Harmonics and Wind Power

A forgotten aspect of the interaction between wind-power installations and the grid

Elforsk rapport 12:51

Math Bollen and Kai Yang, LTU

August 2012

Vindforsk
Energimyndigheten
ELFORSK

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Foreword

With increasing amounts of wind power connected, the power system is impacted in a number of ways. In this study, the emphasis has been on one of those impacts: the harmonic emission from wind-power installations.

In order to deepen the knowledge on this subject and provide future guidance on how to both measure and calculate emission levels, a PhD-project was started with the Vindforsk research program as project V-306.

The project has now come to end of phase 1 with a licentiate thesis by the PhD student Kai Yang under the supervision of Math Bollen at Luleå University of Technology (LTU).

This report describes the main results of the project in a non-academic way.

Vindforsk – III is funded by ABB, Arise windpower, AQSystem, E.ON Elnät, E.ON Vind Sverige, EnergiNorge, Falkenberg Energi, Fortum, Fred. Olsen Renewables, Gothia wind, Göteborg Energi, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, O2 Vindkompaniet, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Stena Renewable, Svenska Kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

Comments on the work and the final report have been given by a reference group with the following members: Urban Axelsson, Vattenfall; Johan Lundqvist, Svensk Energi; Lars Hultqvist, ABB; Erik Thunberg, Svenska Kraftnät; Kjell Gustafsson, Statkraft and Lennart Nilsson, Piteå Energi.

Stockholm, August 2012

Anders Björck

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Sammanfattning

Denna rapport behandlar ett av de fenomen som kan påverkas vid införandet av vindkraft i kraftsystemet: distorsionen av spänningens och strömmens vågform, dvs. avvikelsen från en 50-Hz sinusvåg. Det finns gränser på tillåtna avvikelser på spänningen i elnätet, men även stora avvikelser på strömmen kan leda till problem, som minskad livslängd av transformatorer.

Mätningar av emissionen (avvikelsen från sinusvågen för strömmen) från individuella turbiner har utförts; den visade sig vara låg, med undantag för vissa av frekvenskomponenterna. Samtidigt som nuvarande distorsion i nätet till största del innehåller frekvenskomponenter som är hela multiplar av 50 Hz, så uppvisar vindturbiner även andra frekvenskomponenter (det som kallas för ”mellantoner”). Det behövs ytterligare studier av dessa mellantoner, bland annat för att bestämma rimliga gränser.

Studier utfördes även gällande emissionen från vindparker som helhet, dvs. distorsionen av strömmen som kommer in till elnätet vid anslutningspunkten. Distorsionen visades sig inte vara en enkel addering av distorsionen från de individuella turbinerna. Istället finns det en utjämning mellan turbinerna samt förstärkningar och dämpningar i uppsamlingsnätet. Kapacitansen och induktansen hos nätkomponenter, som kablar och transformatorer, ger upphov till övertonsresonanser. Vid resonansfrekvensen uppstår förstärkning av strömmar och spänningar. Resonansfrekvensen ligger på en eller två kHz vid mindre parker och blir lägre vid större parker. Vid emission av frekvenser över resonansfrekvensen så dämpas dessa i vindparken.

Summary

This report covers one of the phenomena that are affected by the introduction of wind power in the power system: distortion of the voltage and current waveform, i.e. deviation from a 50-Hz sine wave. There are limits on the permissible deviations for voltage in the grid, but also large deviations of the current can lead to problems such as accelerated ageing of transformers.
Measurements were made of the emission (the deviation from a sinusoidal current) from individual turbines. This emission was shown to be low, with the exception of certain frequency components. Where current distortion in the network is mainly present at integer multiples of 50 Hz, the wind turbine also shows emission at other frequency components (so-called ”interharmonics"). Further studies are needed of these interharmonics, including the setting of reasonable limits.
Studies were also done on the emission of wind farms as a whole, ie. the distortion of the current at the connection point with the grid. The distortion was shown not to be a simple addition of the distortion from the individual turbines. Instead, there is cancellation between the turbines and amplification and damping in the collection grid. Capacitive and inductive components, such as cables and transformers, give rise to the harmonic resonances. At the resonance frequency voltages and currents are amplified. The resonance frequency is one to 2 kHz for smaller parks and lower for larger parks. For frequencies above the resonance frequency the emission of the park is damped.

