna förstudie rekommenderar vi att kompletterande undersökningar genomförs för att kunna svara på frågan i vilken omfattning marinens sensorsystem kan störas.

Utbyggnaden av havsbaserad vindkraft i Östersjön kommer att fortsätta under de närmaste åren. Utveckling av ny och mindre störgenererande vindteknik i kombination med utnyttjande av numeriska vågutbredningsmodeller för prognos av uppkomna störningar kan bidra till att underlätta den fortsatta planeringen.

Nyckelord

Bockstigen, bakgrundsbrus, havsbaserad vindenergi, brusnivåer

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Contents

1. Introduction

Passive underwater surveillance systems are in general sensitive to variations in the environment. Most commonly airborne acoustic noise is addressed when discussing windmills, but there is reason to believe that the underwater environment will be contaminated by acoustic noise, as well as electromagnetic (EM) radiation, generated by sea-based windmills.The off-shore mills are so far of mainly isolated small scale, which means that available relevant data is very restricted. Some earlier studies have indicated that the disturbances from these mills are in the low frequency range, <1kHz, [1, 2], in the range where passive surveillance systems usually are most sensitive.

Primarily the rotation of the mill's wings produces a strong acoustic response in both air and water, [3, 4], but also vibrations generated by the tower itself propagate down into the fundament of the mill. The vibrations generate sound waves through the bottom and further out in the water. This raises the acoustic noise levels in the surrounding of the mill. Also the electricity generator, high voltage transformers and electrical cables radiate EM-waves into the air [5] and the surrounding water. This increases the noise levels of the EM-spectrum in a fashion similar to the acoustic case.

In order to examine these effects we have performed measurements for frequency and detection distance analysis. The measurements have been conducted at one of the five wind mills at Bockstigen, located outside Näsudden, Gotland. The mills at this location are comparatively small types (Wind World - 500 kW). Larger mills that are planned to be installed along the Swedish coast (> 2 MW), implying that the noise levels and detection distances estimated here have to be adjusted. A similar consideration must bee valid for the total effect of a large full scale wind farm, [6].

2. Field measurements

Bockstigen offshore wind mill park is located 4 –5 km southwest of the Näsudden peninsula on Gotland, Figure 1. On Näsudden there is also a large windmill park, in total over 100 mills of different types and sizes. Bockstigen number 1, at which the measurements took place, is one out of five identical wind mills. Each of them producing up to 500 kW in favourable winds, i.e. an average wind speed of 15 m/s. The mills are of the 500 kW Wind World-type which is 35 metres high and has a wing span of 37 metres. The monopile steel tower is mounted in a full diameter, drilled hole in the bedrock. This ensures a very good connection to the bedrock allowing a high degree of acoustical energy-transfer through the same.

The data was retrieved during August 22-23 2000. The wind speed was very low but showed an increasing trend from 4 to 7 m/s, which in turn raised the sea state from significant wave heights around half a metre to just over a metre at the end of the field trial, (wind data supplied by FFA).

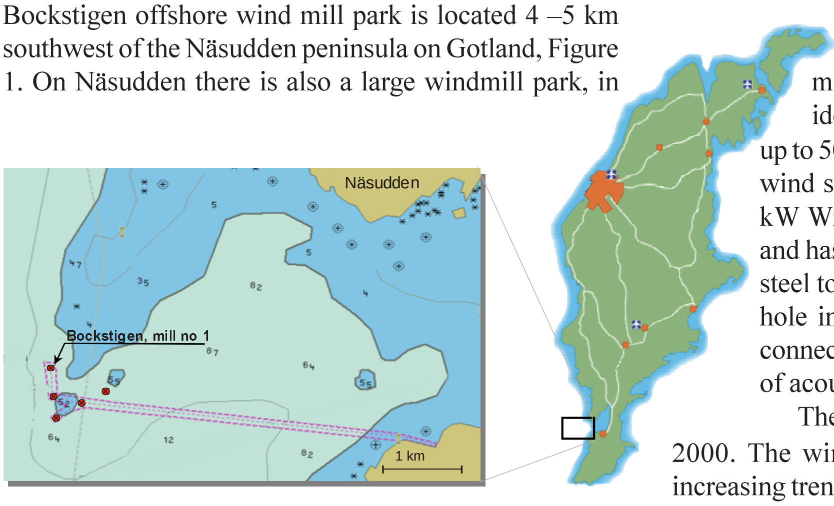

Figure 1. Bockstigen offshore wind mill park is located 4 – 5 km southwest from the Näsudden peninsula on Gotland. The measurements were carried out west of Bockstigen number 1. Indicated in the map is also the power cable connection to the mainland, (the red dotted lines).

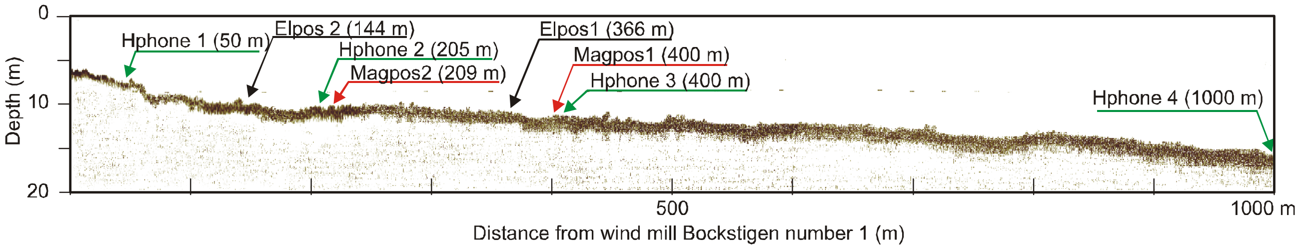

Figure 2. The bottom profile at the studied area, outside mill number 1 at Bockstigen. The positions of the sensors are indicated, where Hphone 1-4 are the four hydrophones. Elpos 1, 2 are the two positions of the electrode and Magpos 1, 2 are the two positions of the magnetometer.

All the measurements, including hydroacoustic noise as well as electrical and magnetic radiation, were concentrated in the water west off the mill. The water depth is around 6 m near the mill and increases smoothly to 17 m at a range of 1000 m, see bottom profile Figure 2. The bottom material consists mainly of gravel on lime stone. There were no considerable stratifications in the water sound speed profile observed during the period of the measurements.

2.1 Hydroacoustics

Hydrophones were deployed at fixed positions at the distances 50 m, 200 m, 400 m and 1000 m from the wind mill, Figure 2. The four positions were along a straight line westwards from the tower. Each hydrophone was placed two metres above the sea bottom.

