Wind-Turbine Harmonic Emissions and Propagation through A Wind Farm

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Thesis for the degree of Licentiate of Engineering

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I hear and I forget
I see and I remember
I do and I understand
—Confucius
Abstract

The increasing demand for sustainable energy is one of the driving forces behind the increasing use of wind power by means of wind-turbines in electric power systems. Modern wind turbines commonly employ variable-speed-generator technology associated with a power-electronic converter as part of the grid connection. A drawback of the use of power electronics is the presence of harmonic emissions. Consequently a systematic study on distortion from wind power installations is needed; this holds for individual wind turbines as well for complete installations.

In the work, measurements and analysis of harmonic emissions were performed on a number of wind-turbines in several wind parks in Northern Sweden. The measurements on the individual wind turbines reveal that the harmonic emissions are different from each other, even for different turbines from the same manufacturer. However in general the characteristic harmonics dominate the harmonic emissions. Furthermore, a long-term measurement shows that the dominant frequencies in the emission change with time.

The total emission from a wind park into the public grid is determined by the emission from individual turbines and by the properties of the wind park. To study the impact of the wind park on the propagation a “transfer function” method has been introduced, and applied by means of calculation and simulation. The method is based on a mathematical model that predicts the harmonic propagation from the wind turbines to the public grid in the frequency range up to 50 kHz. Applying the model to three example parks reveals that, the amplitudes at the resonance frequency are strongly dependent on the resistance of both underground cables and transformer, especially at high frequencies. In other words, the higher order harmonics are damped a lot.

In conclusion, wind park harmonic emissions into the public grid are due to the combination of emission from individual wind turbines and the propagation through the collection grid.

Keywords: Renewable energy, electric power system, wind power, power quality, power system harmonics.
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Kai Yang
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Part I
Introduction
Chapter 1

Introduction

1.1 Background

The ideal voltage or current waveform in the electric power system is sinusoidal at fundamental frequency 50 Hz (or 60 Hz) and at constant magnitude. However in reality, due to a number of reasons, the waveforms are non-sinusoidal (distorted) or of varying magnitude or frequency.

The international standard IEC 61000-4-30 [1] defines power quality as “characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters”. Alternatively, power quality is a combination of voltage quality and current quality, whereas voltage quality is concerned with deviations of an actual voltage from the ideal voltage, current quality is the equivalent for current [2].

Among the disturbances covered by the concept of power quality, power system harmonics, which are described in the classic book by Arrillaga [3], have been an important aspect of power system design and planning. The parameters mentioned in the definition according to IEC 61000-4-30, quantify among others the level of distortion of the voltage and current waveforms.

This distortion is quantified by splitting the waveform in a number of frequency components next to the power-system or fundamental component at 50 Hz (in Europe). The dominant non-fundamental components appear at frequencies which are integer multiples of the fundamental frequency [4,5]. Hence the term “harmonic distortion” is commonly used as synonym for “waveform distortion”, even if some of the frequency components in the waveform are not at harmonic frequencies. Those latter components are also referred to as “interharmonics”. In this thesis, the terms “waveform distortion” and “harmonic distortion” will be used as synonym following common practice.
Increasing levels of harmonic distortion are thought to be produced by the increasing use of power electronic devices from electricity generation to consumption [4]. An example of such power-electronic devices, the one being the subject of this thesis, are the power-electronic converters in modern wind-power installations. The main impact of increased emission of harmonic distortion is an increase in the harmonic voltage levels. The different sources of harmonic emission are discussed in more detail in Section 1.1.1, the impacts of harmonics in Section 1.1.2.

