Propagation of Harmonic Emission from the Turbines through the Collection Grid to the Public Grid

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***Abstract*—This paper addresses the harmonic emission from a large off-shore wind farm. An overview is given of the issues, where a distinction is made between frequencies below and above 2 kHz. Three different approaches are presented: a simplified mathematical model; a more detailed mathematical model; and measurements and the point of connection for an off-shore wind farm. It is concluded from both models and measurements that the emission is small for frequencies above a few kHz. However, specific resonances at higher frequencies involving the power transformers, when coinciding with switching frequencies or harmonics of switching frequencies, could result in high emission even at these high frequencies.**

Keywords – wind power; wind-power integration; power system harmonics, collection grid, power quality

I. INTRODUCTION

Most modern MW-size wind turbines are equipped with power electronic converters. Such converters are known to produce harmonic distortion, i.e. the current waveform is not sinusoidal. The level of distortion depends strongly on the kind of converter technology; measurements have shown that the emission from individual turbines is rather small but that the spectrum contains frequencies that are normally not present in the power system [1,2,3,4].

Section II of this paper presents the harmonic issues related with wind farms, for frequencies up to 2 kHz: the emission from individual turbines and the propagation through the collection grid. Frequencies above 2 kHz are treated in Section III. Simulation results and measurements for an existing off-shore wind farm are presented in Section IV and Section V, respectively.

II. HARMONICS UP TO 2 KHZ

A rather complete framework exists for managing harmonic voltage and current levels in the power system up to about 2 kHz. The upper limit somewhat varies between parts of the world and between different standards and regulations.

Overall, for harmonics up to 2 kHz, compatibility levels are defined in IEC 61000-2-2. These levels are primarily a reference for the setting of emission and immunity levels of equipment as part of the electromagnetic compatibility framework set up by IEC. As equipment is connected to the power system, these levels are also an indirect requirement setting the highest levels of voltage distortion that is acceptable at the equipment terminals. This has been formalized in the European voltage-quality standard, EN 50160 [5] and in the national regulation in many European countries. An overview of such regulation is given in [6].

Measurements on several modern wind turbines show low levels of emission for individual turbines. The emission of a wind park as a whole is however not equal to the sum of the emission from the individual turbines. Two phenomena impact the total emission:

i. Different turbines inject harmonics with different phase angles and with different variations in magnitude. As a result the emission from multiple machines is less than the sum of the emission from the individual machines. This phenomenon is called “aggregation”.

ii. Due to inductances and capacitances present in the collection grid, series and parallel resonances occur that increase or decrease the emission levels.

To quantify these two effects, a mathematical model has been defined in [7,8] where a distinction is made between the “individual transfer function” and the “overall transfer function”. The individual transfer function gives the ratio (as a complex number) between the harmonic current flowing into the public grid and the harmonic current emitted by a turbine at a certain location in the collection grid, assuming there are no other sources of emission in the collection grid. The individual transfer function quantifies the second phenomenon, above.

The overall transfer function relates the emission of the park as a whole with the emission from one turbine, assuming that all the turbines are emitting harmonic currents. The overall transfer function also includes the first phenomenon.

The individual and overall transfer functions for a 10-turbine park are shown in Figure 1 and Figure 2,

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respectively. The collection grid consists of two identical feeders with five turbines each. The transformer size is 30 MVA and the total cable length of the collection grid is 3.2 km. The dominant resonance is located slightly below 2 kHz; the individual transfer functions have a maximum around 17 and occur at slightly different frequencies, the overall transfer function has a maximum around 30. The latter means that the emission from the wind park as a whole is 30 times the emission from one turbine, thus 3 times the sum of the emission from all turbines.

Considering random phase angle for the individual sources, which is an acceptable model at this frequency, would result in a total emission that is 3.2 (square root of 10) times the emission from one turbine. The amplification due to the resonance is in that case about 10 times.

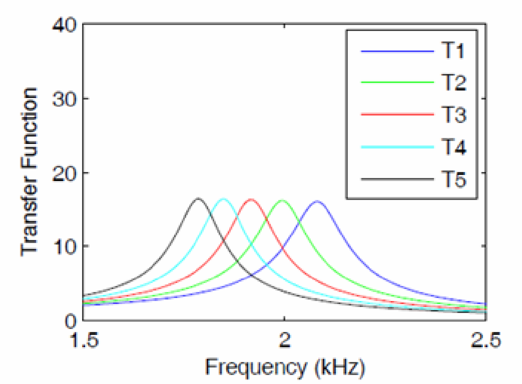

Figure 1. Individual transfer functions for a 10-turbine park; dominant resonance.