The hydrophones used were of type Brüel & Kjær 8101, with sensitivity –184 dB rel 1 V/µPa in the range 1 Hz – 10 kHz. Each sensor signal was preamplified and transmitted to the tower by a separate cable. The recording equipment was established on the working platform of the windmill, Figure 3. The data were low-pass filtered at 1 kHz and recorded with a sampling frequency of 5 kHz. A few complementary recordings were low-pass filtered at 40 Hz. Data sets were recorded both days with the mill in producing mode, unfortunately with limited variations in wind conditions. Some data sets were recorded when the rotation was stopped and some data when the mill was in the start-up process. The duration of each recording was typically 60 seconds.

To get a better range estimation between the tower and the four hydrophones an underwater transducer was deployed close to the tower. Chirp pulses, 100 – 1000 Hz, were used for this purpose. In addition four continuous waves signals, 65 Hz, 135 Hz, 260 Hz and 590 Hz were transmitted. The aim was to obtain a data set suitable for transmission loss analysis at longer distances. Analysis of these data is not included in this pilot study, but is available if further modelling work concerning larger mill constructions located on other places in the Baltic Sea is considered.

Three geophones, two horizontal and one vertical, were mounted on the tower to register its vibrations. The geophones were attached to the tower at the platform level, 5m above the sea surface. The type used, Sensor SM-4, has a low frequency cut-off around 4 Hz. Signals from the geophones were recorded in parallel with the hydrophones at one occasion during the measuring period.

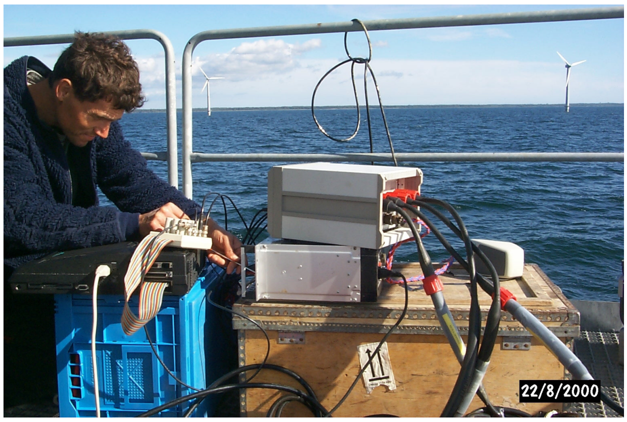

Figure 3. The four hydrophones were simultaneously recorded with the sampling equipment placed outside on the working platform at Bockstigen 1. The wind mills Bockstigen 2 and 3 can bee seen in the background.

2.2 Electromagnetics

The electrical field was sampled by a 2-axis electrode sensor equipped with graphite-fibre electrodes [7], Figure 4. The signals detected by these electrodes were amplified 86 dB (in a frequency band between 5 mHz – 1.1 kHz) before they were low-pass filtered at 1.2 kHz and finally sampled by the A/D converter at a sampling frequency of 2.5 kHz. The 2-axis sensor was located on the bottom at a distance of 366 m from the tower (Figure 2, Elpos1), and after an initial measuring period, it was moved to a second location 144 m from the tower (Figure 2, Elpos2). The two horizontal components of the electric field was hereby sampled at two locations with a precision of 10 nV/m (-40 dBμV/m). The orientation of the sensor was unknown in both cases.

The magnetic field was detected by a 3-axis Bartington fluxgate magnetometer (Figure 4). This sensor was also placed on the bottom, first at a primary location 400 m from the tower (Figure 2, Magpos1), and then at a second location 209 m from the tower (Figure 2, Magpos2). The signals from this sensor were split into 6 channels; 3 direct channels of the total magnetic field (B_x,B_y,B_z) and 3 channels which were zeroed at some instance t_0 after which the residuals ($B'_i = B_i - B_i(t_0)$, i = {x,y,z}) were amplified 24 dB and finally low-pass filtered at 10 Hz before recording, cf. Figure 5. For simplicity and synchronicity the same sampling rate as for the electrical field was used. The precision of the magnetic field measurement is better than 0.1 nT at 10 Hz. The orientation of the sensor in the magnetic field was initially unknown. From independent measurements the vertical component was known to be 47.4 μT and by that the total measured field was orientated by rotation of the axis.

Figure 4. The 2-axis electrode sensor is the cross. The smaller Bartington fluxgate magnetometer is here under preparation.

Figure 5. The registrations of the electrical and magnetic field were performed from the inside of the mill tower.

3. Results

3.1 Hydroacoustics

Spectral levels

For each data set, power spectral densities were estimated by averaging power spectra from 60 equal data frames. The time duration of each window was one second, yielding an analysis bin-size of 1 Hz. We have analysed the frequency band 1 – 1000 Hz. Figure 6 shows results from the four hydrophones, plotted in different colours, when the propeller rotates in a light wind at 4 – 5 m/s blowing from 268°. It can clearly be seen that the noise levels are highest at the hydrophone closest to the mill, at a distance of 50 m. Some of the peaks, for instance 270 and 312 Hz, appear also at the distance of 200 m. At 400 m a small peak at 312 Hz is visible but most of the peaks have disappeared down to the background noise level. At the distance of 1000 m it is not possible to detect any peaks at all.

In the low wind speed around 5 m/s the efficiency of the wind mill is very poor and the power output is at the lowest level, see Figure 7. Unfortunately all our measurements were performed with rather light wind conditions, so we cannot make a statement of how the noise levels increase with higher wind speed.

Figure 8 shows the results from a measurement when Bockstigen 1 was stopped, the wind conditions are similar to the case presented in Figure 6. During the measurement the other four mills at the Bockstigen park and the main part of the mills at Näsudden were rotating. It is uncertain to what extent these more distant wind mills influence the background noise level. The closest distance between Bockstigen 1 and 2 is for instance only 400 m. From a comparison to Figure 6 it is obvious that high noise levels at distance 50 m and all clear peaks caused by a working mill Bockstigen 1 do not appear at all in Figure 8. The water movements affecting the hydrophones at the shallow water depth explain the high noise levels at the lowest frequencies.

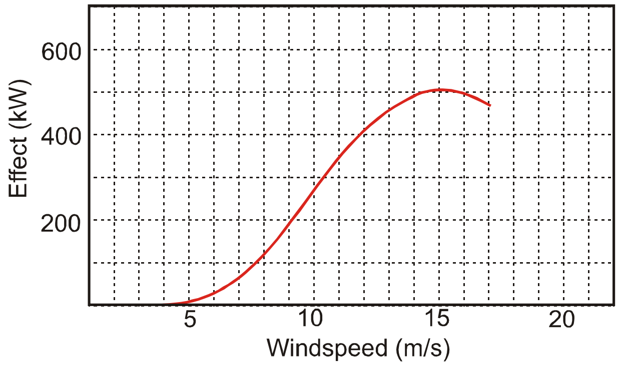

Figure 7. Effective output for Wind World 500 kW, depending on wind speed.

