PROPAGATION OF HARMONIC EMISSION FROM THE TURBINES THROUGH THE COLLECTION GRID TO THE PUBLIC GRID

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ABSTRACT

This paper addressed 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 at 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. Studies, including the propagation through the collection grid, are needed with the connection of any wind park to the grid.

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].

The emission of the park as a whole is determined by the emission from individual turbines and by the propagation through the collection grid. In this paper, we will concentrate on the latter.

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 and in the national regulation in many European countries. An overview of such regulation is given in [4].

PROPAGATION MODEL

Measurements on several modern wind turbines show low levels of emission for individual turbines [1][2]. 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.

Combining these two effects can result in the emission of the park being, at certain frequencies, more than the sum of the emission from the individual turbines.

To quantify these two effects, a mathematical model has been developed in [5] 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 above-mentioned phenomenon.

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.

EXAMPLE

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

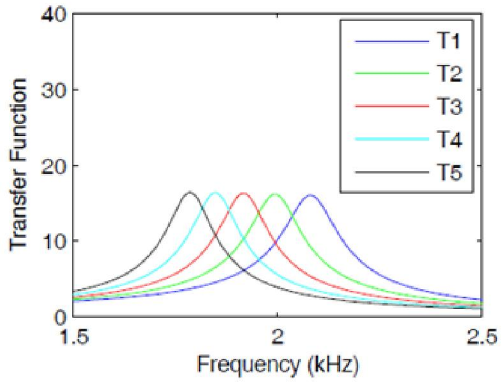

Figure 1. Individual transfer functions for a 10-turbine park; dominant resonance.

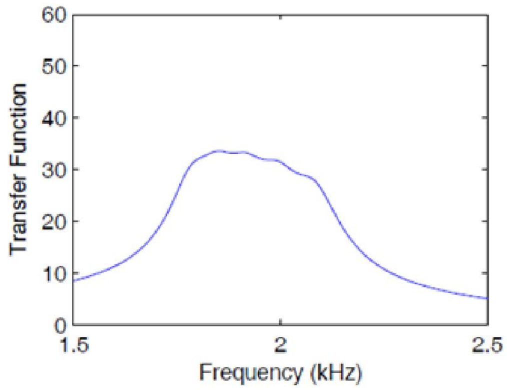

Figure 2. Overall transfer function for a 10-turbine park, dominant resonance.

Considering random phase angle for the individual sources, which is likely to be an acceptable model at these frequencies, 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.

The amplification of the individual transfer function is about 17, as was mentioned before. The low amplification of the overall transfer function is due to the resonance frequency being different for the different individual transfer functions. It is thus important to consider the individual transfer functions when estimating the emission from a wind park as a whole.

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.

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 of 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.

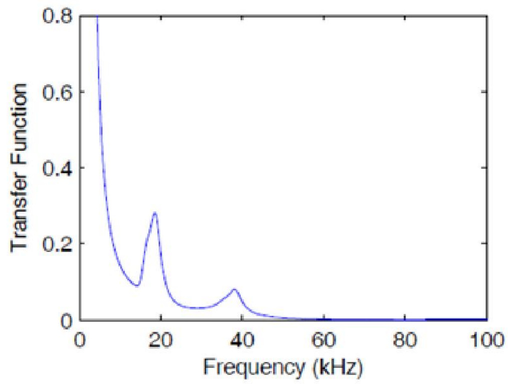

Figure 3. Overall transfer function for a 10-turbine park, high-frequency part.

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.

SIMULATIONS

The theoretical studies referred to in the previous sections did not consider all components in the collection grid. Although a number of important findings were obtained from the theoretical studies, more detailed models are needed to confirm and further develop the results. With this in mind simulations were performed in a model of the Lillgrund off shore wind farm, 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 after the harmonic propagation from the individual wind turbines to the public grid in Bunkeflo were performed using the simulation package PSCAD. The model used in PSCAD is shown, in a simplified way, in Figure 4. An important difference compared to the theoretical studies is in the modeling of the power transformers. Not only its inductance in the simulations, but also the capacitances on primary and secondary side and the capacitive coupling between primary and secondary side of the transformers.

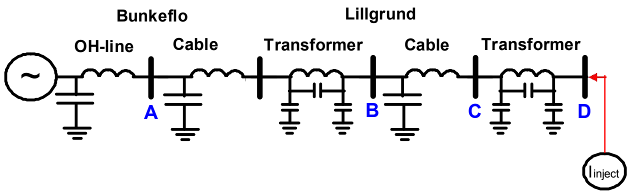

Figure 4. Outline of simulation model of one feeder of the Lillgrund wind farm, with indication of the locations for which harmonics and impedances have been calculated.

