

HARMONICS AND WIND POWER

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Harmonics and Wind Power

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Foreword

"Harmonics and Wind Power" är ett projekt finansierat av Energiforsk och Energimyndigheten genom programmet Vindforsk.

Projektet bygger vidare på en tidigare Vindforskstudie, Elforskrapport 2012:51, om hur övertoner påverkar vindkraftverk och elsystemet. Projektet har resulterat i ytterligare kunskaper, särskilt när det gäller spridning av övertoner genom vindparkerna, från turbiner till det offentliga nätet, mellan turbiner och från det offentliga nätet till uppsamlingsnätet.

Mer förnybar el från vindkraft och sol kommer ställa nya krav på såväl produktion som på elsystemet. Kunskapen från projektet är av stort värde för denna utveckling.

Projektet har utförts av Luleå Tekniska Universitet med Math Bollen som projektledare och Daphne Schwanz som doktorand.

Göran Dalén
Ordförande, Vindforsk

Sammanfattning

Detta projekt har behandlat ett antal aspekter relaterade till vågformsdistorsion i samband med vindkraftverk.

Projektets bidrag är att skapa ytterligare kunskap genom att kartlägga specifika problem, att tillämpa kunskapen och att utveckla metoder för att begränsa distorsionen.

Projektet har resulterat i ytterligare kunskaper, särskilt när det gäller spridningen av övertoner genom vindparkerna. Det handlar om en spridning från turbinerna till det offentliga nätet, mellan olika turbiner och från det offentliga nätet till uppsamlingsnätet.

Kunskapen har tillämpats speciellt på effekten av kondensatorpåkopplingar på vindkraftsanläggningar och på spridning av olika typer av störningar från solcellsinstallationer till lågspänningsnätet.

Summary

This project has treated a number of aspects related to harmonic waveform distortion in association with wind-power installations. The project has made there different types of contributions: creating additional knowledge by mapping of a problem; application of that knowledge; development of methods for harmonic mitigation. The project has resulted in additional knowledge especially concerning the spread of harmonics through the wind parks (from the turbines to the public grid; between turbines; and from the public grid to the collection grid). That knowledge has been applied especially to the impact of capacitor energizing on wind-power installations and to the spread of different types of disturbances from PV installations to the low-voltage grid.

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1 Introduction

Generating electrical energy from the kinetic energy present in the horizontal movement of air (wind power) is an important contribution in the necessary global transition to a sustainable energy system. The details of the energy conversion are discussed in detail in many other studies, as well as the advantages of wind power for the energy system.

The integration of wind power in the electric power system does however introduce a number of challenges. These challenges should not become an unnecessary barrier against the transition to a sustainable energy system. For this to be the case, detailed knowledge is needed on the way in which wind power installations impact the electric power system. Such knowledge is needed to be able to understand the severity (or lack of severity) of the impact. The so-called hosting-capacity approach, which was developed several years ago by the Swedish partners in a European project, is a good example of knowledge used to quantify the severity of the impact.

One of the potential impacts of wind-power installations concerns changes in harmonic voltage and current distortion. When starting the work on harmonic distortion and wind power, the driving force was the emission of harmonic currents by the wind turbines, i.e. the current at the terminals of the wind turbines is not a sine wave. Such a distorted waveform is common for power-electronic converters and wind turbines were expected to be no exception to this rule. Research on harmonics and wind power was started at Luleå University of Technology around 2008 through measurements at a number of installations and was soon extended to include the spread of harmonics. One of the early results was that the emission from wind turbines is relatively low, whereas the impact of harmonic resonances is what matters most.

Within this project, we built on earlier work on harmonics within our group and elsewhere. We have aimed to contribute to further knowledge concerning harmonic distortion of voltage and current in association with large wind-power installations (also known as “wind parks” and “wind power plants”). The activities within the project, as well as the results, consist of three parts: “mapping the problem”, “application of the knowledge”, and “development of solutions”.

Mapping of the problem concerns:

- Primary emission from wind turbines (Section 7.2);
- Spread of primary emission through the collection grid (Section 7.3);
- Primary and secondary emission (Section 7.4).

Application of knowledge concerns:

- Distinguishing between primary and secondary emission (Section 7.5);
- Emission limits (Section 7.6);
- Component modelling for harmonic studies (Section 7.7);
- Switching transients (Section 7.8);
- Protection operation (Section 7.9);
- Hosting capacity studies (Section 7.13).

Development of solutions concerns:

- Mitigation of harmonic emission and distortion;
- Active filtering of harmonic emission (Section 7.11);
- Active damping of harmonic emission (Section 7.12).

2 Some background knowledge

2.1 POWER SYSTEM HARMONICS

The term “harmonics” refers to components of voltage or current beyond the power-system frequency of (approximately) $16^{2/3}$, 50, 60, or 400 Hz. In this report we will only consider systems with the power-system frequency around 50 Hz. The more general term “waveform distortion” is used to refer to the voltage or current waveform not being an ideal sinewave, but the term “harmonics” is also regularly used as a synonym for waveform distortion. More correctly, the term “harmonics” is used in power systems to refer to frequency components that are integer-multiples of the power-system frequency.

An example of the voltage waveform at the wall outlet in a low-voltage network (that is where it matters in the end) is shown in Figure 1. The voltage waveform follows a sinusoidal waveform rather well, but not completely. In this specific case the so-called “total harmonic distortion” was around 1.5% of nominal voltage, with the main frequency components at 150 Hz (harmonic 3); 250 Hz (harmonic 5) and 350 Hz (harmonic 7).

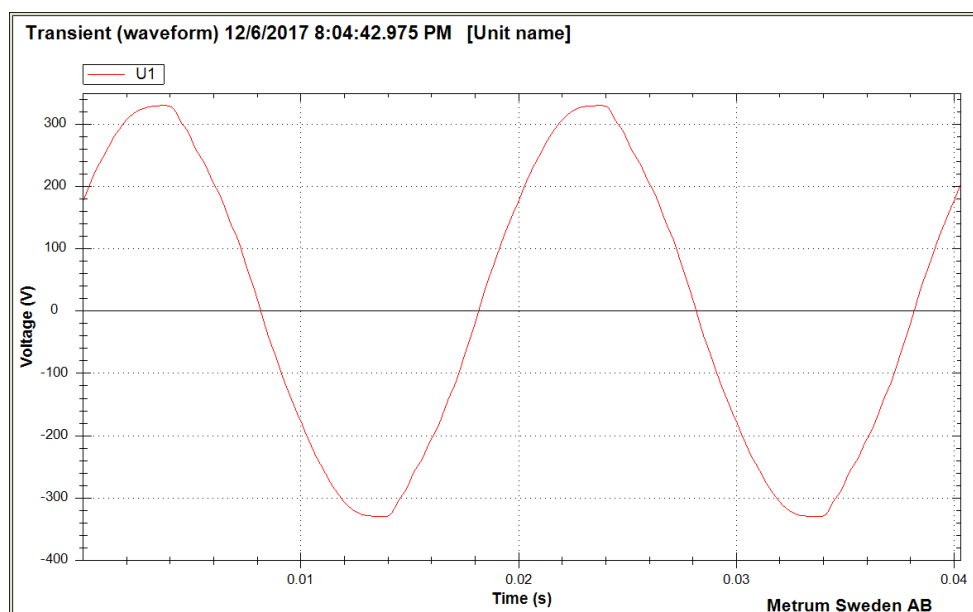


Figure 1. Slightly-distorted waveform; measured in a hotel in Northern Sweden.

More background information on harmonics and waveform distortion is found in the report of the first VindForsk project on wind power and harmonics [30].

2.2 HARMONICS, INTERHARMONICS AND SUPRAHARMONICS

As was mentioned before, harmonics are frequency components at integer multiples of the power-system frequency. The latter is also referred to as the “fundamental frequency” in the context of harmonic studies in power systems.

A further distinction is made between “odd harmonics” (150 Hz, 250 Hz, 350 Hz, etc) and “even harmonics” (100 Hz, 200 Hz, 300 Hz, etc). Traditionally, voltage and current distortion almost exclusively consisted of odd harmonics. In the existing power system, even harmonics are in most cases also much smaller than the odd harmonics.

Interharmonics are components at frequencies that are not an integer multiple of the power-system frequency, for example 18 Hz and 182 Hz. Frequencies below 50 Hz are also referred to as “subharmonics”. Interharmonics have traditionally been small and still today the interharmonic levels are small at most locations.

The term “supraharmonics” has recently been introduced to refer to frequency components in the range between 2 kHz and 150 kHz [9]. In addition, supraharmonic levels have traditionally been small, but recently more and more equipment is shown to emit supraharmonics.

2.3 PRIMARY AND SECONDARY EMISSION

The terms “primary emission” and “secondary emission” were introduced originally as a way of explaining the spread of frequency components in the tens of kHz range (currently known as “supraharmonics”) and especially the observation that emission of an installation decreased with increasing number of devices [31]. The terms also turned out to be very useful in explaining the spread of harmonics (at more down-to-earth frequencies of some hundreds of Hz) in wind parks.