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1 Introduction

The electric power system can accept only a certain amount of windpower before additional investments in the grid are needed. This is not a specific problem with windpower, but it also holds for any other type of production and also for additional consumption of electricity.

This so-called "hosting capacity" varies a lot between different locations in the grid. At some locations, the grid can accept almost no windpower, whereas it can accept large amounts at other locations. The hosting capacity is impacted by a number of electrical phenomena; an overview of these is given in several books, e.g. [1][2][3] and the details are discussed in hundreds of technical papers.

One of these phenomena has been addressed in detail in Vindforsk project 306: the fact that the current waveform is not a perfect sine wave at the point of connection between the grid and a wind-power installation (an individual wind turbine or wind park). This is called "waveform distortion" or also "harmonic distortion[1]". A brief description of this phenomenon is given in Chapter 2.

Other phenomena that limit the amount of wind power that can be accepted by the grid receive a lot of attention in the technical literature and in non-technical discussions; examples are overload, overvoltage, prediction errors, and intermittency. The amount of attention given to harmonic distortion in relation to windpower is much smaller and the phenomenon appears to be sometime completely forgotten in the discussion on wind-power integration. This is partly because other phenomena often put more strict limits on the hosting capacity, but also because of the lack of knowledge on harmonic distortion and the fact that it is a rather complicated phenomenon that requires significant experience to fully understand.

This lack of knowledge on harmonic distortion in relation to windpower has been an important driving force behind this project. Other important driving forces have been the occurrence of unexplained operation of protection relays (resulting in unnecessary interruptions of the power supply) that are attributed to high levels of distortion; the setting of limits on waveform distortion by network operators; and the general concern that modern wind turbines become an increasing source of distortion.

In this report a general presentation of the results from VindForsk project V-306 will be given. For technical details on the research the reader is referred to the licentiate thesis [7] and to the other publications in Chapter 6.

During the project, two issues have been studied in detail: the emission from individual turbines (to be discussed in Chapter 3) and the emission from a complete windpark (the subject of Chapter 4).

[1] Although there are some technical differences between the terms, we will in this report use "waveform distortion", "harmonic distortion" and "distortion" as synonym.

2 Waveform distortion

The term waveform distortion or harmonic distortion is used when the voltage or current waveform in the power system deviates from a sine wave. The waveform is in reality never exactly a sine wave so that there is always a certain level of distortion present. As we will see below, the distortion can be accepted up to certain levels.

An example of a distorted current waveform is shown in Figure 1. The term "emission" is often used to refer to waveform distortion of the current taken by a device or an installation connected to the grid.

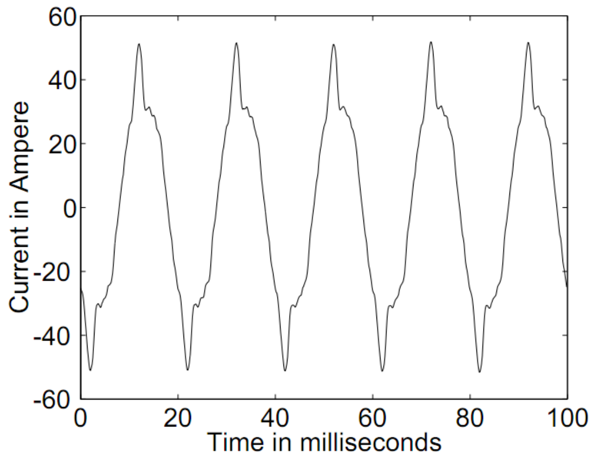

Figure 1, Example of a distorted current waveform [4]

There are a number of concerns with high levels of distortion of the current, which in turn results in limits on the maximum level of distortion.

i. There are maximum-permissible levels for the distortion of the voltage waveform. These limits are set in national or international standards (EN 50160 sets minimum requirements for Europe) or in national regulation (EIFS 2011:2 for Sweden). These limits are chosen such that equipment connected to the grid (including home equipment like energy-saving lamps, televisions and washing machines) does function correctly. It is the task of the network operator to ensure that the actual levels do not exceed these limits. To ensure this, without excessive costs for the other customers, the network operator sets limits on the emission from large installations, like wind-power installations. Limits are also set on the emission from small devices (again including home equipment) but that is not further discussed in this report.

ii. High current distortion gives increased heating of components in the grid (especially transformers are sensitive to this) resulting in a reduced lifetime of these components. High current distortion also increases the risk of the protection operating incorrectly, which in turn results in more interruptions of the electricity supply.