1.1.1 Main harmonic sources

Harmonic distortion, in voltage as well as in current, is due to the presence of so-called nonlinear components in the power system. Even when the voltage is sinusoidal, the resulting current could be non-sinusoidal for a nonlinear element. Power system harmonics may come from a range of different sources, as stated among others in [6], Chapter 3 and [7], Section 2.5.4. Briefly the three main harmonic sources [4] have been listed as the following:

The first type of harmonic sources is the use of a large number of small nonlinear components in the power system, e.g. televisions, personal computers, and fluorescent lamps. They are mainly diode bridge rectifiers acting as DC current source or DC voltage source [7], Section 2.5.4. Although the last few years have seen a shift to more advanced converters including so-called “active power-factor correction”. Non-controlled diode rectifiers show a spectrum with high levels of low-order odd harmonics (mainly harmonics 3, 5 and 7) whereas rectifiers with active power-factor correction show much lower levels of lower-order harmonics but instead emission at frequencies above a few kHz [8,9].

The second harmonic source is formed by large industrial installations. These installations often contain large power-electronic converters but also large and continuously randomly varying nonlinear loads, such as arc furnaces. Such industrial installations are connected to a high voltage level and often even to the transmission network. Because of this, one such source can result in high voltage distortion over a large geographical area.

The third harmonic source is due to the increasing use of large power electronic converters connected to the grid. Converters for high voltage direct current (HVDC) transmission have been known as a source of harmonics for many years. A recent addition to this are wind power generation systems. The presence of power-electronic converters makes that the harmonic emissions of individual wind turbines and of wind parks consisting of multiple turbines have become issues of concern for network operators as well. There remains however a lack of knowledge on this, which has been one of the
1.1. background

1.1.2 Impacts of harmonics

When the distortion of a voltage or current waveform exceeds certain levels it will result in a failure or damage of sensitive components in the power system. The impact is completely different for a distorted voltage waveform and for a distorted current waveform. The distorted voltage affects shunt-connected network components (e.g. capacitor banks) and end-user equipment (like compact fluorescent lamps or induction motors); while the distorted current affects series-connected network components (e.g. transformers) [7], section 2.5. The term “interference” or “electromagnetic interference” is used to refer to failure or damage of components due to voltage or current disturbances.

Excessive levels of harmonics may result in a number of interferences on equipment in the grid as well as with electrical equipment connected to the grid. Such interference can occur in the public grid but also in wind parks. Some examples of interference due to high levels of harmonic distortion are:

- High levels of voltage harmonics may damage capacitors. The displacement current through a capacitor increases with frequency, so especially high frequency voltage harmonics may result in overheating and damage of capacitors. Harmonics lead to increased thermal and dielectric stress with capacitors. The thermal stress is proportional to the square of the frequency and the dielectric stress is related to the amplitude of the voltage peak. All shunt-connected capacitors are impacted by voltage harmonics, capacitors in the grid, capacitors in wind parks, and also capacitors in end-user equipments.

- Voltage harmonics also increase the thermal and dielectric stress of underground cables. High levels of voltage harmonics, especially at higher frequencies, will therefore also result in loss of life-time for cables [10].

- Transformer heating due to current harmonics. A power transformer is designed for power conversion at the fundamental frequency. The other frequency components lead to a higher losses, especially for the current harmonics because of the high RMS current beyond need. The harmonic currents produce higher losses and higher thermal stress than the fundamental current. The overheating is due to the stray flux (the magnetic flux in conducting parts of the transformer due to the current through the windings). The stray losses give rise to “hot spots”, which
are a significant concern. Of more concern is the fact that the losses (for the same RMS current) are higher for higher frequencies. This is the same phenomenon as the increase of the frequency-dependent resistance that is discussed in the simulation part of this work.

- Heating of electrical motors due to voltage harmonics. High levels of especially fifth and seventh harmonic voltage results in currents through induction and synchronous motors that cause overheating and hot spots.

- Incorrect operation of protection due to current and voltage distortions. High levels of voltage and current distortions may result in incorrect operation of protection, especially in unwanted tripping of a protect relay. The consequence of this is that customers experience unnecessary interruptions of the supply.

- Failure of electronic equipment. An indirect example is that, the high frequency voltage couples to the electronic or logic circuit, leading to malfunction [7,11].