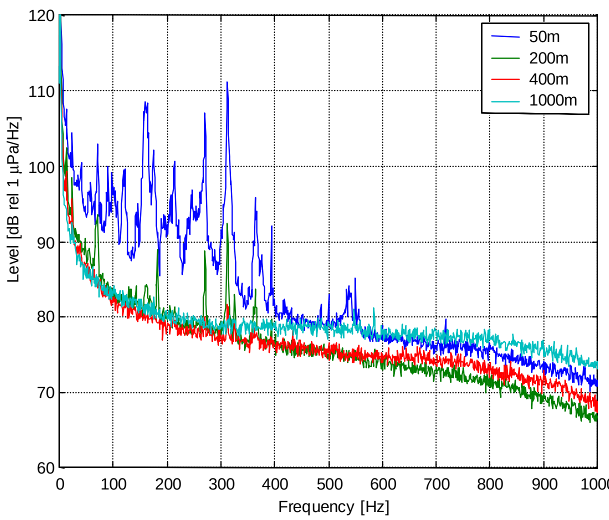

Figure 6. Spectral levels at the distances 50, 200, 400 and 1000 m (different colours) from Bockstigen 1. The mill is here rotating in a light wind at 4 – 5 m/s.

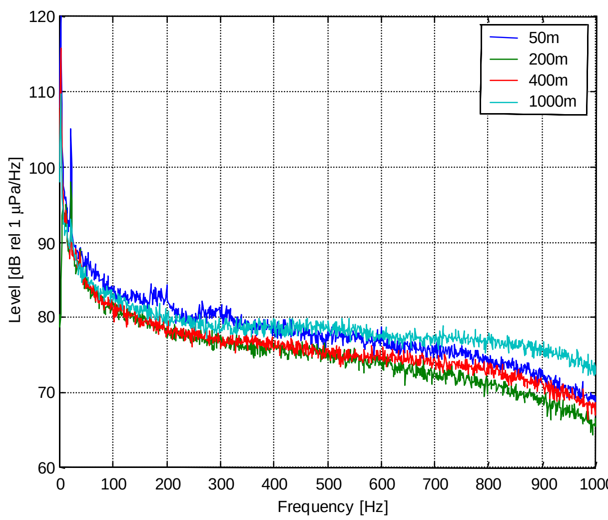

Figure 8. Spectral levels at the distances 50, 400 and 1000 m (different colours) from Bockstigen 1 when the mill is stopped. The wind speed is 4 – 5 m/s, (similar to Figure 6).

During the two days there were only small variations of the wind conditions and generally light winds, 4 – 7 m/s. When we compare the analysis results from different occasions in the period we can observe some small variations in the hydroacoustic levels. An example of such variation between two occasions with similar wind conditions is shown in Figure 9.

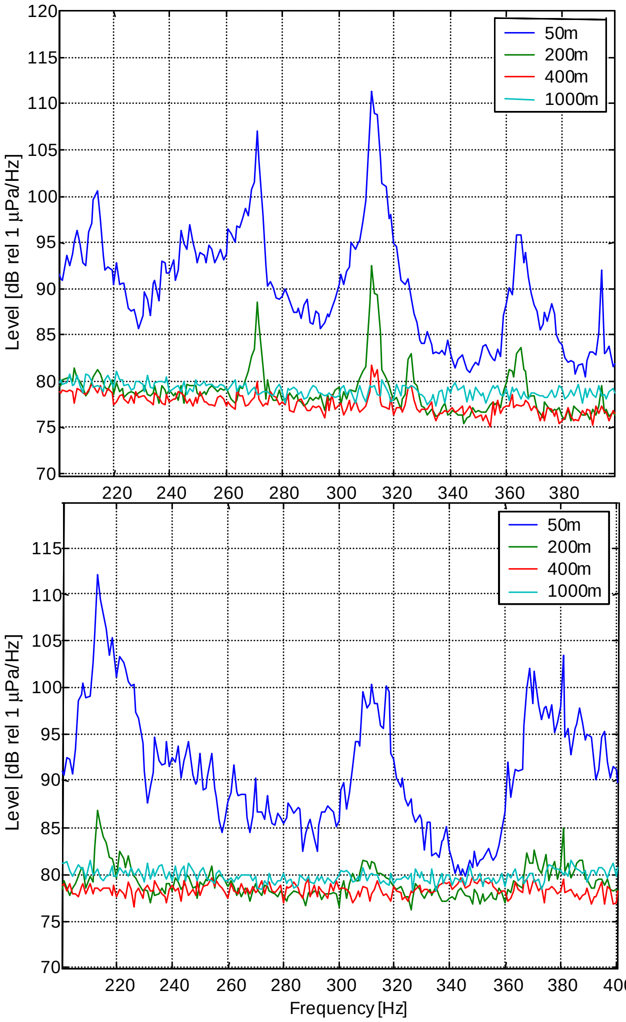

Figure 9. Spectral levels in the frequency range 200 – 400 Hz from two occasions during the measuring period, August 22 (upper) and August 23 (lower). The wind conditions were similar, 4 – 5 m/s blowing from 268 - 286°.

Figures 10 and 11 show two examples of how the range attenuation of the mill noise-levels can vary for different frequencies. Plotted in Figure 10 are the spectral levels for a single frequency, 213 Hz, from seven different measurements, four of these with a rotating mill and the other three with the mill stopped. The peak of 213 Hz, produced by the mill, is above the background noise level at the distance 50 and 200 m. At the distance 400 m the frequency component has disappeared in the ambient noise. In Figure 11 the corresponding range-dependent attenuation for the frequency 312 Hz is plotted. Here we can see that the mill-produced frequency of 312 Hz is over the background noise level at the distance of 400 m in two of the four measurements where Bockstigen 1 mill is rotating.

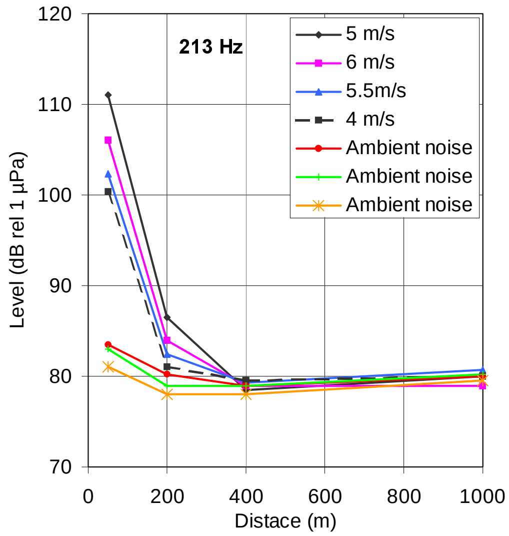

Figure 10. Comparison between seven different data sets for the spectral levels at 213 Hz. Three of these measurements were carried out when the mill Bockstigen 1 was stopped, (ambient noise). The wind speed was in the range 4 – 6 m/s in all seven cases.