To further study the distortion of the voltage and current, the distorted waveform is described as the sum of a number of perfect sine waves. These sine waves are called "frequency components" or "harmonics". All the frequency components together form the "spectrum" of the distorted waveform. The spectrum of the waveform from Figure 1 is shown in Figure 2. Harmonic currents and voltages are complex numbers with a magnitude and a phase angle, but in the figure only the amplitude is shown. The phase angle of the harmonics is rarely considered in power-system studies.

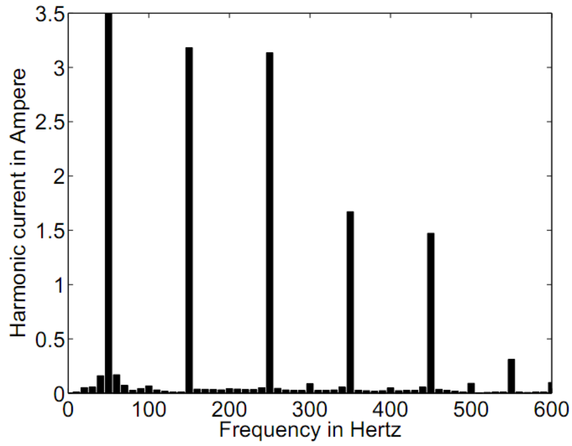

Figure 2, Spectrum of a distorted current [4]. The value for 50 Hz is about 20 A, beyond the vertical scale of the figure.

Due to certain mathematical properties of the power system (linear and time-invariant) the different frequency components can be studied largely independently from each other. This makes harmonics a useful tool to understand and study waveform distortion in power systems.

The 50-Hz component plays an important role in the power system: it is in almost all cases the dominant component in both voltage and current; and the vast majority of energy transport takes place at this frequency. As a result of this, a distinction is made between frequency components at integer multiples of 50 Hz (which are called "integer harmonics" or simply "harmonics") and other frequency components (which are called "interharmonics"). Mathematically there is however no difference between them and the mathematical term "harmonics" covers both.

In power systems, the frequency components are referred to by their order in relation to the 50-Hz component (also often referred to as the fundamental component). The 250-Hz component is called the fifth harmonic; the 350-Hz component is called the seventh harmonic, etc.

3 Emission from individual turbines

Modern, MW-size, wind turbines contain power-electronic converters. This can either be a full-power converter or a part-size converter in a double-fed induction generator. The presence of power-electronic converters makes that distorted currents are expected and that there is concern from network operators that distortion levels in the grid will increase with increased penetration of windpower.

Measurements have been performed, as part of this project, of the emission from four different wind turbines [9][10][21]. All turbines were modern turbines of about 2 MW size, equipped with power-electronics. The average spectra for these turbines, obtained over a period of one to four weeks, are shown in Figure 3.