Despite the long list of possible interferences, in practice, damage or mal-operation due to harmonics is seldom observed in the power system. One reason for this is that accelerated ageing due to the heating by harmonics is difficult to notice. Large observations are needed to find statistically-relevant correlations between harmonic levels and accelerated ageing. However, the main reason for the lack of interference is that harmonic voltage and current levels are strictly limited during planning and design of power systems. Limitation of harmonic levels takes place in different ways: by limiting the emission by equipment and installations, through installation of harmonic filters, and by strengthening the grid [6].

1.2 Related Work

This section presents a review of related research literatures that the thesis has focused on. The main two topics are in terms of harmonic emissions and harmonic resonances.

1.2.1 Wind-park/wind-turbine emissions

In relation to harmonic measurement technology, inductive and capacitive voltage transformers with a nominal voltage of 45 kV are tested up to the 50th
harmonic (2500 Hz) in [12]. It is shown that inductive voltage transformers have a relatively small error up to 29\textsuperscript{th} harmonic, while capacitive voltage transformers have large errors already at frequencies of a few hundred Hz. Inductive voltage transformers are more common at lower voltage levels. This confirms the statement made in [13] that “for voltages to about 11 kV and frequencies under 5 kHz, the accuracy of most voltage transformers is satisfactory”. The same reference shows that at 33 kV between 1 and 2 kHz is an upper limit for which accurate results are guaranteed. Most of the measurements presented in this work concern current harmonics. About current transformers [13, Section 5.2.1] states that the conventional current transformers used for metering and relaying can also be used for harmonic measurements at least up to 10 kHz.

The harmonic emission and resonance of a wind park consisting of three turbines with full-power converter are discussed in [14]. It is shown in this publication that the emissions (quantified as harmonic and interharmonic current subgroups) are small. In [14] an estimation has been made of the network strength required to maintain harmonic voltage levels below the limit. It is shown that interharmonics set strict requirements on the network strength.

In two other papers [15,16], the results are shown of harmonic current measurement up to 9 kHz with a wind farm consisting of 5 turbines of 500 kW size each. The measurements are performed at the point-of-connection between the wind farm and the public grid. Analysis of harmonic magnitude and phase angle has been done, as well as statistic study with the wind farm output power. Among the results, harmonics at lower orders are synchronized with the fundamental frequency, while they show random phase angle at high frequencies up to 5 kHz. The paper shows a spectrum with mainly a continuous broadband emission up to a few kHz. The figures in these publications also shows that there is no correlation between the harmonic levels and the active-power production. It is further shown that the fifth harmonic current shows a normal distribution whereas the 50th harmonic is Rayleigh distributed.

The reference [17] specifies that, by using forced-commutated inverters in the individual turbines the low-order harmonics (to the order around 40) are eliminated and replaced by higher order harmonics (to the order around 200).

In the paper [18], computer modeling together with laboratory experiments are presented on various topologies of large populations of distributed power inverters. As such inverters are found in wind turbines, the results are relevant for our work as well. It is shown that parallel resonance can trip inverters due to a distorted supply voltage. It is further shown that the
topology has a large influence on the distortion in the network.

Paper [19] presents a harmonic distortion study of a wind farm connected to high voltage (HV) submarine cables. Measurement data is injected to the wind farm model, which consists of variable speed wind turbines with converters. The main spectral content between 1.0 and 1.5 kHz is due to the hysteresis PWM current controllers used in the grid-side converters of the wind turbines. Another study [20] based on the same model by the same author concludes that, harmonic distortion issues appear only for the local medium voltage (MV) network and not for the HV system, which was the initial point of concern.

1.2.2 Wind park harmonic propagation

Concerning the simulation work, [21] studies the harmonic impedance using the software package PowerFactory. In the study the investigated network is used as a reference and the results are compared with those of simplified balanced distribution system. A frequency swept method is applied to compare the two models in terms of positive, negative and zero sequence components. The conclusion is the simplified model is sufficient only for the zero-sequence component.