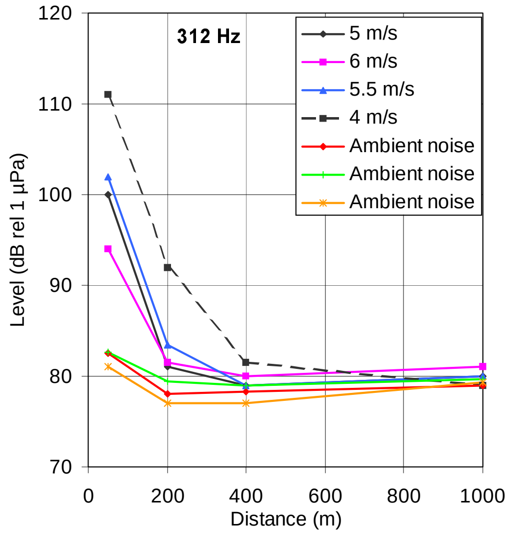

Figure 11. Same as Figure 10 but for the frequency 312 Hz.

As mentioned earlier, we can not exclude that the observed background noise level is affected by the other four mills at Bockstigen and the large mill park on Näsudden. In order to examine if there are frequency components in the water when mill number 1 was stopped, coherence estimates were calculated using hydrophone 1 (50 m from the mill) as a reference. Figure 12 shows the results from one of the background noise measurements, where the mean coherence of two low frequency components appears. The two harmonic frequencies, 12 and 24 Hz, can be seen in the coherence between hydrophone 1 and 2 (50 m and 200 m) as well as between hydrophone 1 and 3 (50 m and 400 m). Between hydrophone 1 and 4 (50 m and 1000 m) the coherence shows up for 24 Hz only. Analysis of other data sets of background noise shows similar results, however with some minor variation of the detected frequencies. These results emphasize that there is an unknown source, besides Bockstigen 1, which generates low frequency components in the measured ambient noise. On the other hand we cannot for certain draw the conclusion that the source is distant mill noise. Other possible sources can for instance be distant ships and activities along the shore of Gotland.

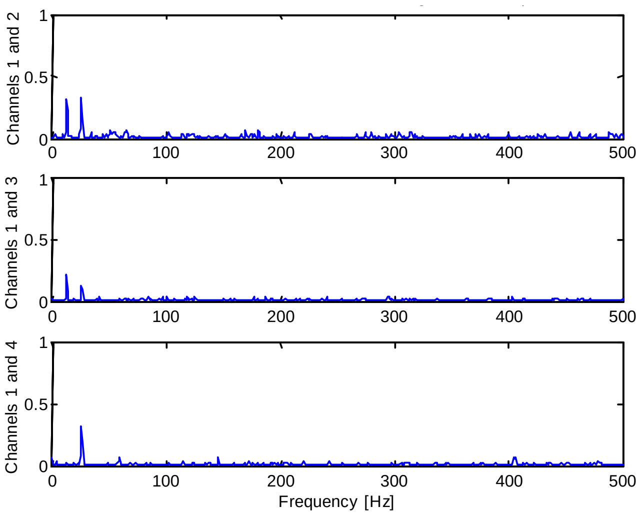

Figure 12. The mean coherence between the hydrophones, calculated from a background noise measurement. Upper; the coherence between hydrophone 1 and 2, (50 m and 200 m). Middle; the coherence between hydrophone 1 and 3, (50 m and 400 m). Lower; the coherence between hydrophone 1 and 4, (50 m and 1000 m).

3.2 Electromagnetics

Signal contents

The signals of the 2-axis electrical-field sensor at the primary location, Elpos1 (366 m away from the wind mill) are shown in Figure 13a where the two records correspond to the two components of the horizontal electrical field in µV/m. The black line corresponds to the signal of a 10-Ω termination of the amplifier which thus gives a measure of the signals picked up (within the tower) by the amplifier, filters and the sampling device. The signal content in the frequency domain is shown in Figure 13b and c, graphed with a logarithmic and a linear frequency scale, respectively. The low frequency part of the signals (<100Hz) is about the same for the two components with a small characteristic spectral broad peak around 8 Hz. This is the well know Schumann-resonance effect and is a consequence of tropical thunderstorms exciting EM-waves in the equatorial wave guide. The small spikes just above 10 Hz are visible in the 10-Ω termination record, which indicates that this frequency component is from the recording equipment. A considerable amount of the energy of the signals is from the 50 Hz power supply and its higher harmonics. From the linear frequency graph c it is seen that the higher frequencies (300 – 1000 Hz) also contain a large part of the energy. Since this spectral shape also partly is present in the 10-Ω termination record it is most probably due to vibrations or noise generated within the wind mill and is not a result of a propagating electrical fields detected in the water.

As for the magnetic field around the wind mill, disturbances of the total field (B_x, B_y, B_z) are impossible to detect with the present accuracy of the magnetometer in combination with the A/D converter's dynamical range, Figure 14a. The vertical component of the magnetic field, B_z, can be fitted to the known value of 47.4 µT through a rotation of the three magnetometer records. This manoeuvre makes it feasible to compare B_z as well as the total field |B| at the two locations (Magpos1 and 2), which otherwise had been impossible. The frequency content of the magnetic field has to be limited to the 24-dB amplified (but 10-Hz low-pass signal), shown in the time domain for location Magpos1 in Figure14b and the spectral domain in 14c. It is recognised that the horizontal components contain oscillations with a period between 2-5 seconds. The amplitude of these are around 10 nT, which disqualifies them as motionally induced by waves [8]. Instead, these fluctuations are due to microbaroms and microsesmic activity due to distant storms, feeding pressure energy into the atmosphere and the sea bottom via the wave field, [9]. The short time span of the record, however, prevents these fluctuations to be significant features of the spectrum in Figure 14c. The peaks just above 10 Hz have leaked through the low pass filter and have probably been generated by either the filter or the amplifier.