The primary emission is defined as the emission coming from a single device or installation measured at the terminals of the device or installation. The secondary emission is coming from other devices or originating outside of the installation. These definitions, after discussion in an international working group, are presented in [16]. The definitions are illustrated in Figure 2 [18] for a wind park: the primary emission is the part of I_{pcc} driven by J_1 ; the secondary emission is the part of I_{pcc} driven by E_2 :

$$U_{pcc} = I_1 + I_2 = J_1 \cdot \frac{Z_1 Z_2}{Z_1 + Z_2} + E_2 \cdot \frac{Z_1}{Z_1 + Z_2} \quad (1)$$

$$I_{pcc} = U_1 + U_2 = J_1 \cdot \frac{Z_1}{Z_1 + Z_2} - E_2 \cdot \frac{1}{Z_1 + Z_2} \quad (2)$$

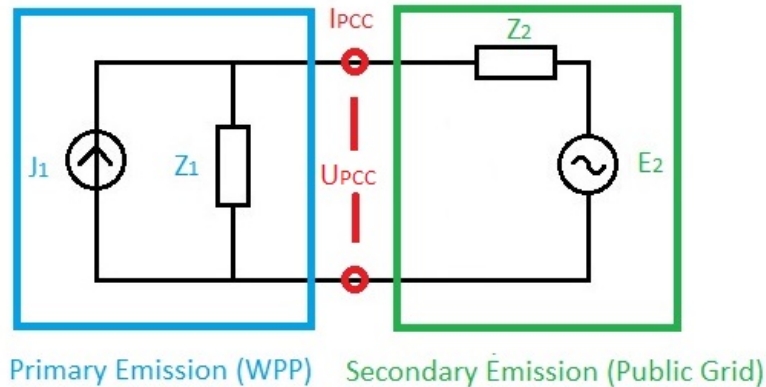


Figure 2. Primary and secondary emission; at the point of connection between the wind park and the public grid.

3 Primary emission from wind turbines

This part of the work is an example of “mapping of the problem”, mainly in the form of measuring the emission from individual turbines under real operating conditions; and in the form of analysing and presenting those measurement results.

When considering measurements it is important to realize that the measurement always gives the sum of primary and secondary emission. As is for example shown in [18] and in Section 7.4, it is not generally possible to distinguish between primary and secondary emission. What is referred to in the sections below as primary emission is therefore in fact the sum of primary and secondary emission but under conditions that make us conclude that the primary emission is dominating. This is further discussed in Section 7.4.

3.1 LOW-ORDER ODD HARMONICS

Measurements have been performed with a number of wind turbines, and other publications present such measurements as well. The general conclusion from our measurements and from other studies is that the primary emission for low-order odd harmonics is low.

The emission from three modern wind turbines is compared with the emission from an incandescent lamp in Figure 3, (taken from [24]). On a base of the rated power, the harmonic emission from an incandescent lamp is higher than the emission from a wind turbine. In other words, an installation containing 2 MW of incandescent lamps (about 33 000 60-W lamps) would have a more distorted current than a 2-MW wind turbine.

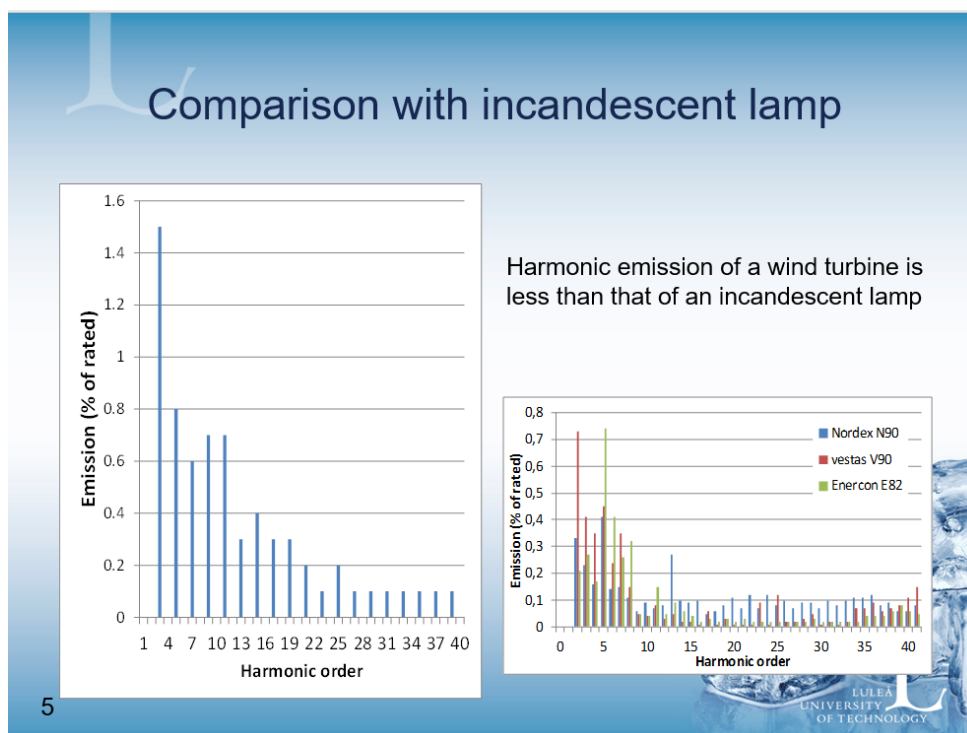


Figure 3. Comparison of the harmonic current for an incandescent lamp (left) and for three MW-size wind turbines.

From this observation, the conclusion was drawn, already early on in the project, that the issue is not so much the emission of low-order odd harmonics from the power-electronics in the wind turbines. The voltage distortion in the grid is typically highest for these high-order odd harmonics, with harmonics 3, 5, 7, 15 and 21 being the ones most often close to the limits. As the primary emission from wind turbines is small at these frequencies, further reducing their emission at these frequencies does not appear to be the right approach to keep low-order odd harmonics within acceptable levels.

Note, as mentioned before, that this conclusion was drawn under the assumption that the measurement was mainly primary emission. However, even when a large part of the measured current would be secondary emission, it would mean that primary and secondary emission would largely cancel each other. Also in that case, the impact of the wind turbines on the levels of low-order voltage harmonics would be small.

3.2 EVEN AND OTHER NON-CHARACTERISTIC HARMONICS

The primary emission from wind turbines is relatively high at frequencies for which there was low emission in the past: high-order even harmonics; interharmonics; and supraharmonics.

The measured emission from three wind turbines is shown in Figure 4, in a different way as in the right-hand plot of Figure 3. The measured 95%-values of the emission during about two weeks have been divided by the current emission limits in IEEE 519 (from [32] and [33]).

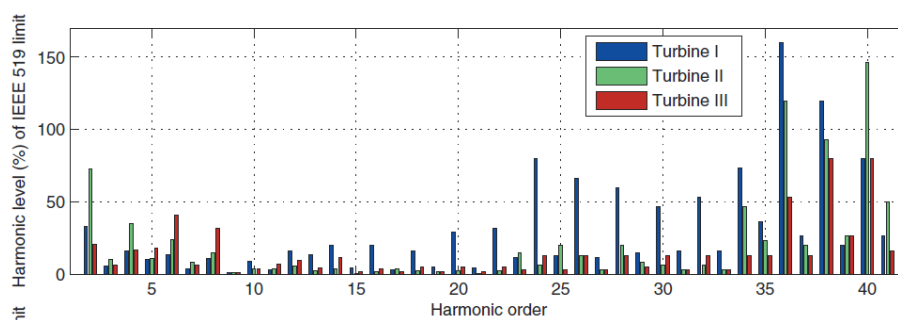


Figure 4. Harmonic emission for three wind turbines as a percentage of the IEEE-519 limits

The plot shows that the emission for harmonic 2 can be a significant part of the limit (around 70% for one of the turbines). For the frequencies between harmonic 3 and 23, the emission is much below the limits and not of any concern. For even harmonics above harmonic 23, the emission becomes a significant part of the limit and for some even harmonics the limits are even exceeded.

Many of the discussions with wind turbines, wind parks and emission limits being exceeded, concern high-order even harmonics. This not also follows from our measurements, it also follows from other published and non-published studies and from discussions in international working groups.

Here it is important to give some more background information. From the above one would easily get the impression that the emission is high for high-order even harmonics. That emission is the same or even lower than for neighbouring odd harmonics. The difference is in the emission limits: under IEEE 519, the limits for even

harmonics are set at one quarter of the limits for odd harmonics in the same frequency range. This issue is under discussion at several platforms, but for the time being there is no official work going on for changing limits of even harmonics. Also is there a natural resistance from several stakeholders on allowing higher voltage and/or current distortion, at any frequency. The setting of harmonic emission limits has traditionally been ruled by carefulness: setting the limits to the highest observed levels that were safe; i.e. did not cause any interference. As emission of even harmonics and interharmonics (see below) has traditionally been low, emission limits are low for those frequencies, unnecessary low according to some.

A further discussion on this is important, but beyond the scope of this project.

3.3 SUPRAHARMONICS

Supraharmonics (waveform distortion in the range from 2 kHz to 150 kHz) are getting increased attention the last few years [9]. The measurements referred to in Section 7.2.1 covered a frequency range up to 6 kHz. The instrument transformers used were however such that the measured levels should not be seen as very accurate. It was shown that wind turbines do show emission at supraharmonic frequencies, but the amplitude of the emission could not be accurately determined. An example is shown in Figure 5 (from [20]): emission is shown to peak around 2300 Hz, most likely related to the switching frequency in the wind-turbine inverter. For these frequencies, medium-voltage current transformers are still reasonably accurate, but at higher frequencies their accuracy deteriorates quickly.