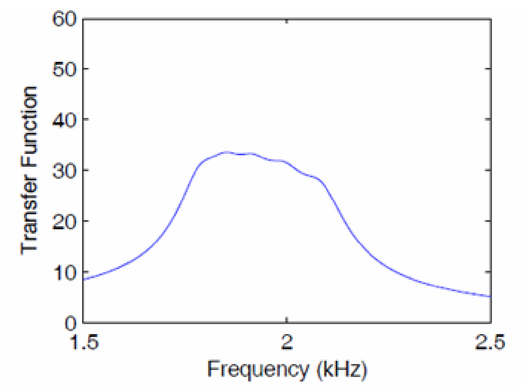

Figure 2. Overall transfer function for a 10-turbine park, dominant resonance.

An important conclusion from the theoretical work is that the emission from a park as a whole can be significantly higher than what would be expected without resonances. The highest amplification takes place around the dominant resonance frequency. The dominant resonance frequency can be estimated from

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

Where C is the total capacitance connected to the collection grid and L the inductive part of the source impedance (mainly due to the impedance of the transmission transformer). To calculate the amplification of the emission around the resonance frequency, a more complicated model is needed however. In such a model, inductance and capacitance of individual components need to be considered.

III. HARMONICS ABOVE 2 KHZ

For harmonic frequencies above 2 kHz, no reference levels or standard emission limits exist. Limits on emission in the range 2 to 9 kHz exist in a number of countries.

Emission from individual turbines is expected to take place at the switching frequency of the power-electronic converter in the turbine and at integer multiples of this switching frequency. The switching frequency varies between manufacturers and types of turbines, but is in the order of a few kHz. It is therefore not possible to neglect the emission from individual turbines at frequencies above a few kHz.

When the switching frequency is close to the dominant resonance frequency mentioned in the previous section, high levels of emission from the park as a whole can be expected. However, beyond the dominant resonance frequency, the overall transfer function decreases very quickly, as is shown in Figure 3. Note that a transfer function equal to one means that the emission of the park as a whole is equal to the emission of one single turbine.

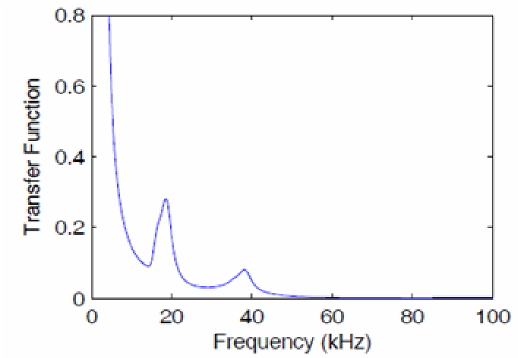

Figure 3. Overall transfer function for a 10-turbine park, high-frequency part.

A conclusion from the theoretical study is that the emission from the park as whole will be small for frequencies that exceed a few times the dominant resonance frequency.

IV. SIMULATIONS

Simulations were performed in a simplified model of an off shore wind farm called Lillgrund located in the south of Sweden. The farm consists of 48 turbines in 5 feeders with a maximum capacity of 3.6 MW per turbine. Simulations were performed using PSCAD; the model used in PSCAD is shown in Figure 4.

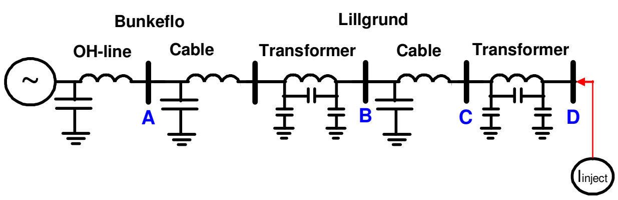

Figure 4. outline of simulation model of one feeder of the Lillgrund wind farm.

Studies of the damping of harmonics were performed by injecting a current at the equivalent place of a turbine at the far end of a feeder behind the step up transformer (0.69 kV) (position D in the figure) and current and voltage were calculated in positions A (130 kV switchgear on shore), B (33 kV switchgear on offshore platform) and C (33 kV after step up transformer at the wind turbine).