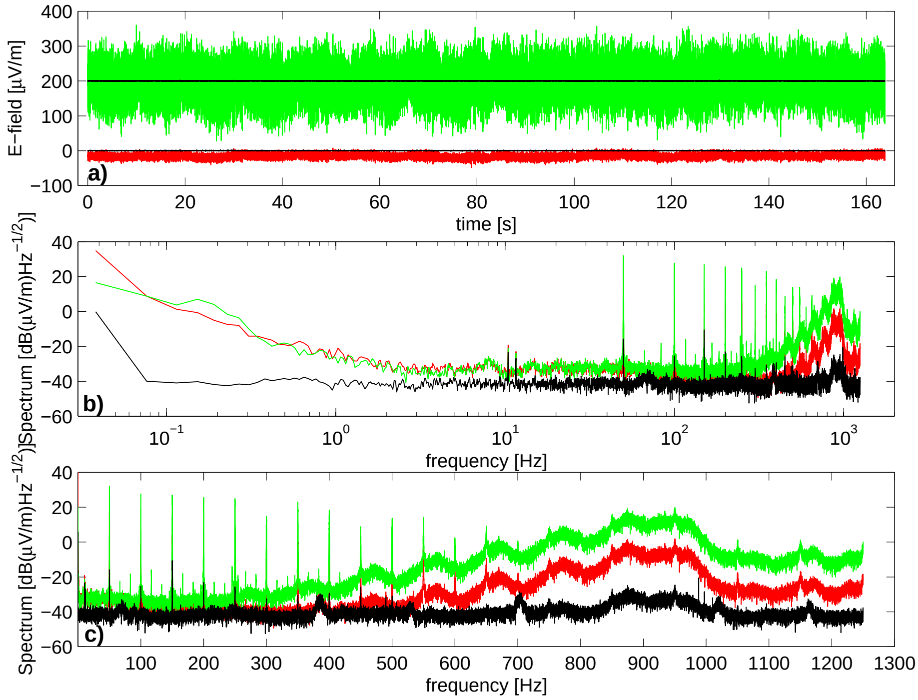

Figure 13. 160 s recording of the electrical field at location Elpos1 (366 m).
a) *Time series where the two signals denote the two perpendicular components of the horizontal electrical field. One channel has been offset with 200 $\mu V/m$ for clarity. The black line shows the background noise level over a 10-Ω resistor.*
b) *Logarithmic spectral representation. The black curve shows the noise level.*
c) *Linear spectral representation. The black curve shows the noise level.*

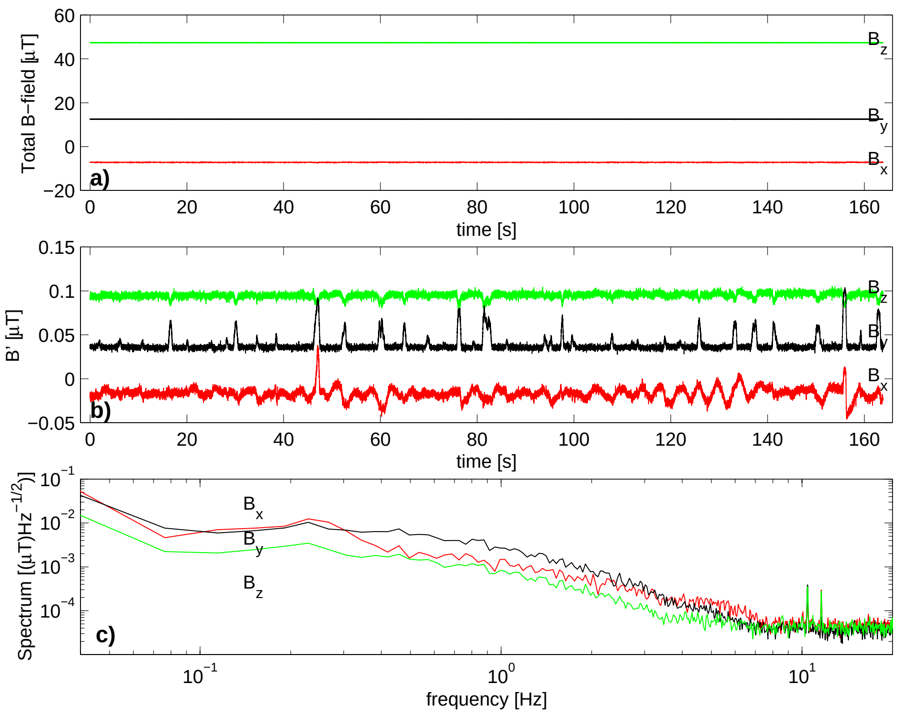

Figure 14. 160 s recording of the magnetic field at location, Magpos1 (400 m).
a) *Time series of the three axes of the total field.*
b) *Time series of 24 dB-amplified fields.*
c) *Spectral representation of the three axes of the amplified signals from panel b.*

Wind Mill on/off

When Bockstigen 1 was switched off, i.e. the rotation of the propeller stopped, the background noise levels were measured. As mentioned earlier in the hydroacoustic part the other four mills at the Bockstigen park were still rotating during these recordings. Figure 15a shows the sequence when the mill first is halted at time 200 s and then started again at time 620 s. The length of the start-up process is dependent on wind speed, but it is seen that the variability of the signals increases in two steps. These instances occur when the mill is first activated (but not producing any electricity) and when the mill is connected to the electrical power grid supplying it with electricity (at time 740 s). The spectral content is not significantly affected, Figure 15b, except for a general trend of increasing energy levels over the whole frequency interval. The most pronounced increase in energy is, not unexpectedly, located at 50 Hz and its harmonics and in the higher kHz vibrational noise.

The corresponding response (as that of the electrical field) is not discernible in the magnetic field, Figure 16a. Here the off-, startup- and producing-periods, clearly identified from the electrical field, are marked in a similar manner, whereas no clear changes are visible in any of the three magnetic field components. The corresponding frequency spectrum does not show any prominent peaks or identifiable features.

When the sensors are moved to their second locations, (Elpos2 and Magpos2) the distance from the tower is decreased and higher signal levels are expected. The electrical field at the second location is shown in Figure 17a where the same off-, startup- and producing-periods are illustrated. When comparing to the first location, Figure 15, the variability seems much smaller. This is due to lower levels of the 50 Hz power frequency and is probably a result of better isolation and connection to the amplifier. This was adjusted between the two measurements and indicates that not all of the 50 Hz found at Elpos1 originated from the water was induced just before the amplifier. The general levels of the spectrum are, higher for Elpos2 than Elpos1 and the difference between the two is shown in Figure 18 as a function of frequency. Based on a theoretical (spherical) decay rate of the electric field, proportional to the inverse squared distance, the fields are expected to decrease around 16