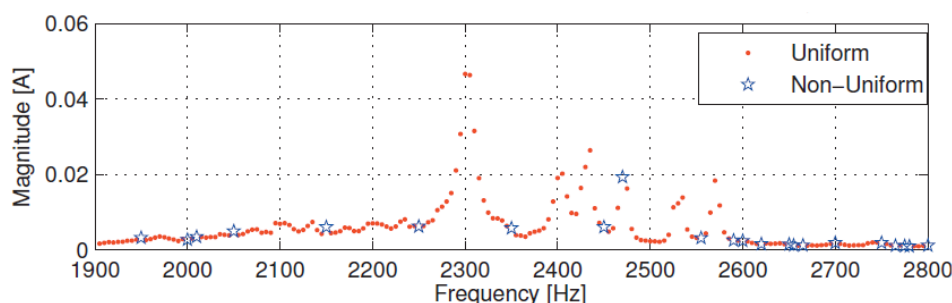


Figure 5. Current magnitude spectrum around 2 kHz for one of the wind turbines.

For further studies on supraharmonic emission from wind turbines, dedicated transducers are needed instead of the conventional instrument transformers used for these measurements.

3.4 INTERHARMONICS

Wind turbines have been shown to be a source of significant levels of interharmonics. This was found from our own measurements [6][32][33] and by several other sources.

The interharmonic emission, measured for the three turbines, is shown in Figure 6, again compared to the emission limits in a standard. The IEEE harmonics standard, IEEE 519, does not give limits for interharmonic voltages or currents. Neither does any other suitable document. Therefore, the IEEE standard has been somewhat adapted; so as to be able to make a comparison with what could be possible limits. The emission

limits for an interharmonic subgroup were considered equal to the emission limit for the neighbouring even harmonic.

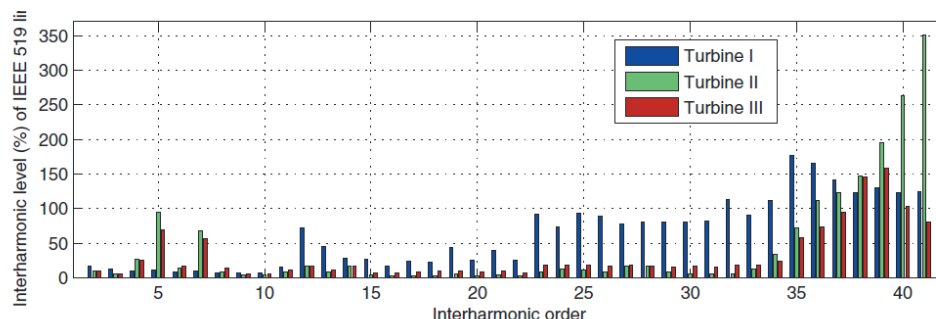


Figure 6. Interharmonic emission for three wind turbines as a percentage of IEEE-519 limits adapted for interharmonics

The plot clearly shows that interharmonics 5 and 7 (using the official notation they should be referred to as 5.5 and 7.5, but for simplicity we use the more-commonly used notation) are close to the limits and that the limits are exceeded for high-order interharmonics.

Here it is important to emphasize that the limits used are not existing limits, or even that these would be appropriate limits. A discussion about what are appropriate limits for interharmonics is completely beyond the scope of this project. The above figure only aims to convey the message that interharmonic emission from wind turbines is higher than what is seen as normal for devices or installations.

An important contribution from the project is a model for explaining the interharmonic emission from wind turbines. Emission at interharmonic frequencies was reported by various sources, but no satisfactory explanation for it has been given. In this project, we developed and applied a novel method for studying correlations between emissions at different frequencies. From this, we found that a rather simply, long known, model for interharmonics due to frequency conversions could be used to explain the emission. Details of the model and the method for studying correlations are given in [6].

4 Spread of primary emission through the collection grid

4.1 INTRODUCTION

This is another example of “mapping of a problem”: when the primary emission from the individual turbines is known, what will be the primary emission at the point-of-connection between a wind park and the public grid? This is in itself the classical harmonic propagation question and the subject of many simulation studies performed before connecting a wind-power installation to the grid.

Such studies are typically performed by consulting companies, using detailed or less-detailed models and presenting the results following instructions from the operator of the grid to which the installation is connected. It turned out however that the instructions are not always up to date with knowledge on power-system harmonics. Even in case the models are in accordance with state-of-the-art knowledge; performing the studies rarely results in further knowledge dissemination and increased understanding. (Dissemination of knowledge is after all not the primary task of consultants.)

To disseminate knowledge and increase understanding, a number of case studies were performed for existing wind parks and for hypothetical but realistic parks. The results have been published or are in the process of being published.

This part of the work has been based on simulations, but with measurements as input. The spread through the park consists of two parts, referred to as “aggregation” and “amplification”, where the amplification may be less than one.

4.2 OVERVIEW

A rather complete but still simplified model of aggregation and amplification for a generic wind park is presented in [1]. Several transfer functions are used to quantify the transfer. For the aggregation, the distribution of the argument (phase angle) of the complex harmonic current is used. The work is summarized and somewhat extended in [10]. In [3] the transfer functions are extended to include both primary and secondary emission and applied to one case study.

The amplification is highest around the “main resonant frequency” with a value of the order of 1 kHz. At this frequency, there is a resonance between the capacitance of all the cables in the collection grid and the inductance of the transmission transformer. (Note: there are also other inductances and capacitances affecting the value of the frequency, but these two are the main ones.).

The current transfer (ratio between current emitted into the public grid and primary emission from the turbines) is highest at the main resonant frequency. Additional resonances are shown to occur for higher frequencies, but according to the simulation results, these are narrow and/or highly damped. An overall, albeit somewhat preliminary, conclusion is that above the primary resonant frequency the current transfer from the turbines to the public grid is small.

4.3 DISTRIBUTION OF PHASE-ANGLE OF COMPLEX HARMONIC CURRENT

A chi-square goodness-of-fit test has been performed to test a uniform distribution of the phase-angles of the complex current for every frequency component. The test is based on a 95 percent significance level with the Matlab function `chi2gof`. Results are shown in Figure 7. In the figure, a distribution is referred to as “uniform” when the chi-square goodness-of-fit test passes with a 95 percent significance level; otherwise the distribution is referred to as “non-uniform”.

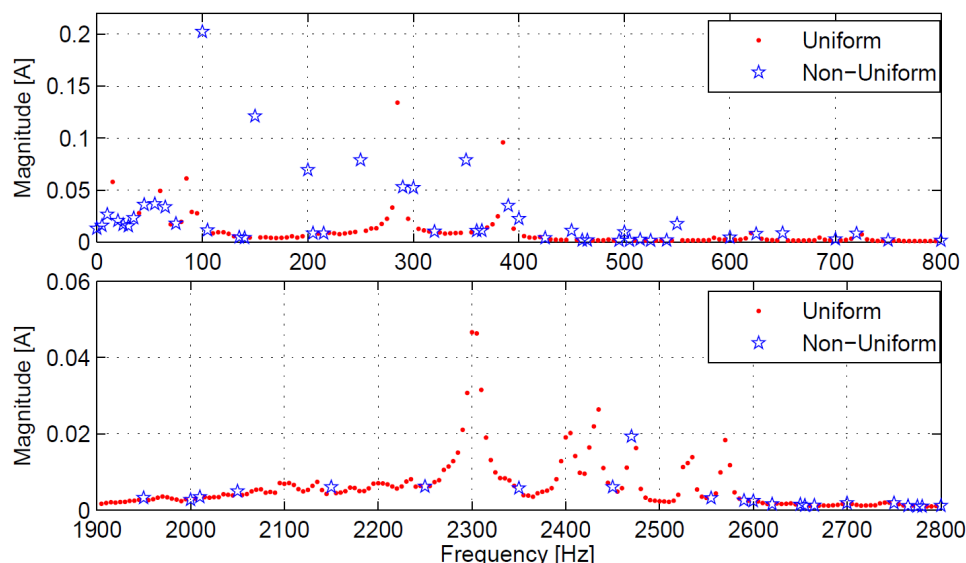


Figure 7. Current magnitude spectrum (5 Hz increment) with uniform and non-uniform distributions of the phase angle indicated. Upper figure: 0 - 800 Hz; lower figure: 1.9 - 2.8 kHz.

The red dots in Figure 7 represent frequency components for which the phase-angles are uniformly distributed; and the blue stars represent frequency components with non-uniform distributions for the phase angles. There are some general patterns to be observed in the phase-angle distribution:

- Most distributions for harmonics are non-uniform distributions;
- Many of the frequency components below 100 Hz are non-uniformly distributed;
- Phase-angles of spectrum components at interharmonic orders are mostly uniformly distributed; this also is the case for the components around 2.3 and 2.4 kHz, which are related to the switching frequency of the turbine converter;
- With increasing frequencies more components are uniformly distributed.

It should be mentioned again here that “non-uniform” only means that there is less than 95% confidence that the distribution is uniform. The actual distribution might still be uniform, but due to limited data points this cannot be confirmed with sufficient confidence.