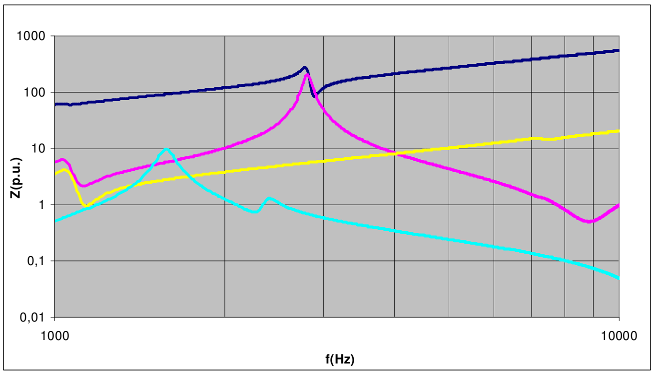

Figure 5. Calculated impedance as a function of frequency at: Pos. A light blue; Pos. B yellow; Pos. C purple, Pos. D dark blue

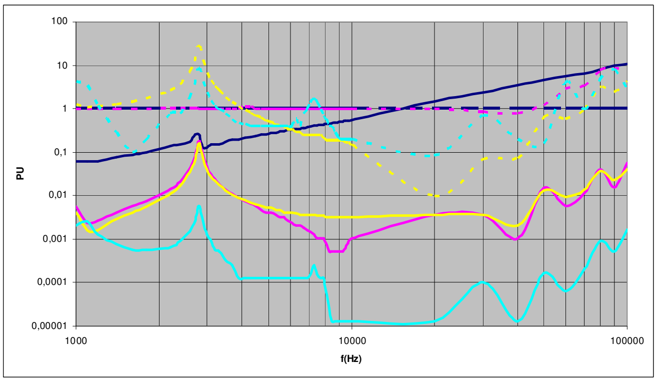

Figure 6. Calculated current, dashed, and voltage, solid line, at different frequencies (1-100 kHz). The current is injected in position D Pos. A light blue; Pos. B yellow; Pos. C purple, Pos. D dark blue.

In Figure 5. and Figure 6. it is seen that there is a resonant frequency at about 2.8 kHz. Due to the resonance, the current for this frequency is larger expressed in P.U. at the positions B and A than the injected current at position D. The dashed light blue curve shows the current in Bunkeflo (Pos. A). When comparing this current to the current at the 33 kV bus in Lillgrund (Pos B) it is seen that there are resonant frequencies in Bunkeflo that are not present at the 33 kV bus, for example at 7.3 kHz. These results imply that measured current levels in different parts of the grid do not necessarily reflect the emission from the turbines, but are due to a combination of emission and resonances. This also implies that all harmonics not necessarily are damped to a low level at a certain distance from the source.

The transfer function from D to A (light blue) is higher than one for 1 kHz. There appears to be a resonance around 1 kHz already. When comparing the simplified mathematical model with the more detailed simulation model, it is observed that there is an increase in transfer function for frequencies above about 20 kHz. This is where the series capacitance (between primary and secondary side) of the transformers starts to play a role. This has not been included in the simplified mathematical model. This could be a problem when in future very high switching frequencies are used. The good news is that these frequencies can be used for power-line communication between the turbines and the grid.

The most important curves from the network-operator viewpoint are the light blue ones (location A). Here amplifications are visible (transfer function greater than 1) around 1000 Hz, around 2800 Hz and above 55 kHz. The latter is not of concern because the turbine is not expected to emit anything at these frequencies. The resonance around 2800 Hz could amplify the switching frequency. Also the one around 1000 Hz could be a concern if there is a significant amount of emission coming from the turbine at those frequencies.

In Figure 6. it is seen that at frequencies above about 5 kHz the voltage distortion can differ by a factor of 100 between voltage levels, when expressed in per unit (i.e. as a fraction of the nominal voltage). That is from 0.69 to 30 kV and from 30 to 130 kV. The current amplitude is however around the same level in p.u. at all the different voltage levels.

In the figure it is also seen that the injected current on the 0.69 kV level is in p.u. the same at the 33 kV level of the transformer up to about 30 kHz. It is not totally clear if this is a correct representation of the transformer at higher frequencies. Some damping through the transformer is expected. Therefore the transformer model should be addressed further to verify this model against measured values.

An important conclusion from the calculations is however that the high-frequency behavior of the transformer can have a significant influence on the total transfer from a turbine to the public grid.

V. MEASUREMENTS

Power quality measurements have been conducted during one year at the 130 kV connection point, Bunkeflo, for the 110 MW offshore wind farm Lillgrund. The simplified connection scheme is shown in Figure 4. The normal short circuit capacity in Bunkeflo is around 1350 MVA. The measurements were performed with three different systems as illustrated in Figure 7.