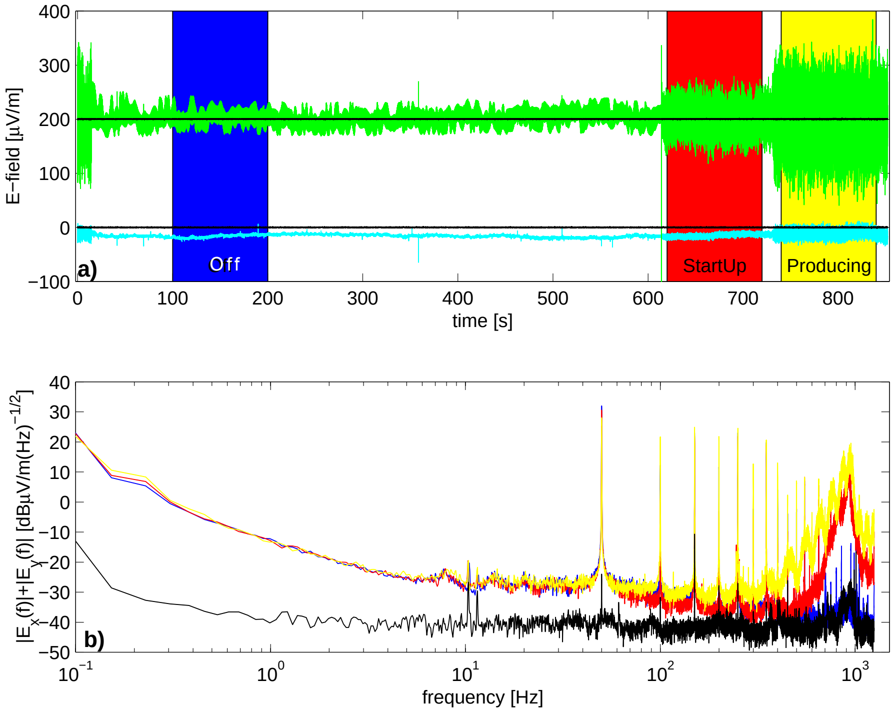

Figure 15. 900 s recording of the horizontal electrical field during halt-, startup- and producing-periods at location Elpos1 (366 m).
***a)** Time series where the three stages are marked by different colour.*
***b)** Spectral representation where the displayed quantity is defined as the sum of the absolute values of the horizontal components of the electrical field in the frequency domain, i.e. $|E_x(f)| + |E_y(f)|$. Each stage is represented by a curve with corresponding colour. The black curve shows the signal detected by the 10-Ω termination.*

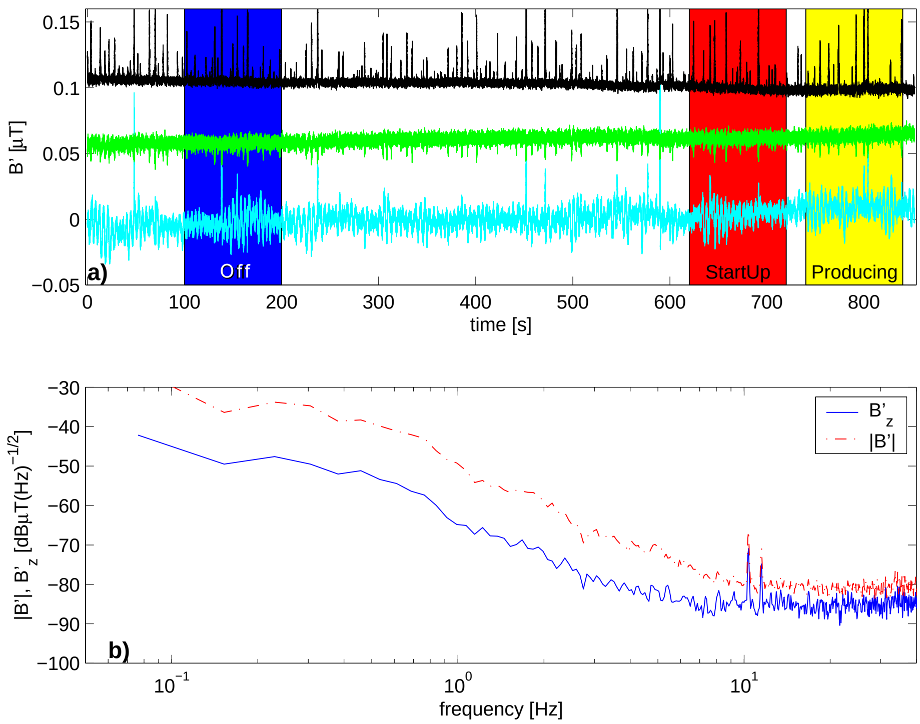

Figure 16. 900 s recording of the 24 dB-amplified part of the magnetic field during halt-, startup- and producing-periods at the location Magpos1 (400 m).
***a)** Time series where the three stages are marked by different colour. The three curves are denoted (from the bottom of the panel) B'_x, B'_y and B'_z, respectively.*
***b)** Spectral representation of the vertical component of the magnetic field B'_z and the sum of the absolute value of all three components in the frequency domain, i.e. $|B'_x(f)| + |B'_y(f)| + |B'_z(f)|$.*

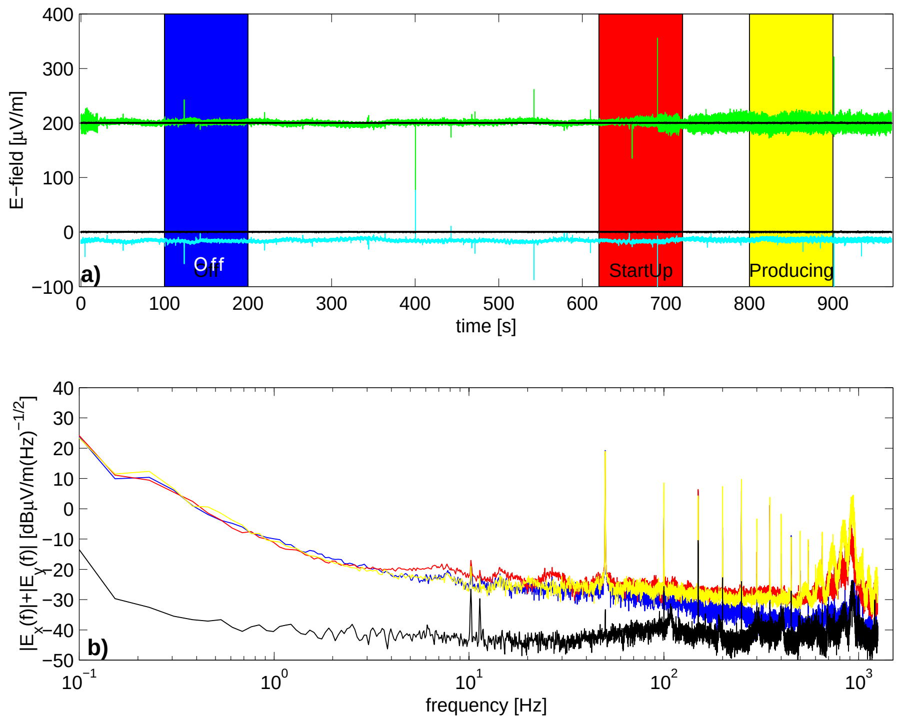

Figure 17. 1000 s recording of the horizontal electrical field during halt-, startup- and producing-periods at the location Elpos2 (144 m).
***a)** Time series where the three stages are marked by different colour.*
***b)** Spectral representation where the displayed quantity is defined as the sum of the absolute values of the horizontal components of the electrical field in the frequency domain, i.e. $|E_x(f)| + |E_y(f)|$. Each stage is represented by a curve with corresponding colour. The black curve shows the signal detected by the 10-Ω termination.*