The phase-angles of almost all harmonics show a non-uniform distribution. The only exception are some of the higher order even harmonics (42, 44, 46, 48 and 50). The complex harmonics (at lower orders) are more likely synchronized to the fundamental component. Our study shows that the phase angles for harmonics are non-uniformly distributed up to 2 kHz for even harmonics and at least up to 2.8 kHz for odd harmonics. Interharmonics are mainly uniformly distributed.

4.4 AGGREGATION AND AMPLIFICATION

The impact of aggregation and collection grid on the emission has been quantified by introducing the so-called aggregation factor. The aggregation factor has been defined as the ratio of the emission from the park into the public grid and ten times the emission from an individual turbine (as there are 10 turbines in the park). Results are shown in Figure 8. In the figure, the aggregation factor obtained using the stochastic model (blue line) has been compared with the aggregation factor as calculated from the two different models. The green curve corresponds to “uniform phase angle”; the red curve corresponds to “identical phase angle”. The difference in aggregation factor between interharmonics and harmonics up to about 1650 Hz, is also here clearly visible.

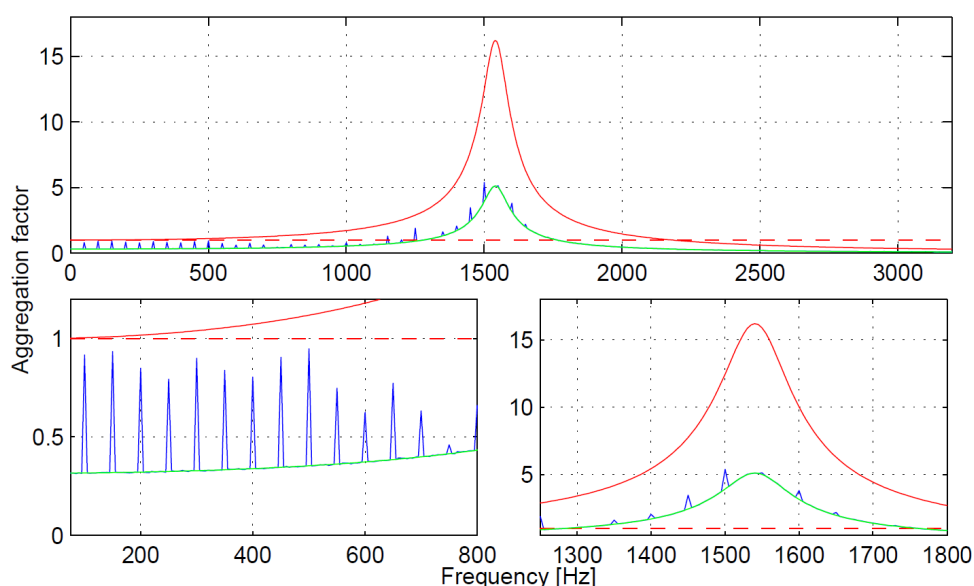


Figure 8. Aggregation factor (blue line, ratio of park emission and ten times turbine emission) and overall transfer function with identical phase-angle (solid red line) and uniform phase-angle (solid green line).

For most interharmonic frequencies, the uniform phase angle model is a good approximation. The red dashed line in the figure marks an equal level: values below that line represent attenuation and above that line amplification. Amplification of the emission takes place from around 1.25 to 1.75 kHz. This is due to a combination of high individual transfer functions and limited cancellation for these harmonic orders.

The aggregation factor calculated from the stochastic model is between the results for identical phase-angle (solid red line) and for uniformly-distributed phase-angle (solid green line). The aggregation factor of the interharmonic components is close to the transfer function with uniform phase-angle. The aggregation factor for integer harmonics at lower frequencies is closer to the transfer function with identical phase-angle.

The left-bottom figure shows that integer harmonics (at integer multiples of the fundamental frequency) aggregate less than other frequencies, especially for the frequency range below 1.3 kHz. The lowest aggregation factor below the resonance peak is obtained at interharmonics in the low-frequency range. The value is around 0.316, or $1/\sqrt{10}$. Due to the random phase angle, the emission aggregates with the square-root of the number of turbines, 10 in this case.

4.5 AGGREGATION ONLY

A study without considering the impact of resonances in the collection grid has been performed. The individual transfer functions of the ten turbines have been defined unity. The aggregation factor for this case is shown in Figure 9. Next to the results for the turbine in the previous section, the figure also contains the results for two other turbines.

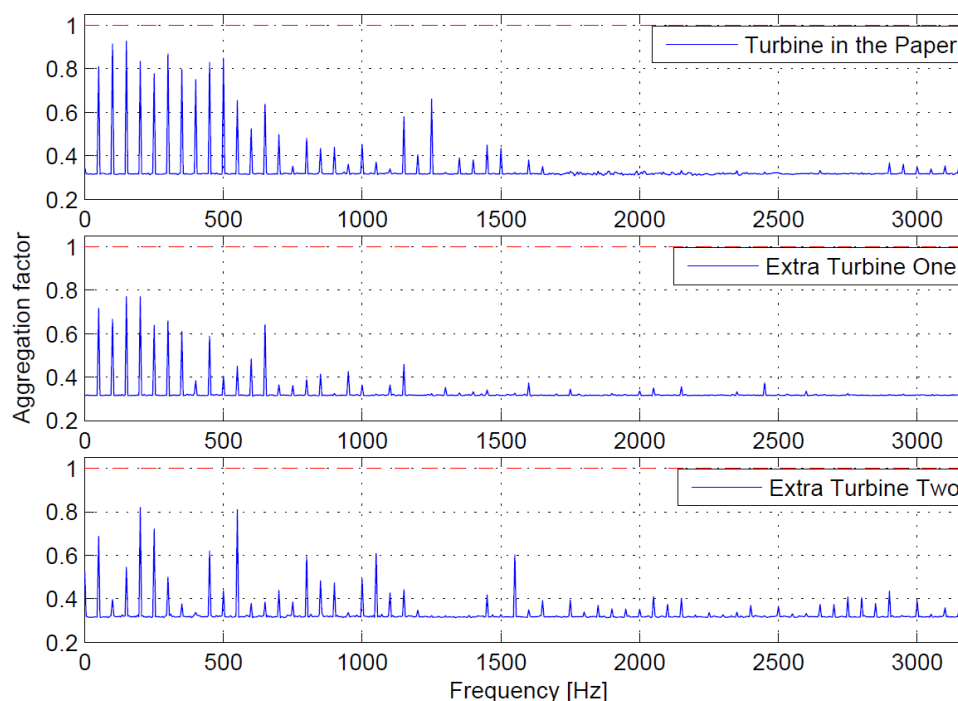


Figure 9.. Aggregation factor only, without considering any amplification in the collection grid.

The harmonics aggregate less than interharmonics, especially for the low orders. The largest aggregation happens for interharmonics and high-order harmonics, around the aggregation factor 0.316. For the Turbine used through the rest of the paper the aggregation factor is around 0.8 for harmonics up to order 10 (500 Hz). For higher frequencies, the aggregation factor becomes smaller but it does not reach the value for random phase angle till about 1600 Hz (order 32). The other two turbines show similar overall behaviour, with aggregation factor around 0.316 for all interharmonics, highest aggregation factors for low-order harmonics and reducing towards higher frequencies. The details are however different for each turbine. Extra Turbine One shows a lower aggregation factor for harmonics over the whole spectrum. Extra Turbine Two shows aggregation factors close to 0.4 all the way up to 3 kHz.

4.6 CONCLUSIONS

Some important conclusions, from a practical viewpoint, from this part of the work are:

- Primary emission around the main resonant frequency will be amplified and result in a higher emission into the public grid. This resonant frequency is in the order of 1 kHz; it could result in high levels of high-order even harmonics and interharmonics being emitted into the public grid.

- The combination of a relatively low switching frequency and a relatively high resonant frequency could result in amplification of the remnants of the switching frequency. Such could occur at frequencies up to a few kHz.
- Supraharmonic emission, well above the main resonant frequency, is not of a concern for wind-power installations with an internal collection grid. The supraharmonic emission from the turbines will be shorted by the capacitance of the medium-voltage cables.

5 Primary and secondary emission

This is another case of “mapping the problem” and in that way gaining knowledge. The specific issue considered here is the presence of multiple sources of harmonic distortion. These multiple sources are formed by the emission from the individual turbines but also the emission from sources outside of the park.

An early attempt at quantifying the secondary emission for individual turbines was made using the plots shown in Figure 7 (taken from [20]), especially the left-hand plot.

For this study, measurements of harmonic voltage and current were performed at two locations in a wind park: at the MV side of the turbine transformer with one of the turbines; at the MV side of the transmission transformer.

By coincidence, the individual turbine with which the measurements were made, switched off occasionally, but the transformer and filter remained connected. The plots show voltage and current harmonics over a period of about two weeks. Each dot corresponds to one measurement instant. In the left-hand plot, the diagonal line corresponds to instances when the inverter was in operation; the steep curve towards the left of the plot corresponds to instances when the turbine and the inverter were not in operation. For those instances, there was no primary emission and the measured harmonics could only be secondary emission.