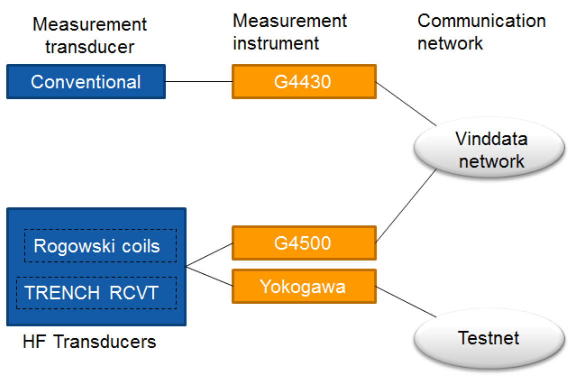

Figure 7. Measurement setup used to obtain the emission from a large wind farm.

Results are shown from a one-week long measurement campaign period. The two Elspec instruments G4430 and G4500 were set with 12 kHz sampling rate and higher resolution than normal. The Yokogawa instrument was set with a sampling rate of 1 MHz. The Elspec instruments measured continuously while the Yokogawa instrument recorded a 200-ms window every 10 minutes.

Some of the variations in active power injected into the public grid and variations in voltage at the connection point, are shown in Figure 8. The active power shows large variations at time scales of one hour and longer.

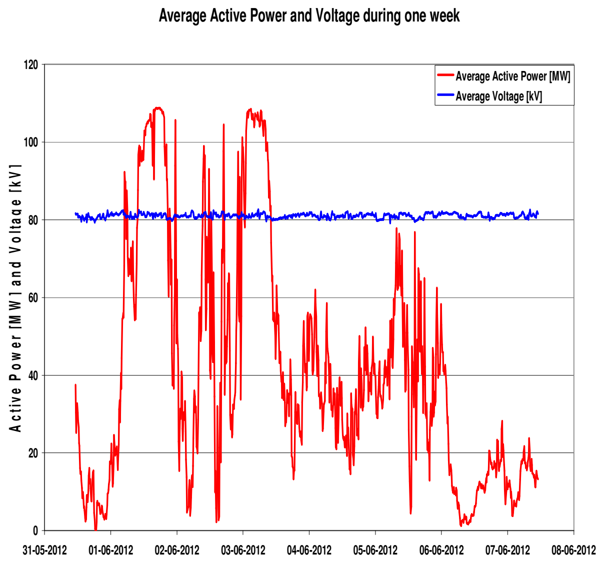

Figure 8. Variations in active power (red) and voltage (blue) at the 130-kV connection point of the wind farm, during a 9-day period.

The harmonics were analyzed up to 150 kHz with the Yokogawa measured data and the HF transducers. A typical spectrum is presented in Figure 9. The spectrum shows that the voltage distortion above a few kHz is very low. The remaining distortion in the spectrum is likely due to quantization noise.

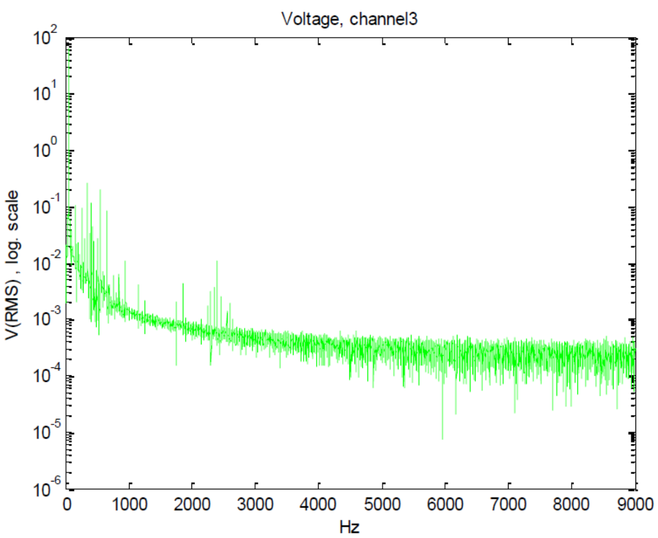

Figure 9. Typical voltage spectrum at the 130-kV point of connection. Note the logarithmic vertical scale.