dB between Elpos2 and 1. As a comparison a cylindrical wave field is expected to decay as the inverse distance, i.e. 8 dB between the two positions. From Figure 18 it seems like the lower part of the frequency band attenuates slightly more than the upper part, i.e. > 1 Hz and that these attenuation levels conform to cylindrical decay rates. Higher up in the frequency band, around 10 Hz, the attenuation levels in producing modes does not reach higher than a few dB. It is also recognised that during the producing stage, the mill affects the surrounding area to a lesser degree than during the startup period. This is probably due to the fact that the mill consumes electricity during startup, in order to accomplish a faster acceleration to optimal productive rotation-conditions.

The magnetic field at Magpos2 does not qualitatively differ from that of Magpos1, cf. Figure 19a. There is a smaller gap in spectral energy content between the total magnetic field |B| and the vertical component B_z as seen from Figure 19b, in that the two spectra here are almost identical. The difference in spectral content between the two locations is shown in Figure 20. It is basically only the vertical component of the magnetic field that is changed when moving closer to the mill. Since the magnetic field follows the same basic rules as the electric field, a 6-12 dB attenuation is expected in a manner analogous to the electrical discussion (though with a different magnitude due to the shorter distance for the magnetic case). Apparently the vertical component of the magnetic field is attenuated according to a cylindrical propagating field at lower frequencies and reaches the spherical attenuation levels for frequencies in the range 1-3 Hz (the rotation rate of the propeller for ideal conditions).

It can therefore be concluded that the magnetic field is sensitive to the motion of the mill wings, whereas this was not directly seen for the case of the electrical field. With the present measurement equipment it was impossible to study the higher frequency part (> 10 Hz) of the magnetic field. In general it is expected that the effects will be stronger in the magnetic field than in the electric counterpart, which was sensitive to the 50 Hz power frequency and the frequency band up to 300 Hz. The attenuation of the electromagnetic fields suggests that the propagation is something in-between cylindrical and spherical waves, depending on frequency. By adopting inverse distance attenuation and assuming cylindrical spreading, the electrical field is seen to be detectable (>10 nV/m) up to a distance just below 1 km for the frequency range 10 – 300 Hz. Harmonics of the power grid frequency 50 Hz may be detectable much further away. As for the magnetic field frequencies around 1 Hz may be detected (> 0.1 nT) up to 800 m from the source, whereas slightly lower frequencies (~0.5 Hz) may be encountered at distances just over 1 km.

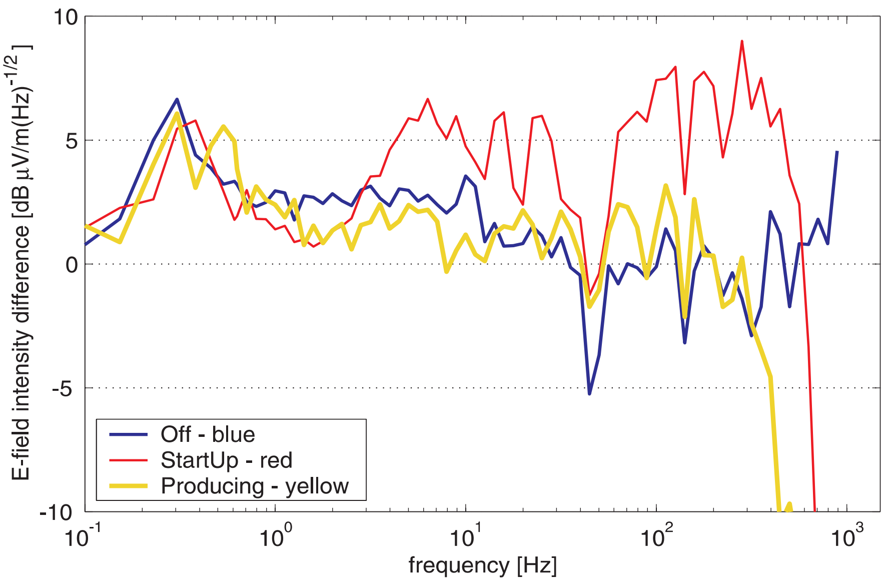

Figure 18. Difference between the energy content of the horizontal components of the electrical field at the two locations, Elpos1 and Elpos2, as a function of frequency. The three stages (Off, startup and producing) are colour coded according to Figure 15-17.

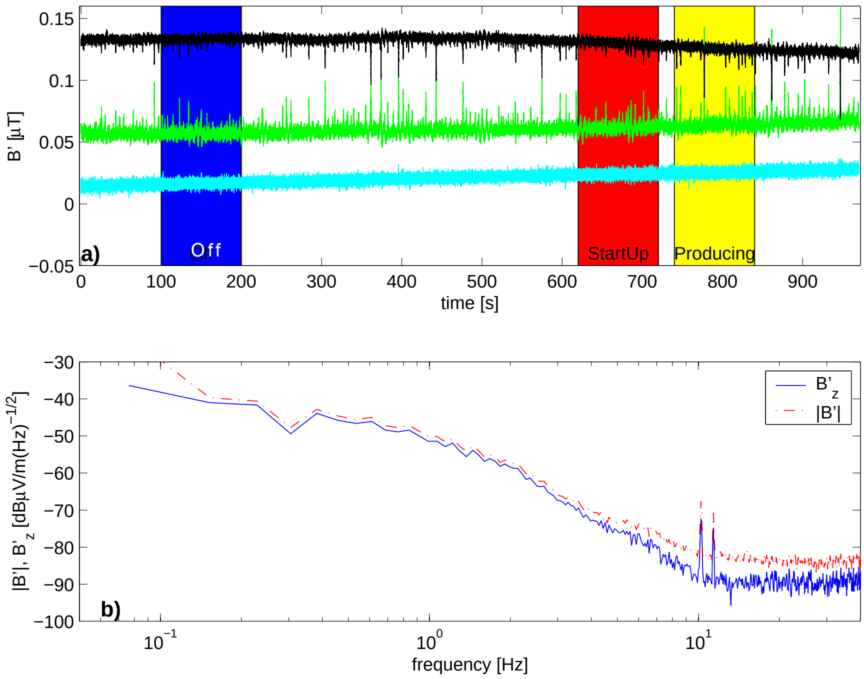

Figure 19. 1000 s recording of the 24 dB-amplified part of the magnetic field during halt-, startup- and producing-periods at the location Magpos2 (209 m). ***a)*** *Time series where the three stages are marked by different colour. The three curves are denoted (from the bottom of the panel) B'_x, B'_y and B'_z, respectively.* ***b)*** *Spectral representation of the vertical component of the magnetic field B'_z and the sum of the absolute value of all three components in the frequency domain, i.e. $|B'_x(f)| + |B'_y(f)| + |B'_z(f)|$.*