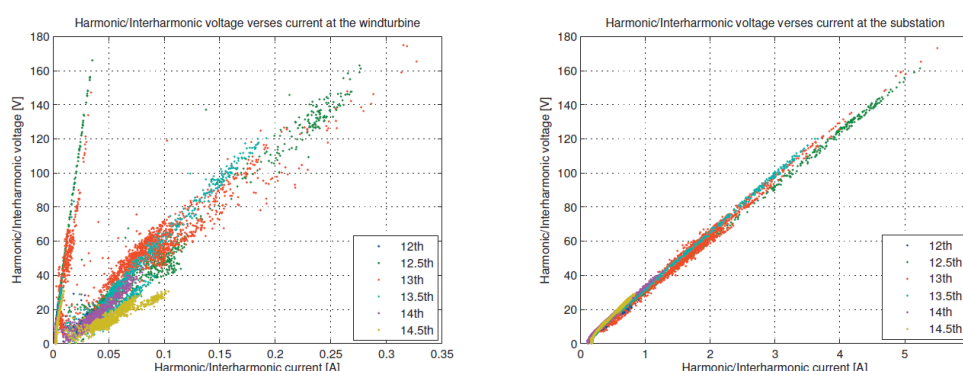


Figure 10. Relation between harmonic/interharmonic currents and voltages; harmonic orders 12, 12.5, 13, 13.5, 14 and 14.5; with an individual turbine (left) and for the park as a whole (right).

From this plot, it was concluded that the secondary emission at turbine level was small. The conditions were however not fully realistic as the turbine inverter was not in operation and could not conduct any harmonic currents. The measured secondary emission was thus only due to the filter (on LV side of the turbine transformer). With the inverter in operation, this one is also likely to conduct some current with an increase in secondary emission as a result.

Studies presented in [21] indicate that the secondary emission is likely to be higher than what was concluded from Figure 7. Especially for larger wind parks, the secondary emission at the MV side of the turbine transformer could be around half of the primary emission. Around the main resonant frequency, the secondary emission from neighbouring turbines may be by far dominating in the measured current.

The discussion on the size of the secondary emission returns in the end to the on-going discussion between voltage-source model and current-source model for the inverter. The voltage-source model appears to have a somewhat higher popularity among researchers. Whereas the two models do not have any impact for primary emission (it would be choosing between a Norton and a Thevenin model), they do give significantly different results for the secondary emission. This will be further studied (from a measurement and from a simulation viewpoint) in a new project [34].

The spread of harmonic emission through the park is more complicated than just primary and secondary emission. Several sources and sinks of harmonic voltages and currents need to be distinguished:

- Transfer from turbine to public grid;
- Transfer from turbine to turbine
- Transfer from public grid to the collection grid
- Transfer from public grid to an individual turbine

In [3] a distinction is made between different types of primary and secondary emission, using a number of transfer functions as a base.

Some calculated transfer functions for a hypothetical wind park are given below. Some assumptions have been made to simplify the equations. The individual current transfer from a turbine to the public grid is defined as the ratio in absolute value of the complex currents at the connection to the public grid and at the turbine transformer. When calculating the individual current transfer function it is assumed that the other turbines do not emit any current. This individual current transfer is shown in Figure 11 for this example. There is a strong amplification around 1.2 kHz due to the main resonance (see discussion above). Above the main resonant frequency, the transfer function decays quickly with frequency, as is shown in the bottom figure. Some resonance peaks appear in the supraharmonics range, but the amplification at those frequencies is far below the value for the main resonance.

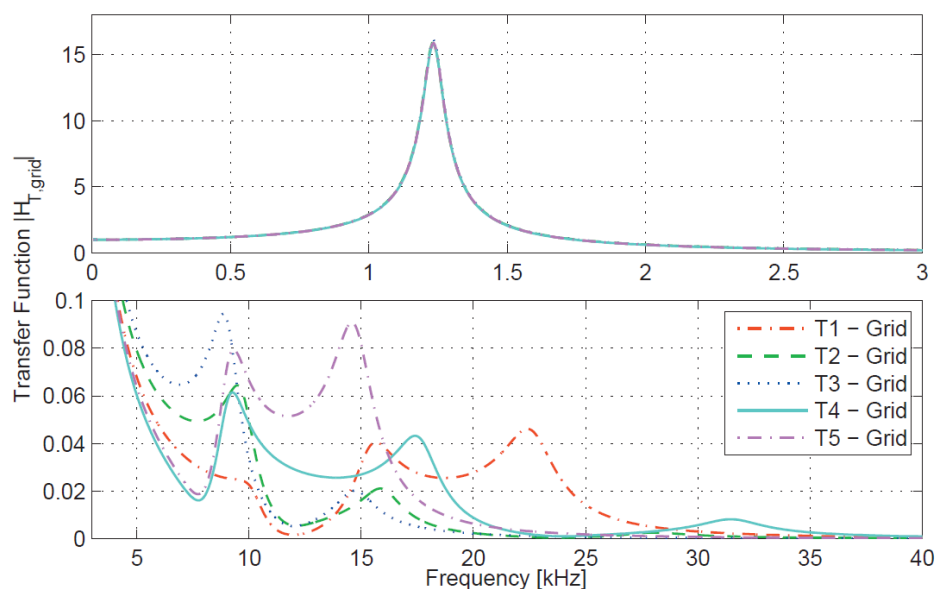


Figure 11. Individual transfer function from one turbine to the public grid.

The overall transfer function is obtained by considering the aggregation between individual sources. It is the ratio between the amplitude of the harmonic current at the connection to the grid and the amplitude of the current with a turbine transformer. For the calculation of the overall transfer function it is assumed that all turbines emit harmonics. The results are shown, for the same park as in the previous example, in Figure 12. The two curves correspond to two levels of aggregation, where the red curve is more realistic for lower frequencies and the dotted blue one for higher frequencies. See discussion on aggregation in the previous chapter.

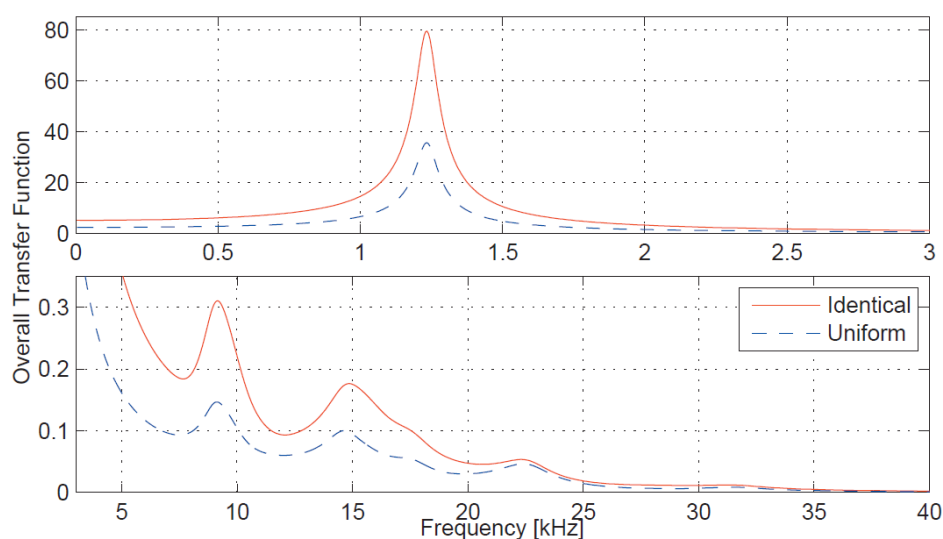


Figure 12. Overall transfer function from all the turbines to the public grid.

The individual current transfer function from turbine to turbine is defined as the ratio of the absolute values for the secondary emission with one turbine and the primary emission with another turbine that causes this. For calculation of the individual current transfer the emission from all other turbines is considered equal to zero. The results from the hypothetical park are shown in Figure 13. Around the main resonance, the secondary emission can be 1.5 times the primary emission that causes it. It should be noted that this is only the contribution from one of the other turbines. In a wind park with many turbines, the secondary emission can be substantial around the main resonance.

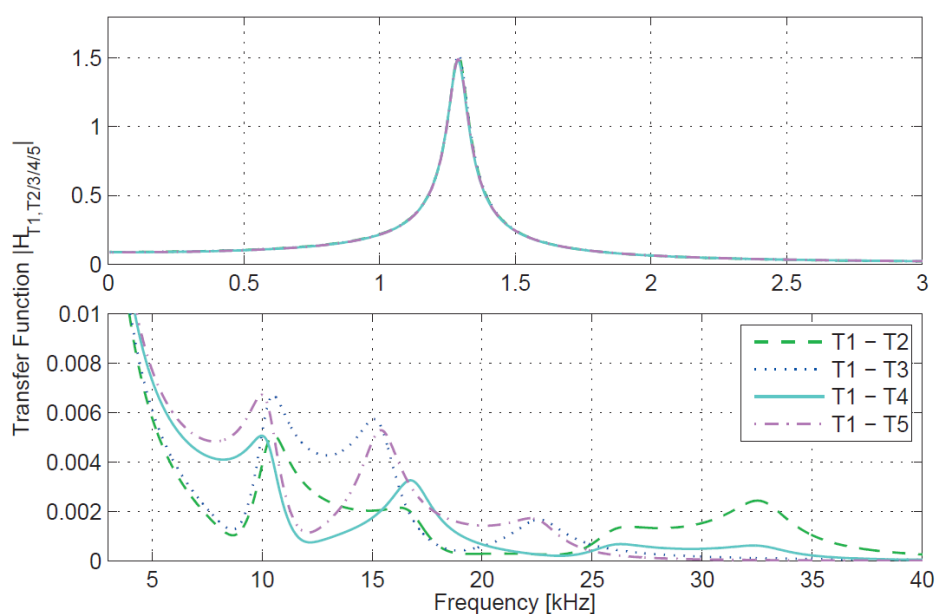


Figure 13. Individual transfer from turbine to turbine.