Papers [22,23] present measuring methods of system harmonic impedance. The former one presents the measurements of time-local impedance of the single phase power system loaded with switched and nonlinear loads. The latter applies a modal transformation which decomposes three phase power system voltages or currents into three sets of de-coupled quantities.

Paper [24] performs an impedance modeling, with frequency dependent resistances of both cable and transformer. The frequency dependent cable and transformer resistances are modeled up to 1.25 kHz. The measurements of resistance vs. frequency are used to curve-fit the parameters both in linear and exponential approximations.

The resonance phenomenon is indicated in [17] that, shunt capacitor banks associated with the grid inductance result in an oscillating circuit, which will amplify a single harmonic (most common according to [17] is an amplification of harmonic orders 7 and 11).

Paper [25] presents the results of a measurement with a converter for power-factor correction. The aim of the measurement is to analyze the interaction between the converter and the source. The paper concludes that the converter source interactions can lead to excessive harmonic current distortion. An impedance model is developed and used to improve the accuracy of the prediction of the interactions. Similarly [26] performs the harmonic resonance study by involving grid-connected parallel inverters in an impedance
Based approach.

Papers [27, 28] provide methods for modeling of MV overhead lines for frequencies up to 100 kHz. In those papers a comparison is made between different models. Both papers consider the modeling of power lines, while the latter also considers the transformer. Reference [29] presents the simulation of an offshore wind farm in the software IPSA. The turbines are of the double-feed induction generator (DFIG) type. A 30% reduction in voltage harmonics is observed when 70% of the wind turbines are operating. It is also shown that the harmonic impedance seen by the wind farm is dominated by the long transmission cables and characterized by resonances of the wind farm.

In paper [30], the impact of wind turbine generator connections on resonant modes of system impedance and total harmonic distortion in the network are discussed. The resonance is impacted by the injected number of wind turbines, as well as cable length. Additionally the total harmonic distortion (THD) is also impacted by the number of turbines in operation.

1.3 Motivation

A lot of wind power is installed in the grid and the amount is only increasing. One of the most important reasons is the requirement of global carbon dioxide emission reduction.

Unlike conventional thermal power generation or hydro power generation, large numbers of power-electronic converters are used in wind parks, mainly in the wind turbines. These power-electronic devices have many advantages but they inject waveform distortion into the collection grid and into the public grid. When these emission levels become too high a range of problems can appear. As wind turbines with large power-electronic converters as well as large wind parks have appeared only recently, there is a lack of knowledge on their harmonic emission and on the way this harmonic emission spreads from the individual turbines to the grid.

The harmonic levels are a concern to both wind park owners and network operators. Network operators are concerned that voltage distortion limits in the grid will be exceeded. Wind park owners have to cope with the emission limits set by network operators and are concerned about damage to equipment and protection mal-operation due to harmonics.

Additionally, wind parks are in almost all cases built with large numbers of underground cables; also capacitor banks are sometimes used for reactive-power compensation. The capacitance of cables and capacitors introduces harmonic resonances at rather low frequencies.

The main aim of this work is to study the harmonic emission from individ-
ual wind turbines into the collection grid and from wind-power installations consisting of multiple turbines into the public grid. Both measurements in existing wind parks with modern wind turbines and simulations of realistic installations will be part of this work.

1.4 Outlines of the Thesis

The thesis comprises of two main parts: Part I and Part II. Part I includes 6 chapters: Chapter 1 generally introduces the background of this research, phenomenon, source and consequence of harmonic distortion in the power system, as well as motivation and contribution of this work; Chapter 2 presents the principals of wind power conversion system; the wind park configuration and harmonic generation of individual wind turbines are discussed in Chapter 3; Chapter 4 discusses the simulation of harmonic propagation in a wind park; Chapter 5 indicates the harmonic distortion impacts on the grid; and the conclusion is summarized in Chapter 6. Part II includes the related papers in the work.