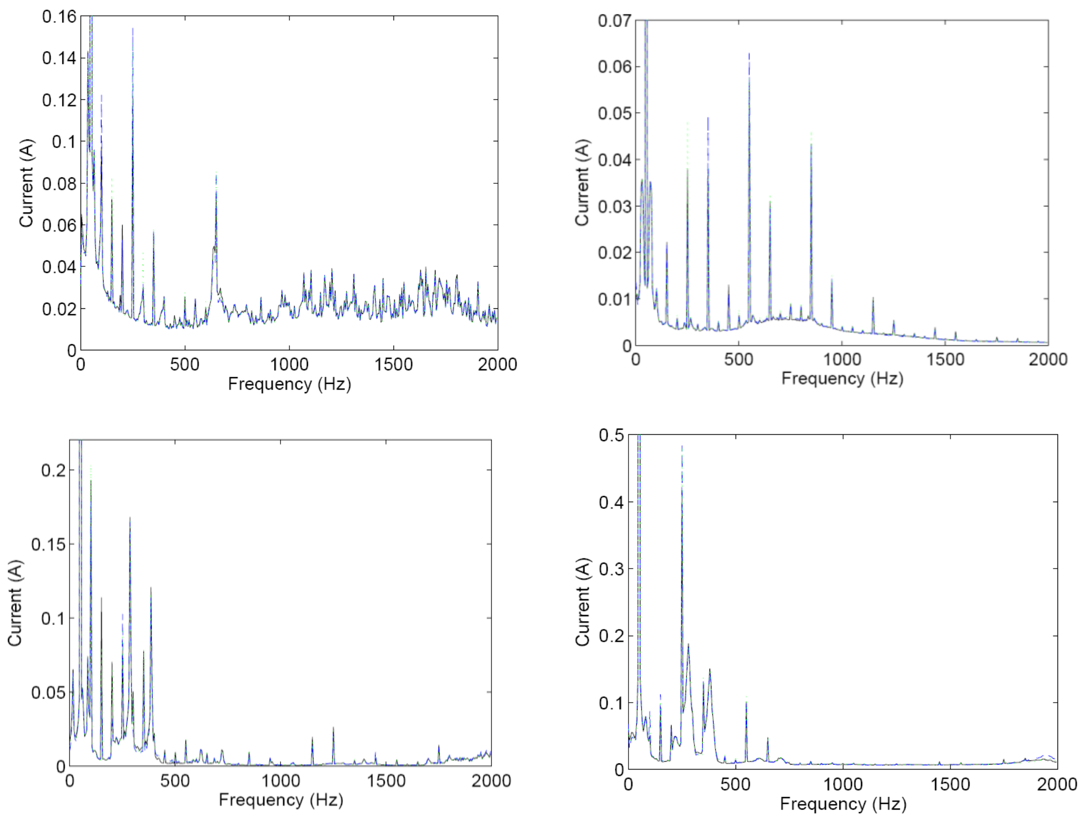

Figure 3. Emission spectrum from four individual turbines, obtained as the average over a period between one and several weeks.

The main observation is that the spectra show a combination of harmonics and interharmonics. The latter especially in the form of a broadband spectrum but some spectra even contain narrowband interharmonics. The emission of the turbines at harmonic frequencies is much smaller than for other installations; however the emission at interharmonic frequencies is not present with most other installations. Although all four spectra show this combination of harmonics and interharmonics, they are further all four different.

An important conclusion for future work is that these interharmonics should be studied in more detail especially to find out what are acceptable levels.

The variation of the emission with time is shown in Figure 4 as a time-frequency chart: a so-called "long-term spectrogram". The horizontal scale gives the time in days; the vertical scale the frequency (in multiples of the 50 Hz fundamental frequency) and the intensity of the emission is given in the form of a colour intensity scale: blue is lowest intensity; red is highest intensity.