Another case study is shown in Figure 14. The modelling of the components is more detailed than in the earlier figures, but the rest of the model holds only for frequencies below the main resonant frequency. It is shown that about one fifth of the primary emission from a wind turbine ends up as secondary emission for the neighboring park. The good news is that the transfer to the public grid becomes less than unity even for frequencies well below the main resonance.

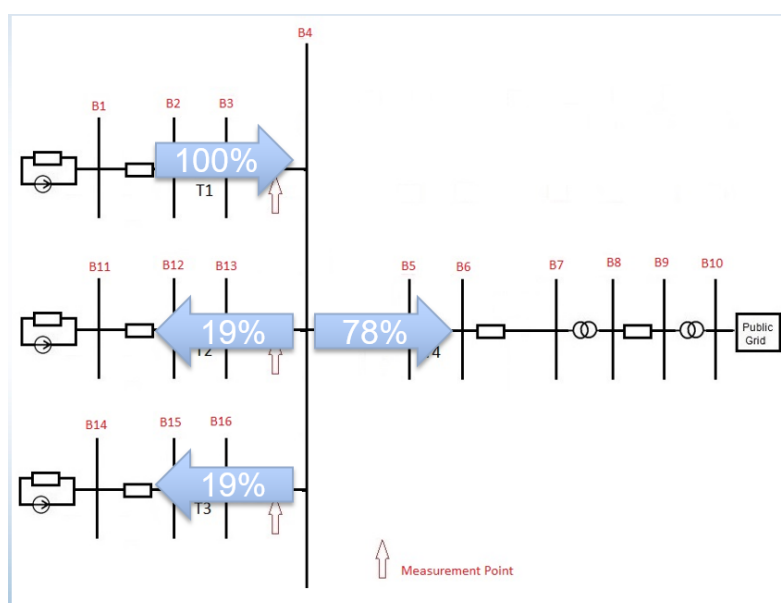


Figure 14. Primary and secondary emission in a small wind park.

Based on this example, a generic model of a wind park has been created, shown in Figure 15. The model is simplified but complete. The simplification is in that only the inductive part of the impedances are included. Neglecting resistance does not impact the spread very much because the inductive part is dominating. Neglecting capacitance implies that the model doesn't hold when the frequency moves towards the main resonant frequency.

Under the assumption that turbine and grid transformer have similar per unit impedance (on a base equal to the transformer rating), the individual transfer from a turbine to the public grid is about 50%. The rest of the primary emission from a turbine becomes secondary emission for the other turbines connected to the same collection grid.

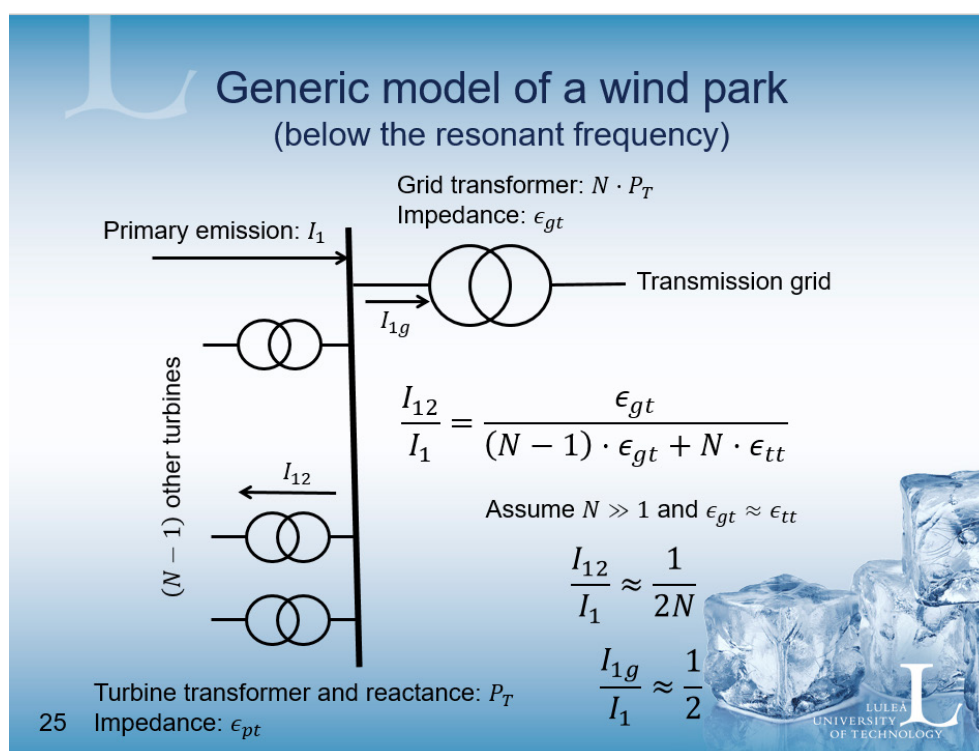


Figure 15. Simplified but complete model of a wind park for spread of primary emission at frequencies below the resonant frequency.

6 Distinguishing between primary and secondary emission

6.1 PROBLEM FORMULATION

In [18] a critical overview is given of methods proposed in the past to distinguish between primary and secondary emission. The somewhat depressing conclusion from the work is that there is no general method for this that works under all circumstances. Any of the methods requires assumptions that rarely can be verified. The paper does however serve as a base for further discussion on this. This limitation of the methods is not generally known and this part of the work can therefore be seen as “application of knowledge”.

With reference to Figure 2 in Section 2.3, I_{pcc} and U_{pcc} are known from a measurement. Unknown are the two impedances (Z_1 and Z_2) and the two sources (J_1 and E_2). That results, mathematically in two equations with four unknowns, which cannot be solved. This means that assumptions are needed, e.g. that secondary emission can be neglected or that the impedances are known.

6.2 HARMONIC POWER FLOW METHOD

This is the most common method for harmonic source determination and it is regularly used in industry, both in power-quality monitors and in commercial software for analysis of monitoring data. The method indicates the direction of harmonic power flow. The side that generates harmonic power is considered to contain the dominant harmonic source.

The method is easy to implement and several monitor manufacturers have implemented the harmonic active-power flow in their monitors or software. There is however no mathematical basis for the method, merely a physical reasoning based vaguely on the causality principle. Where this principle may hold for travelling waves (transients) it does not hold for standing waves (harmonics). See also the reasoning in the next section.

The method uses the harmonic active power, which requires knowledge on the angular difference between harmonic voltage and current. Angular errors in voltage and current transducers will give an error in active power with possibly erroneous direction as a result. This error increases with increasing nominal voltage and increasing frequency. For low-voltage measurements, at the wind-turbine terminals, the method is expected to be rather accurate. However, for measurements at the terminals of the wind power plants (at high or extra-high voltage) larger errors are expected.

The method is however worth further investigating, where a combination of detailed simulations and experiments are needed to evaluate the appropriateness of the method for wind-power installations. Issues that especially require attention are the usefulness of the method for interharmonics and the behavior of the method around resonant frequencies. Furthermore, this method only indicates the highest harmonic contribution. The method cannot quantify the size of the contribution.

6.3 USEFUL OR HARMFUL INSTALLATION CONNECTION

Assume that an installation draws a harmonic current I_h from a source with harmonic source voltage E_h and impedance Z_h . The measured voltage at the terminals of the installation is U_h . Without loss of generality, it is assumed that the latter is directed along the positive real axis.

The source voltage is obtained from the measured voltage and current, together with the source impedance, as in (5). Which can easily be rewritten as (6).

$$I_h = I_x + jI_y \quad (3)$$

$$Z_h = Z_x + jZ_y \quad (4)$$

$$E_h = U_h - (Z_x + jZ_y) \cdot (I_x + jI_y) \quad (5)$$

$$E_h = U_h + Z_y I_y - Z_x I_x - j(Z_x I_y + Z_y I_x) \quad (6)$$

Note that the harmonic active power equals $U_h \cdot I_x$ (assuming a single-phase representation). The resistive part of the source impedance (Z_x) can be assumed positive. The sign of the third term thus corresponds to the direction of the harmonic active-power flow.

A criterion for determining if an installation is “useful” or “harmful” for the grid would be to determine if its removal would increase or decrease the voltage distortion. This is obtained from the change in absolute value of the harmonic voltage. The difference between the voltages square before and after connection of the installation is obtained through (8).

$$E_h^2 = (U_h - Z_x I_x - Z_y I_y)^2 + (Z_x I_y + Z_y I_x)^2 \quad (7)$$

$$E_h^2 - U_h^2 = 2U_h(Z_y I_y - Z_x I_x) + [(Z_x^2 + Z_y^2)(I_x^2 + I_y^2)] \quad (8)$$

Where $E_h^2 = |E_h|^2$.

When (8) is positive, the harmonic voltage before connection (E_h) is higher than the harmonic voltage after connection (U_h), and the installation has a positive (i.e. reducing) impact on the harmonic voltage at that point.

Note the role of the harmonic active power in (8). Harmonic active power production, i.e. a positive value of $Z_x I_x$, reduces the value of the right-hand side expression and in that way it makes the harmonic emission more harmful. A positive value is however neither a sufficient nor a necessary condition for a harmful contribution of the installation.