1.5 Contribution of the Work

In this thesis contributions are made on two related subjects: emission from individual wind turbines and propagation of this emission through the wind park to the public grid.

**Part A**: Emissions from individual wind turbines. Measurements from four types of wind turbine in different wind parks were analyzed and compared.

- The analysis and comparisons are performed among the individual wind turbines, and the general emission properties are described for the turbines. The similarities and differences from wind turbines have been addressed.

- Distinction between characteristic and non-characteristic harmonics have been obtained for the different types. Also the emissions have been divided into broadband and narrow band components. A high emission of non-characteristic harmonics has been found in wind generation.

- The method of minimum short-circuit ratio to quantify the impact of harmonic emission on the grid has been applied to the turbines. The evaluated emission levels have been presented by both harmonics and
interharmonics. An obvious high requirement due to the limits has been indicated.

**Part B:** Propagation through a wind park. A model based on a general wind park configuration is built up, based on the “transfer function”, which is the emission from wind turbines to the public grid.

- An “overall transfer function” has been introduced. The overall transfer function indicates the emissions from all wind turbines to the public grid. The emission aggregation and propagation have been considered in the model.

- The developed method has been applied to different wind parks, with consideration of the impacts of capacitance and frequency-dependent resistance. Amplification associated with resonances has been found to affect the propagation a lot with large amplitudes appearing at frequencies up to a few kHz. The transfer is negligible above this frequency range.

- Measurements at two locations in one wind park have been analyzed. The spectra of the emission measured with an individual turbine and with the substation show a similar trend, but different amplitudes. The aggregation effect is bigger for the total interharmonic distortion than for the total harmonic distortion.
Wind Power and Wind Turbine Emission

2.1 Wind Power Generation System

2.1.1 Wind power background and practical need

The atmosphere of the earth is being heated by the sun unevenly. This makes that some parts are warmer than others and these temperature differences result in the movement of air. The warmer air has a lower density than that of the cooler air. It makes the unbalanced atmospheric pressure, which results in the rising of low density air and sinking of high density air and finally the global airflow. Additionally the rotation of the earth associated with Coriolis effect makes that the patterns of movement are much more complicated. The horizontal movement of air (what is popularly called “wind”) contains mechanical energy in the form of “kinetic energy”.

The power from the wind has being used by human beings date back to 3000 years ago. For the last few hundred years wind power was used to pump water or to grind grain. Due to the oil crises of 1973 and 1978 [31], interests in new energy sources increased enormously, triggering among others research in wind power for electricity production. Danish engineers improved the technology by Dane Poul La Cour, who is credited with first using wind power for producing electricity, during the late 1890s [32,33]. The aim of this new development was to cover the shortage of electrical energy in Denmark. The technology quickly spread over the rest of the world.

In the foreseeable future, the petroleum production is expected to reduce and to drop below the demand. For electricity production, oil plays a relatively small role in a number of countries [34]. Natural gas and coal cover a
large part of the growth in consumption. Especially coal has, as one of its
disadvantages, the emission of large amounts of carbon dioxide [35], so that
these are not seen as a sustainable solution. Global carbon dioxide emission
and the resulting global warming are another reason for further developing
and employing wind power. Many countries prefer to increase the fraction
of wind power, not only for reducing their carbon dioxide emission reduction
reason, but also because it offers an economic alternative.

The global cumulative installed wind capacity (1996 - 2010) shows a fast
increasing trend as in Figure 2.1 (Figure from [36], which data originated
from Global Wind Report [37]).

\[ \text{Figure 2.1: Global Cumulative Installed Wind Capacity (1996-2010).} \]

The amount of electricity from wind power is also significantly increasing
in Sweden as shown in Figure 2.2 (data is coming from Elforsk and Swedish
Energy Agency [38]). The capacity and production from wind-power plants
in Sweden is dramatically increasing during the last decades. Sweden is an
attractive market for wind power development, because of the very good
wind resources especially in the south of the country and because of large
amounts of space (especially in the north).