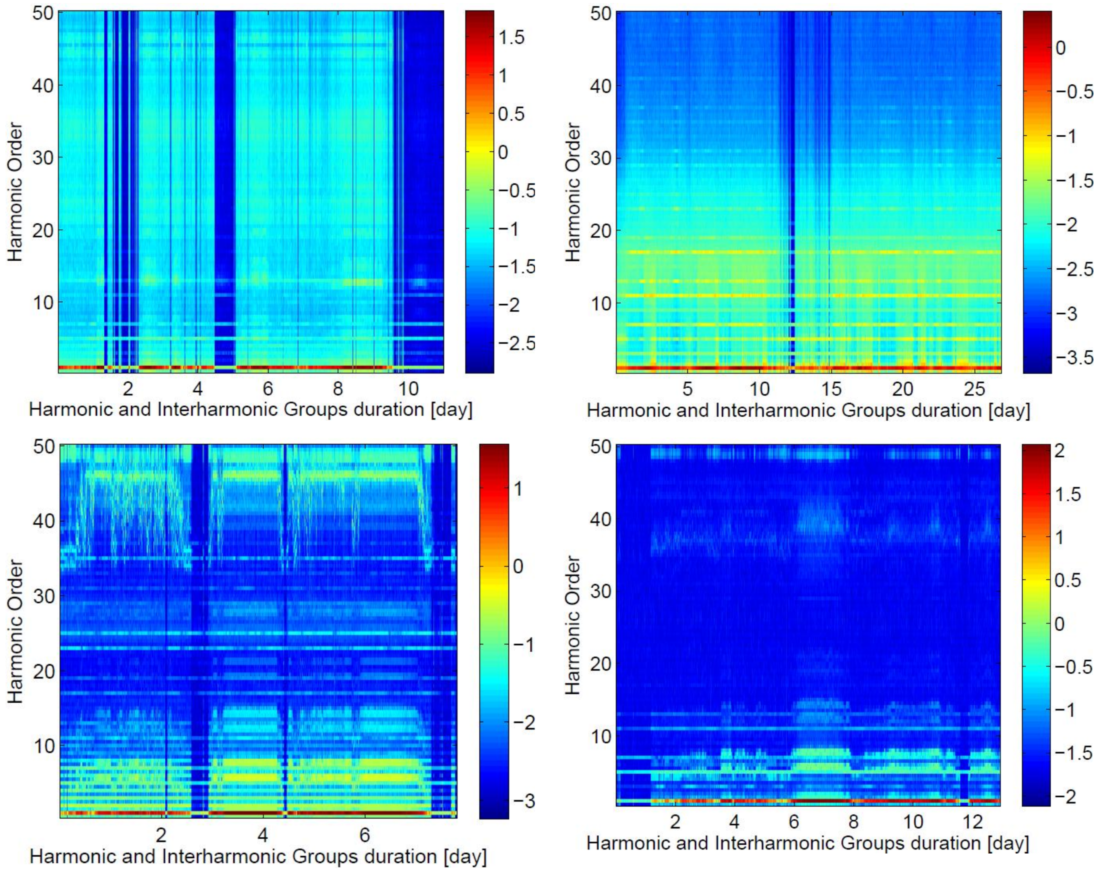

Figure 4. Variation in time of the emission from four modern wind tubines.

For example, the upper left plot shows that the turbine emits a continuous spectrum (light blue) most of the time, but that during certain periods (the dark blue vertical bands) this continuous spectrum disappears and only a small number of frequency components (harmonics 3, 5, 7, 11 and 13) remain. From the magnitude of the 50-Hz component (the thick line at the bottom of the plot, red most of the time) we see that this occurs when the emission from the turbine is low.

The bottom right figure shows that the emission is small between harmonic 15 and 35. During days 6 and 7, emission occurs are frequencies that are not there on other days. The 50-Hz line gets dark red during these days, which indicates high amount of wind-power production.

The four turbines not only show different spectra; their spectra also show different variations with time. Further studies have shown that the variation of the spectra with time is not only due to the variation of produced power with time. No explanation has yet been found for the spectrum and for its variation with time.

To quantify the effect of the measured emission (shown e.g. in Figure 3), allowed voltage distortion limits are used to quantify the required grid strength to meet these limit. For harmonics, the standard EN 50160 is applied. For interharmonics, the standard IEC 61000-2-2 is applied. Notable is that the allowed voltage distortion for harmonics is in the range of 0.5 to 6% with the larger values for the characteristic harmonics 5 and 7. For interharmonics, the standard 61000-2-2 stipulates a limit of only 0.3 %. The requirements are thus tougher for interharmonics. The effect of this is clearly visible when the required grid strength is calculated.