6.4 HARMONIC IMPEDANCES

From the methods discussed in [18] it was concluded that accurate knowledge of the harmonic impedances is necessary for an accurate estimation of the harmonic contributions. There are several challenges to this, as is for example clear from the on-going work in CIGRE group C4.38 [35].

For some methods it is possible to use estimated “reference impedances” to estimate the harmonic contributions. However, errors in the impedance result in errors in the source current, which in turn propagate to errors in primary and secondary emission estimation. In WPPs, one of the additional issues is to model the harmonic impedance of the turbine converter. The converter impedances cannot be assumed linear. To

consider linear elements (as in Figure 2 and in fact as in all of the proposed methods) is not appropriate for a study close to the turbines.

From the reasoning at various places in the paper, arises the need for further studies about harmonic impedances, especially considering devices with non-linear characteristics. Furthermore, studies regarding resonances are very important: not only are the highest voltage and current found typically around resonances; this is also where the uncertainty in harmonic impedance is biggest.

Recent developments, related to WPPs, make the problem even more complicated. Emission shifts to higher frequencies, where impedance models are less developed. At the same time, resonances shift to lower frequencies, so that even for lower frequencies impedance estimates become less accurate [4].

7 Emission limits

The discussion about different emission limits and verification of those limits, presented in [7] is another example of “application of knowledge”.

For an overview of the different limits and the way in which those limits are set, the reader is referred to [7] and to the original documents that define those limits.

Once the limits are set, they need to be verified one way or the other. Also for this, different methods are in use, each with their own advantages and disadvantages. The two main approaches, in the eyes of the authors, are summarized in the two forthcoming sections.

7.1 VERIFICATION OF MODEL USED

The network operator may give detailed instructions on how the calculations should proceed. As long as those instructions are followed and the resulting estimated emission is below the limits, the wind power plant is allowed to connect. However, if excessive harmonic distortion is estimated during the simulation, further analysis and solutions to the problem are required. No verification is done after connection.

Preliminary simulations should be performed to identify expected harmonic levels and system response characteristics. These simulations should be performed for different system conditions to identify the conditions of potential concern. A complex model in order to accurately determine frequency response characteristics is needed. Accurate representations for transmission lines, cables, transformers, capacitor banks, loads, and machines are required. The potential impact of the WPP should be evaluated at this point.

The risk of high emission and high voltage distortion is with the network operator. But it is the network operator that sets the instructions. The instructions often are based on rather extreme operational states and other worst-case assumptions. The risk carried by the network operator is therefore typically not very big.

The advantage for the wind power plants operator is that no detailed knowledge is needed for performing harmonic studies. Also, there is no risk that the plant cannot be connected once the criteria are complied with. Furthermore, once the design is approved by the network operator, the latter takes over all risks for high harmonic distortion.

7.2 VERIFICATION OF CURRENT AND/OR VOLTAGE DISTORTION

The harmonic emission level is defined as the magnitude of the harmonic current/voltage vector at each harmonic frequency at the point of evaluation. The harmonic emission vector results in increased levels of harmonic distortion on the network and the emission level needs to be less than the emission limits defined in the standard.

According to IEC 61000-3-6, the harmonic emission level can be defined as a vector considering the distortion before and after the installation under consideration. In this approach the pre-connection assessment of the harmonic emission level for the WPP can be determined using basic assumptions about the characteristics of the system

and its installations. However, as the actual emission level could be higher or lower than the calculated value. Therefore, it may be necessary to assess the level of emissions that will be present when the WPP is connected to the system.

The advantage for the network operator is that the harmonic distortion can be estimated with actual values and different operation situations. The disadvantage for the WPP owner is the non-zero risk that the plant cannot be connected when the limits are exceeded.

8 Component modelling for harmonic studies

As was shown earlier, the main resonant frequency plays an important role in both the spread of the primary emission and the secondary emission. The resonant frequency is determined by all capacitance and inductance in the system. The main contributions are the capacitance of the MV cables in the collection grid and the inductance of the HV/MV transmission transformer. When the park is connected to the main grid through long AC transmission cables, the capacitance of these cables also has a big impact on the resonant frequency.

For an accurate estimation of the resonant frequency, it is important that the mentioned inductances and capacitances are accurately known. However, not only these capacitances and inductances should be known. Capacitance and inductance elsewhere in the system also have an impact (albeit less) on the resonant frequency.

The main concern in component model is however not in finding values for inductance and capacitance, but in finding values for the resistance. The amplification of primary and secondary emission around the resonant frequency is determined by component resistances around the resonant frequencies. Values for inductance and capacitance of components are reasonably known and to a good approximation frequency independent; values for resistance are much less known and often frequency dependent. Finding accurate values for component resistance as a function of frequency is a major challenge in all harmonic studies, especially where it concerns values around the resonant frequency.

The impact of the load model on the impedance as seen from the transmission grid is studied in [15].

A major inventory of knowledge on component modelling for harmonic studies is part of the scope of a CIGRE working group [35]. The technical brochure (report) for that working group is currently being written; the brochure will contain a wealth of information on how to model components. One of the preliminary conclusions is that a lot of knowledge remains lacking, especially where it concerns modelling of loads.

The work on component modelling will be continued in two new projects [34][36]: one project among others aims at including modelling uncertainties in decision making as part of planning or design; the other project among others aims at developing methods for verifying harmonic component models through measurements. The before-mentioned discussion on primary and secondary emission, and the difficulty in distinguishing between them, is one of the reasons that verification of harmonic models is not trivial.

9 Switching transients

The switching of a component, like a cable or a capacitor bank, results in oscillations with frequencies corresponding to the resonant frequencies found in harmonic studies. Switching of a cable or capacitor bank in the transmission grid will result in a damped voltage oscillation at the point of connection between a wind park and the transmission grid.

In terms of the earlier discussions, this voltage oscillation will result in secondary emission flowing into the park. When the resonant frequency for the secondary emission (maximum in input admittance, transfer admittance or voltage transfer) is close to the oscillation frequency, oscillations of high amplitude can be the result. This can be high currents through the transmission transformer; it can also be high voltages in the MV collection grid.

10 Protection operation

Incorrect protection operation, especially unwanted protection operation (“mal trip”), has been reported in association with wind power installations at several occasions. It has not always been possible to explain the cause of the incorrect operation, but harmonics are often mentioned as the cause, possible cause, or suspected cause.

This part of the project is an example of “Application of knowledge”. That knowledge is presented in the previous section and in the various publications that followed from this project. Most importantly, in the context of protection operation is:

- The primary emission from wind turbines, at the classical harmonic frequencies (low-order odd harmonics) is small. Emission is however higher than for non-wind installations for (especially high-order) even harmonics and for interharmonics.
- High harmonic current or voltage levels could exist around the main resonant frequency of the installation.
- High voltage and current oscillations could occur in or near the park due to switching of cables or capacitor banks in the transmission grid.

There is still no known mechanism explaining the incorrect operation of protection around or in wind-power installations. The authors nevertheless suspect a link with the above-mentioned high levels of harmonics or oscillations in voltage and current. Some possible mechanism that should be further investigated, are:

- Harmonic voltage distortion causing a rise in peak voltage (in phase with the fundamental voltage at the voltage maximum) will be detected as an overvoltage by the overvoltage protection of the park or the turbines. Amplification of interharmonics from the primary emission could be a suspect, as interharmonic distortion will always add to the peak voltage somewhere during the course of its cycle.
- Harmonic current distortion causing a rise in peak current will be detected as an overcurrent by the overcurrent protection of the park or the turbines. The comment about interharmonics in the previous bullet also holds here.
- Oscillations due to cable or capacitor bank switching will result in overcurrent or overvoltage being detected by the protection.

There is a general lack of knowledge on the behaviour of modern protection relays during harmonic voltage and current distortion. Additionally, there is a lack of detailed studies on actual cases of incorrect operation of protection involving wind power and harmonics. What is especially lacking are publicly available studies.

The problem of incorrect protection operation due to harmonics associated with wind-power installations remains. This project has resulted in some additional insight but no further explanation or mitigation of the problem.

11 Active filtering of harmonic emission

An increasingly used method for reducing harmonic voltage and current distortion is through so-called “active harmonic filtering”. Different types of active harmonic filters are in use; an overview of such filters and their control techniques is given in [12]. A commonly used method is to compensate the harmonic emission downstream of a certain location, by injected a current of same frequency and magnitude, but with opposite phase (180 degrees phase angle differences). Seen from upstream of the filter, the emitted current from the device or installations flows directly into the filter; the impact of the emission on the upstream part of the network is zero.

A comparison of different locations for active filters in a wind park is presented in [13]. It is shown that a location closest to the source, i.e. closest to the wind turbines, is most advantageous.

An important advantage of an active filter compared to a passive harmonic filter is that the active version does not introduce new resonances, as it does not contain any capacitance. An active filter does however affect the resonant frequency. Its impact is far less dramatic than for a passive filter, but the impact can still not be neglected. When capacitor banks are tuned to stay away from harmonic frequencies, the presence of an active filter may actually change the resonant frequency such that it moves closer to a harmonic frequency. This could especially be the case for a weak grid.

12 Active damping of harmonic emission

Within the “development of solutions” part of the project, the use of active damping has been investigated to reduce the amplification of the emission around the resonant frequency.