According to the Swedish Wind Energy Association, the technical wind
energy potential in Sweden is estimated to be around 540 TWh/year, which
would be about four time the annual electricity production. The Swedish
Wind Energy Association estimates that Sweden will increase its wind en-
ergy production to around 30 TWh in order to reach the 2020 target [39].
The annual consumption of electricity in Sweden was 125 649 GWh (pure
consumption, not losses in the grid). Thus wind power was almost 2.8% of
consumption in 2010.
2.1.2 Power conversion

The kinetic energy stored in the wind is extracted and converted into electrical energy via a wind power generation system (i.e. a wind turbine). The wind turbine blades, which are designed to be rotating in a vertical plane, are driven by the kinetic energy of the horizontal wind movement under the fluid mechanical effect. Consequently the mechanical energy is extracted from the moving wind to the form of mechanical torque on the turbine shaft. The rotating shaft associated with the turbine generator converts the mechanical torque into electrical energy.

Wind flowing past a wind turbine can be considered as an airstream, as shown in Figure 2.3. Assume that, the wind velocity before the air reaching the turbine is $v_1$, air density $\rho$, and the cross-section area of the airstream $A_1$, and air volume $V_a$ that passes through the wind turbine per unit of time.

When the wind passes the turbine vertical plane, the wind kinetic energy is extracted by the wind generation system. The loss of the wind kinetic energy results in the decreasing of the wind velocity to be $v_3$. And suppose the airstream cross-section area is now $A_3$. The total volume of air remains constant, on the assumption that air density $\rho$ keeps constant, which gives:

$$V_a = v_1 \times A_1 = v_3 \times A_3$$  \hspace{1cm} (2.1)

The kinetic energy of the flowing air $W_{kin}$ is proportional to the moving mass $m$ and the square of the wind velocity $v$:

$$W_{kin} = \frac{1}{2} mv^2$$  \hspace{1cm} (2.2)
Figure 2.3: Power conversion from kinetic energy to electrical energy through a turbine airstream.

After passing the vertical plane of the wind turbine in the airstream (associated with energy extraction), the loss of air kinetic energy (manifests itself by a reduced velocity) is converted into the electrical energy. The amount of mechanical energy lost from the air stream and extracted by the wind turbine per unit of time can be expressed as [40]:

$$W_W = \frac{1}{2} \rho a (v_1^2 - v_3^2) \quad (2.3)$$

In reality not all the kinetic energy contained in the wind is converted into electricity. The theoretical maximum amount of power that can be extracted from the wind has been given as 59%, which was first discovered by Betz in 1926.

Instead of the equation (2.3), the power extraction from the wind can also be written in terms of power as:

$$P_W = \frac{1}{2} \rho c_p A_R v_1^3 \quad (2.4)$$

where the output power $P_W$ is a function of the dimensionless performance coefficient $c_p = \frac{P_W}{P_0}$ with $P_0$ the potential power in the air, and the swept area of blades $A_R$.

In practice, the power extracted from the air is less than the upper limit of 59%. Furthermore, due to mechanical and electrical losses, there is a limit of the lowest wind speed before the generator can start producing electricity, which is called “cut-in speed” (normally around 3 m/s). And the highest
speed (normally around 25 m/s), called “cut-out speed”, at which the turbine is shut down to protect it against excessive forces during storms. Thus a wind turbine is only producing electricity when the wind speed is between the cut-in speed and the cut-out speed.