To be able to illustrate the variations in harmonic voltage during the whole week, special coloured diagrams were created based on a method developed in [8,9]. The results is shown in Figure 10, 3 to 9 kHz, and Figure 11, up to 3 kHz. The time variations of the spectrum are shown in Figure 10. and Figure 11. , where red indicates the highest magnitude and blue the lowest magnitude. It was already concluded from the previous figure voltage distortion is very low above 3 kHz. The same can now also be concluded for the current.

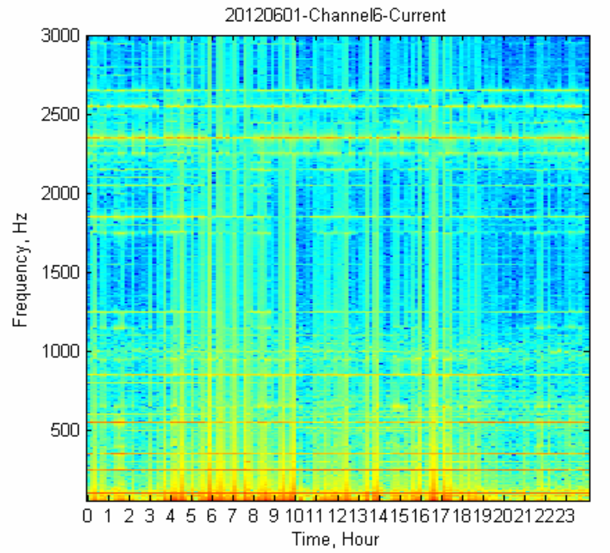

Figure 10. Long-term spectrogram of the current injected into the public grid at 130 kV, during a 24-hour period (horizontal scale); 0 – 3000 Hz (vertical scale).

Below 3 kHz, the strongest emission occurs at the low-order characteristics harmonics, 5, 7 and 11. Also harmonics 17, 19, 23 and 25 are visible, but less strong. A number of narrow-band components are also visible in the current around 2.5 kHz. A comparison with Figure 6 shows that these are most likely amplifications of emission from the turbines due to resonances in the collection grid.

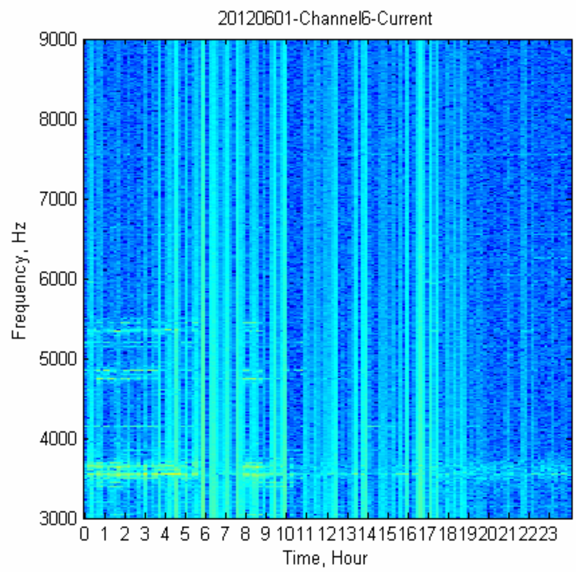

Figure 11. Long-term spectrogram of the current injected into the public grid at 130 kV, during a 24-hour period (horizontal scale); 3000 – 9000 Hz (vertical scale).

Above 3 kHz, some minor emission is present almost continuously around 3500 Hz, and intermittent around 4500 and 5500 Hz. The emission levels above 3 kHz are however much smaller than the ones below 3 kHz.

The spectrogram also shows a number of vertical lines; these indicate broadband emission, likely related with switching actions.

VI. CONCLUSIONS

The emission from individual turbines is small at most frequencies, especially when compared with for example industrial installations. However, emission takes place at some frequencies, interharmonics and above 2 kHz, where the distortion level is normally low in the power system.

Resonances in the collection grid and in the connection between a wind farm and the public grid, can amplify harmonic levels. A theoretical model has been developed to quantify the propagation from the individual turbines to the public grid. The model has been applied to a 10-turbine wind farm. The calculations show that frequencies higher than 2.5 kHz are damped in the collection grid. This would imply that emission from individual turbines at higher frequencies will not reach the public grid.

The simulations for the Lillgrund wind farm indicate a resonance frequency between 2 and 3 kHz. Measurements show a high level of emission in this range, most likely due to current amplification in the grid.

The simulations also indicate that frequencies above a few kHz are strongly damped in the collection grid. Also this is confirmed by the measurements.

The simulations do suggest a possible increase in transfer at frequencies above some tens of kHz due to the capacitive transfer through power transformers at higher frequencies.

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