Studies of the propagation of individual harmonic components 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 side of the step up transformer at the wind turbine).

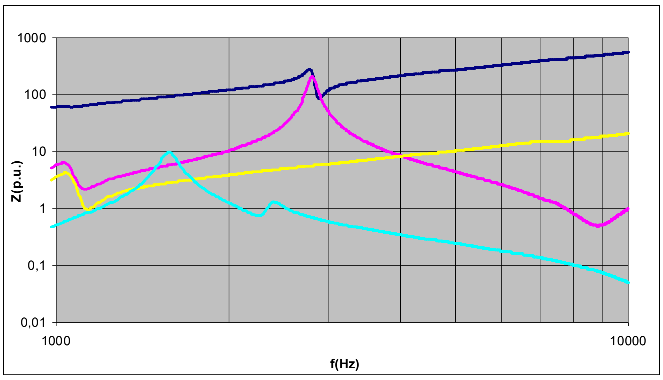

Figure 5. Calculated impedance as a function of frequency at: Pos. A light blue; Pos. B yellow; Pos. C purple, Pos. D dark blue

Figure 5 shows the impedance (from the turbines into the public grid) at four different locations. For positions B and D (on secondary side of a transformer) it is the transformer that dominates the impedance. For position C a serious resonance is visible around 2.8 kHz; for position A such a resonance is present around 1.8 kHz.

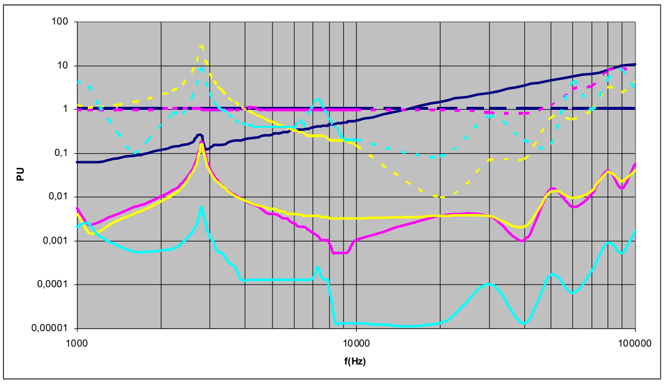

Figure 6. Calculated current, dashed, and voltage, solid line, at different frequencies (1-100 kHz). The current is injected in position D Pos. A light blue; Pos. B yellow; Pos. C purple, Pos. D dark blue. Note the difference in horizontal scale compared with the previous figure.

The transfer function (current divided by current) and the transfer impedance (voltage divided by current) are shown in Figure 6. For the transfer function amplifications are visible above 50 kHz and around 2.8 kHz. Above 50 kHz no significant emission from the turbines is expected, but around 2.8 kHz remnants from the switching frequency in the power-electronics converters can be present. The amplification is around 10 times to position A and around 30 times to position B. The aggregation effect between the individual turbines will have a damping effect on this. If we assume the square-root law associated with random phase angle, which is expected to be valid at these frequencies, the current from 48 turbines will be damped by a factor of square root 48, or about 7. The resulting emission at position A is about 1.5 times and at position B about 4 times the sum of the emissions from the individual turbines.

The voltage shows a decreasing trend from the turbines towards the public grid due to the overall decreasing source impedance in this direction.

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 and 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 conclusion 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.

CONCLUSIONS

It has been shown in earlier work that the emission from individual turbines is small at most frequencies, especially when compared with for example with industrial installations. However, emission takes place at 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. The simulations also indicate that frequencies above a few kHz are strongly damped in the collection grid.

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.

Further studies are needed to study the transfer at higher frequencies in more detail. Also measurements are needed to validate the components models used, especially the transformer models, to quantify the emission from the turbines in this frequencies range, and to verify the emission from the park as a whole.

Important future work also includes the development and verification of a model for the aggregation of emission from individual turbines, and the impact of secondary emission driven by the background voltage distortion in the public grid.

Finally, an important conclusion from the studies summarized in this paper is that harmonic studies should be performed with the connection of any wind park to the public grid. Such studies should include the propagation of the emission from the turbines to the public grid and any resonances that impact this propagation.

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