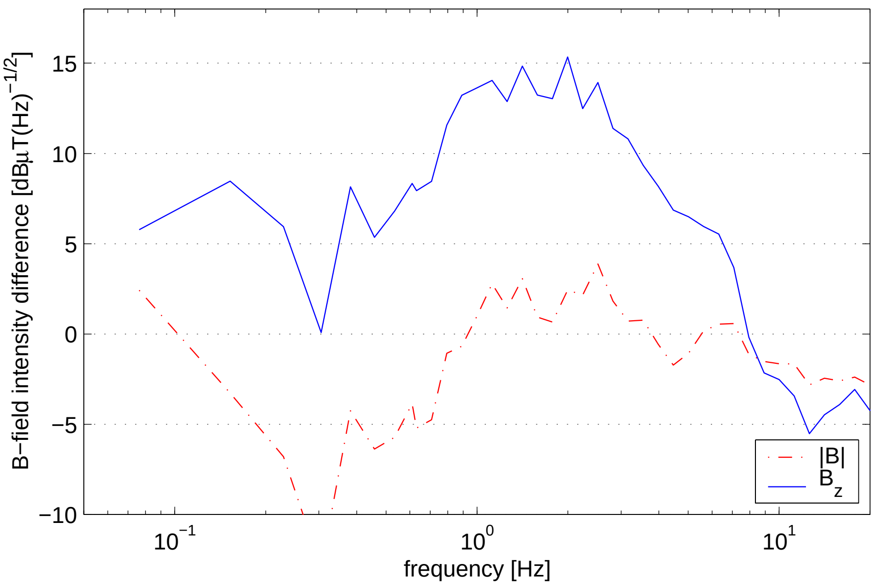

Figure 20. Difference between the energy content of the vertical component of the magnetic field B'_z and the sum of the absolute value of all three components in the frequency domain at the two locations Magpos1 and Magpos2.

4. Conclusions

4.1 Hydroacoustics

The wind power station at Bockstigen generates hydro-acoustic noise and tones in the studied range up to 1 kHz.

From these measurements it is not possible to make a statement on how wind mill generated noise will affect the performance of naval surveillance systems. The measurings are limited to be performed during operating conditions with low wind-force and consequently with low output from the power stations. The hydroacoustic noise pattern generated from the mill might be different at other wind forces and wind directions.

It is difficult to state to which extent the acoustic backgrund noise level measured by us is affected by the windmills in the neighbourhood, i.e. the other four stations at Bockstigen and about a hundred land-based ones at Näsudden.

Obviously the environment in which the sea-based power stations are built is of vital importance regarding the hydroacoustic noise and disturbances. If the power station is embedded into the rock by means of drilling, tied to moraine, built on rock or clay it will most certainly have an influence on the sound pattern. Furthermore there will be an influence from the topography and nature of the seafloor with regard to the bottom sediments.

Until now only a few hydroacoustic measurements have been performed at other types of power stations. A cautious comparison between these results indicates that the field of interference might differ dependent on the construction. The interference pattern for larger power stations and ”wind power forests” erected at sea is still unknown.

4.2 Electromagnetics

The fields that could cause disturbance of the electro-magnetic sensor equipment are mainly of alternating field character (AC). This means that direct current (DC) fields from high-voltage power cables should not represent any direct threat of disturbing to these facilities. On the other hand, direct influence derives from rotating parts in gearboxes and generators, and also from transformers that raise the voltage to transporting levels that are favourable with regard to the effect. This implies that future wind power stations of the type manufactured by e.g. ABB (Windmill) could, after improvements and reduction of the number of mechanical parts, be considered more suitable for sea-based power production near zones that are delicate from military aspects.

The measurements made at the relatively small power station at Bockstigen 1 show that alternating fields in the frequency interval below 10 Hz can be found within an area of up to 1 km from the power station. However, it should be emphasized that this distance will increase if advanced signal processing like reference filtering is to be used, in which case a larger number of sensors and a considerably higher measuring input would be required. One should also remember that there are measuring instruments with much higher precision than those used during the measuring period in question. The distance measured up should accordingly be looked upon as a typical lower limit within which activeness and possible disturbing of electromagnetic sensor equipment might occur.

As in case of the acoustic noise it is not known whether a low wind velocity (and consequently the effect) has an influence on the radiated electromagnetic energy. Further, one cannot give a general statement about all types of wind power stations as they are all of different designs and different technical solutions. As a conclusion a statement about safety ranges given today, with only one limited measurement, would be unspecified. In order to obtain a more exact characterization it is obvious that additional measuring tests need to be performed .

5. Recommendations

This pilot study with implications for underwater surveillance systems has shown that sea-based wind power stations generate hydroacoustic and electromagnetic disturbances. However, it is still not clarified if these disturbances might get such proportions that they could affect the performance of passive naval surveillance systems used by the Swedish Armed Forces. Therefore we would suggest that a complementary measuring test should be made in order to establish the effect of different wind-forces compared to an undisturbed reference noise background. Such a test may very well be performed at another and larger wind power station in contrast to Bockstigen.

Further, we recommend that the wind companies together with the Swedish Armed Forces support or possibly direct the development of silent wind power stations with low radiation.

The performance of existing computer models for predictions of hydroacoustic, as well as electromagnetic propagation, should be evaluated to find out how applicable these models are in environments were wind stations are built. Reliable modelling work would most certainly be a support in projecting new off shore wind power stations.

6. Acknowledgement

Vindkompaniet, the owner of the windmills at Bockstigen, is acknowledged for our access to the mill. Ulf Skotte for valuable help before, under and after the field campaign. HMS Urd and her crew assisted during the work at sea. FFA for providing meteorological data used in the study. This pilot study was made under a contract with FMV.

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