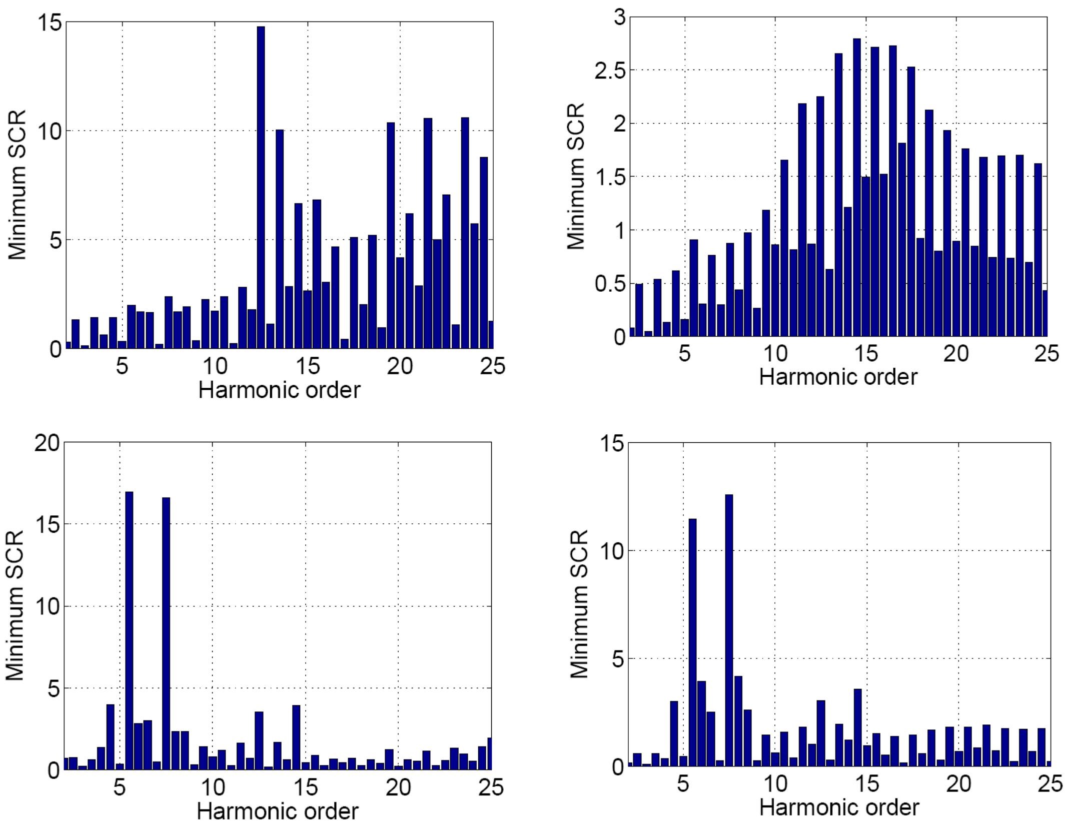

Figure 5. Estimated impact on the grid per harmonic and interharmonic group, for four modern wind turbines. Note the difference in vertical scale.

Figure 5 shows the required short-circuit ratio, SCR, (grid strength) that is needed to maintain voltage distortion below the limits set in the standards. When harmonic distortion is setting the hosting capacity, a higher value of this SCR implies more impact on the grid and a lower hosting capacity. When the SCR is below five it is unlikely that distortion will set the hosting capacity.We can see that the SCR is less than five for most frequency components, with the exception of interharmonics and some high-order harmonics. The impact on the grid is especially big for three interharmonics with three of the turbines.

As the requirements on grid strength a mainly set by the interharmonics, a discussion has started about the need for low limits for interharmonic voltages. The proposal being presented is that allowing higher interharmonic voltage will make it easier to connect wind-power installations without a significant increase in the risk of damage to other installations or equipment [11][12][13][14][15].

4 Emission from a wind park

As a next step studies have been done of the emission from a wind park as a whole. The emission is in this case defined as a distorted current at the point of connection between the public grid and the park. A distinction is thereby made between "primary emission" and "secondary emission". This distinction is made based on what causes the currents to flow.

Primary emission is caused by the distorted current coming from sources inside of the wind park. This are in most cases the wind turbines, but also power-electronic devices to control reactive power[2]. Even the turbine and grid transformers are sources of distortion, albeit minor ones in most cases. This primary emission is the one that is normally considered first and often it is the only one considered, thereby neglecting the secondary emission. The secondary emission is due to all other sources of harmonics, outside of the wind park. It is the distorted part of the current that would flow in case there would be no sources of harmonics inside of the wind park.

In this study, only the turbines have been considered. The primary emission from the park is in that case due to the emission from the turbines. But it is not simply the sum of the emissions from the individual turbines. To calculate the primary emission from the park, two phenomena have to be considered: cancellation of harmonic currents from individual turbines; and the propagation from the turbines to the grid. Both phenomena have been considered in a general model of a wind park and applied to 3-turbine, 10-turbine and 100-turbine parks [16][22].

The results for a 10-turbine park are shown in Figure 6, where a distinction is made between "individual transfer function" and "overall transfer function". The individual transfer function gives the relation between a frequency component emitted by an individual turbine and the same frequency component at the point of connection to the grid. All other emission sources are neglected in this case. The individual transfer function is strongly frequency dependent and somewhat different for each turbine location. For this example, the highest value occurs somewhere around 2 kHz, where the emission into the grid is almost 20 times the emission from the turbine: this amplification is due to resonances in the collection grid.