The more damping present in the system, the lower the peak of the transfer function. Damping in the form of physical resistances normally results in increased losses in the installation. An alternative investigated in this project, is to use the power-electronics control of the inverter with the turbine to create a “virtual resistance”. The control algorithm of the inverter normally aims to inject a clean sinusoidal current (of 50-Hz frequency) into the grid. The control algorithms can be adjusted such that the inverter also injects harmonic currents, where the harmonic currents are determined by the harmonic voltages at the terminals of the inverter. In that way it is possible to make the combination of turbine transformer, filter, converter reactance and converter behave like a resistance. This virtual resistance creates damping of the resonances in the collection grid.

13 Hosting capacity studies

13.1 APPLICATIONS OF THE TRANSFER-FUNCTION APPROACH

The method for quantifying transfer through the collection grid has been used to study the impact of solar power in the distribution grid. The method of transfer functions and transfer impedances is not new for this project, but for the first time has been applied to wind-power installations in this and the proceeding project. The original application within these two projects has been the spread of harmonics between individual wind turbines and the grid.

The method has next been extended, combined with a stochastic model to create random connection of installations, and applied to the spread of disturbances for PV installations in low-voltage networks. The resulting stochastic transfer impedance method has been applied to

- Negative-sequence unbalance [5][14][37]
- Overvoltages [38][39]
- Harmonics [17][19][40]
- Voltage variations in the time scale between one second and ten minutes.

The application of this method to solar power has resulted in three additional Energiforsk projects; the method further plays an important role in another PhD project [41] and has been applied to studies after undervoltage due to connection of large numbers of electric vehicles chargers [38][42].

13.2 HARMONIC TRANSFER AND AGGREGATION

The harmonic voltage was calculated for each customer using the transfer impedance matrix for the 6-customer network. The transfer impedance links the harmonic voltage at a certain location (r) with the harmonic current injected at another location (s).

The contribution to the harmonic voltage distortion at busbar r is obtained by (9).

$$\underline{U}_{r-h} = \underline{Z}_{sr-h} \cdot \underline{I}_{s-h} \quad (9)$$

With multiple (N) inverters, the harmonic voltage at location r is obtained from the superposition of the contributions from the individual units and the background harmonic voltage $\underline{U}_{bg-h}$.

$$\underline{U}_{r-h} = \sqrt{\left(\underline{U}_{bg-h}\right)^\alpha + \sum_{s=1}^N \left(\underline{Z}_{sr-h} \cdot \underline{I}_{s-h}\right)^\alpha} \quad (10)$$

More details are found in the above-mentioned references and in the final reports (to be published) of the above-mentioned Energiforsk projects.

14 Discussion

The electric power system plays an important role in the transition to a sustainable energy system. Renewable energy enters the energy system in most cases in the form of electricity. Increased energy efficiency and reduced environmental impact is often achieved by replacing other energy carriers with electricity. An acceptable performance of the electric power system is therefore one of the requirements for this transition.

The introduction of wind-power installations adds a new source of harmonics to the power system. The primary emission from these installations is however small and the main impact is because of the introduction of new resonances by the capacitance of the cables in the collection grid or by the capacitance of long AC transmission cables.

This project has contributed to a better understanding on these resonances and the way in which they affect the spread of harmonics from the turbines into the public grid and from the public grid into the collection grid.

Several methods for reducing the amplification around the resonant frequency have been studied. The most promising one is the introduction of a virtual impedance by including harmonic frequencies in the control system of the turbine inverter.

Knowledge from the project has further been applied to obtain some better understanding of the impact of capacitor and cable energizing on a wind-power plant and (admittedly to a small extent) to obtain a better understanding of the mechanisms behind incorrect protection operation in association with wind-power plants.

An important application of the knowledge obtained from the project has been on hosting-capacity studies for solar power in low-voltage networks.

The transition to a sustainable energy system will not be stopped by a lack of knowledge on harmonics or interharmonics. Nevertheless, additional knowledge and tools on harmonics and interharmonics are pieces of power-system knowledge that make the transition easier. In that way, the results from this project contribute, albeit in an indirect way, to the transition.

15 List of publications

15.1 JOURNAL PAPERS FROM THIS PROJECT

- [1] Kai Yang, M.H.J. Bollen, E.O.A. Larsson, Aggregation and amplification of wind-turbine harmonic emission in a wind park, *IEEE Transactions on Power Delivery*, Vol. 30, April 2015, pp.791-799.
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- [5] Daphne Schwanz, Friedemann Möller, Sarah K. Rönnberg, Jan Meyer, and Math H.J. Bollen, Stochastic assessment of voltage unbalance due to single-phase-connected solar power, *IEEE Transactions on Power Delivery*, Vol. 32, No.2, April 2017, pp. 852-861.
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- [7] Daphne Schwanz, Math H.J. Bollen, Some thoughts about harmonic limits in connection agreements for wind power plants, *Renewable Energy and Power Quality Journal*, No.15, April 2017.
- [8] Sarah K. Rönnberg, Math H.J. Bollen, Hortensia Amaris, Gary W. Chang, Irene Y.H. Gu, Łukasz H. Kocewiak, Jan Meyer, Magnus Olofsson, Paulo F. Ribeiro, Jan Desmet, On waveform distortion in the frequency range of 2 kHz–150 kHz – Review and research challenges, *Electric Power Systems Research*, Vol. 150, pp.1-10, 2017.
- [9] Sarah K. Rönnberg, Math H.J. Bollen, R. Langella, Francisc Zavoda, Jean-Philippe Hasler, Philip Ciufo, Vladimir Cuk, Jan Meyer, The expected impact of four major changes in the grid on the power quality – a review, *CIGRE Science and Engineering*, No.8, June 2017.

References [4], [8] and [9] were more general publications, but containing some of the results from this project.

15.2 CONFERENCE CONTRIBUTIONS FROM THIS PROJECT

- [10] K. Yang, D. Schwanz, M. Bollen, Harmonic aggregation and amplification in a wind-park, *Int. Conf. Electricity Distribution (CIRED)*, Lyon, France, June 2015.
- [11] Daphne Schwanz, Math Bollen, Anders Larsson, A Review of Solutions for Harmonic Mitigation, *Int Conf Harmonics and Quality of Power*, October 2016.

- [12] Daphne Schwanz, Azam Bagheri, Math Bollen, Anders Larsson, Active harmonic filters: control techniques review, Int Conf Harmonics and Quality of Power, October 2016.
- [13] Daphne Schwanz, Math Bollen, Anders Larsson, Lukasz Kocewiak. Harmonic Mitigation in Wind Parks : Active Filter Solutions, Int Conf Harmonics and Quality of Power, October 2016.
- [14] Daphne Schwanz, Friedemann Möller, Sarah K. Rönnberg, Jan Meyer, and Math H.J. Bollen, Stochastic Assessment of Voltage Unbalance due to Single-Phase-Connected Solar Power, Int Conf Harmonics and Quality of Power, October 2016.
- [15] F. Barakou, M.H.J. Bollen, S. Mousavi-Gargagi, O. Lennerhag, P.A.A.F. Wouters, E.F. Steenis, Impact of load modeling on the harmonic impedance seen from the transmission network, Int Conf Harmonics and Quality of Power, October 2016.
- [16] M.H.J. Bollen, S.K. Rönnberg, Primary and secondary harmonics emission; harmonics interaction – a set of definitions, Int Conf Harmonics and Quality of Power, October 2016.
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- [27] Math Bollen, Changes in probability of interference, contribution to panel session at IEEE T&D Conf, May 2016.
 - [28] Math Bollen, Harmonics and wind power, Seminarium om vindkraftforskning, Stockholm, 7 oktober 2016.
 - [29] Math Bollen, Changes in Probability of Interference, contribution to panel session at ICHQP, October 2016.
- References [19][20][22][23][24][26] were more general tutorials or presentations where results from this project were included.

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- [30] Math Bollen and Kai Yang, Harmonics and Wind Power - A forgotten aspect of the interaction between wind-power installations and the grid, Elforsk report 12:51, August 2012.
- [31] S. Rönnberg, A. Larsson, M. Bollen, J.-L. Schanen, A simple model for interaction between equipment at a frequency of some tens of kHz, Int. Conf. Electricity Distribution (CIRED), Frankfurt, June 2011.
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- [41] Hosting capacity for solar power in Northern Sweden, 2016-2019, funded by Swedish Energy Agency, Umeå Energi and Skellefteå Kraft.
- [42] Snezana Cundeva, Aleksandra Krkoleva Mateska, Math Bollen, Hosting capacity of LV residential grid for uncoordinated EV charging, ICHQP 2018.

HARMONICS AND WIND POWER

The introduction of wind-power installations adds a new source of harmonics to the power system. The primary emission from these installations is however small and the main impact is because of the introduction of new resonances by the capacitance of the cables in the collection grid or by the capacitance of long AC transmission cables. This project has contributed to a better understanding on these resonances and the way in which they affect the spread of harmonics from the turbines into the public grid and from the public grid into the collection grid.

The project has resulted in additional knowledge especially concerning the spread of harmonics through the wind parks (from the turbines to the public grid; between turbines; and from the public grid to the collection grid). That knowledge has been applied especially to the impact of capacitor energizing on wind-power installations and to the spread of different types of disturbances from PV installations to the low-voltage grid.

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