[2] SVC and StatCom are examples of such.

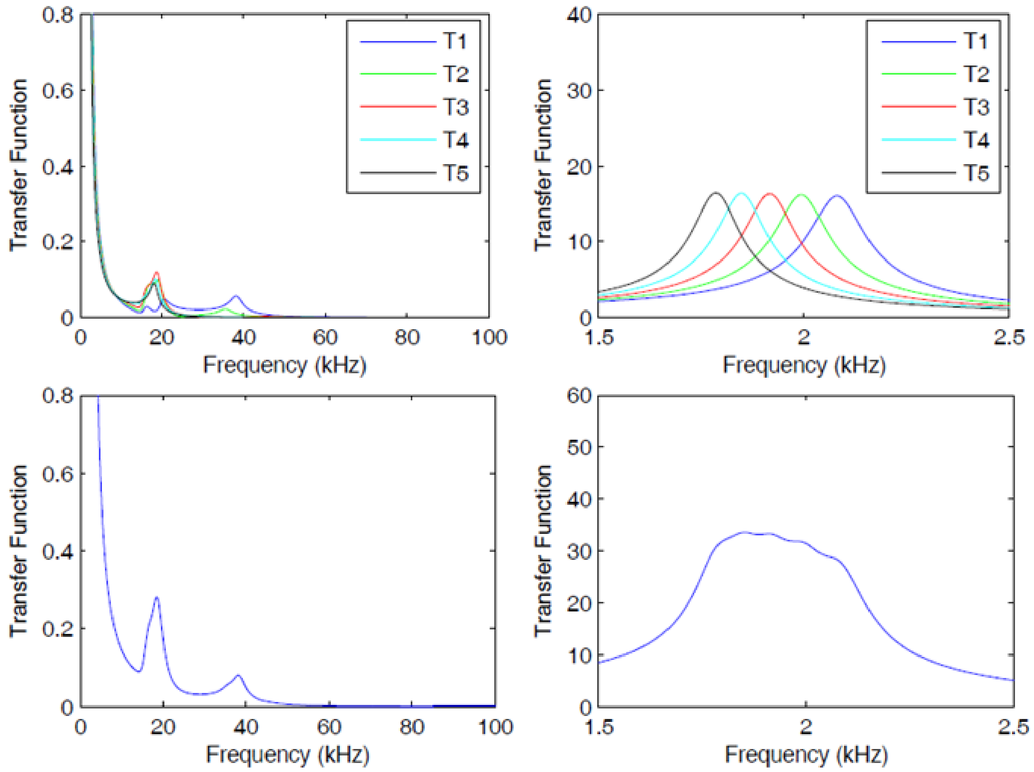

Figure 6. Individual transfer functions (top) and overall transfer function (bottom) for the 10-turbine windpark.

For higher frequencies, the individual transfer function reduces in magnitude quickly: the collection grid actually damps these frequencies. The emission into the grid is smaller, and for most frequencies a lot smaller, than the emission from the individual turbine.

The overall transfer function considers all turbines in the park and the cancellation between harmonics from the different turbines. Its value is the ratio between the primary emission from the park and the emission from one turbine. For the calculation it is assumed that all turbines are emitting harmonic distortion. Also for the overall transfer function we see a maximum around 2 kHz and a fast drop for higher frequencies.

Measurements have been performed at two locations in the same wind park to further study the propagation from the turbines to the grid [17][18]. These measurements are current being analysed.

Studies on secondary emission have been performed outside of this project [5][6]. It was shown that secondary emission can reach high values and should not be neglected.

5 Conclusions

Measurements have been performed on four modern wind turbines equipped with power-electronic converters. The emission from such turbines is moderate: at harmonic frequencies their emission is much smaller than the emission from industrial, commercial or domestic installations. However at interharmonic frequencies their emission is larger than for other installations. Although the levels are still small they could result in interharmonic voltages in the grid increasing.

A discussion has been started on what are acceptable levels of interharmonic voltages.

A mathematical model has been developed to quantify the propagation of harmonics from individual turbines in a wind park to the point of connection with the public grid. It is important to distinguish between primary emission (driven by the turbines) and secondary emission (driven by sources outside of the park). The primary emission from the park is amplified at a frequency of one to several kHz, depending on the size of the park. For higher frequencies the primary emission quickly drops.

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