2.1.3 Wind turbine topologies and electricity generation

Wind turbines are classified into four main topologies belonging to two groups. The first topology is the fixed-speed and the other three are variable speed. During 1980s and 1990s, two-thirds of the worlds installed wind turbines were fixed-speed models, which were developed in the late 1970s by pioneers in Denmark [41]. Those wind turbines are equipped with a gear box, an induction machine (squirrel cage or wound rotor), and a capacitor bank for reactive power compensation. The turbine’s rotor speed is fixed by the supply grid frequency, independent of the wind speed. This kind of turbine has a low investment cost, is reliable and requires limited maintenance. However there are some other problems: for example, uncontrollable reactive power consumption, and power fluctuations at sub-second time scale potentially resulting in light flicker [42], but also the limited efficiency and the need for a gear box.

![Figure 2.4: Fix-speed wind turbine.](image)

During the past few years, variable speed wind turbines are widely used. They can achieve higher efficiency from the wind power conversion. They comprise of induction or synchronous machines and are connected to the grid through power converters. There are a number of advantages to use power converters, e.g. the power conversion efficiency. However, it increases the cost of the wind turbine, and makes the technology more complicated and possibly less reliable. The power-electronic converters cause waveform distortion which is the subject of this work. In the late 1990’s development was going on towards permanent-magnet DC generators [43].
The three types of state-of-the-art variable speed wind turbines are shown in Figure 2.5:

- **Type A** Limited variable speed. This type of wind turbine is equipped with variable generator rotor resistance to control the rotor speed. It uses a wound rotor induction generator, together with a soft-starter and a capacitor bank. This turbine type offers limited amount of speed variation, but the wound-rotor induction motor is more expensive and requires more maintenance than the squirrel-cage motor. Also this type does still require a gear box, a soft starter and a capacitor bank.

- **Type B** Variable speed with partial scale frequency converter. The double fed induction generator concept, which is equipped with a wound rotor induction generator and partial scale frequency converter. It has a wide range of dynamic speed control, depending on the frequency converter. While the drawbacks are the use of slip rings and protection in the case of grid faults [32].
• **Type C** Full-scale frequency converter. The generator is connected to the grid through a full scale frequency converter. The frequency converter performs the reactive power compensation and the grid connection smoother. The generator could be a wound rotor synchronous generator or a permanent magnet generator. There is no need for a gear box in this type of wind turbine.

The frequency converters used in Type B and Type C of variable-speed wind turbines can be used to control the reactive power exchanged with the power grid.

### 2.1.4 Wind parks

A wind turbine is normally equipped with a turbine transformer, either in the hub or beside the turbine tower. The rated voltage is around several hundred volts with 690 V and 960 V typical values. The voltage on medium-voltage side of the turbine transformer is some tens of kV (as shown in Figure 2.4 and Figure 2.5). In the wind park, a number of wind turbines are connected into the collecting point by means of underground cables. Normally each turbine is equipped with its own turbine transformer and the collection grid at medium voltage (typically 10 to 30 kV) is used to transfer the power towards the point of connection with the public grid.

The voltage is next, by the grid transformer, increased to a proper level suitable for the transmission grid. In some large installations the transformation to grid voltage takes place in two stages; e.g. from 20 to 130 kV at a substation close to the wind turbines and from 130 to 400 kV at a substation in the public transmission grid.

An example layout of a wind park is shown as in Figure 2.6. Numbers of wind turbines are collected through underground lines/cables. These wind turbines are distributed along several cables. The “voltage source symbol” (circle around sine wave) represents a wind turbine equipped with a turbine transformer, which is installed inside or beside the wind tower. The layout of a wind farm is mainly determined by the wind condition throughout the whole year, and by the effects of the neighboring turbines. Normally due to a consideration of energy efficiency and wind turbulence, the distance is roughly 5-7 rotor diameters between neighboring turbines (often the distance is more in the direction of the prevailing wind).
2.2 Harmonic Distortion in Wind Power Generation

The main sources of harmonic distortion in a wind-power installation are listed in the following [6,44]:

- Induction motors produce some harmonics and interharmonics.
- Power transformers emit a small amount of low-order odd harmonics due to the magnetizing current. This emission is normally small but increases fast with rising RMS voltage.
- The main source of harmonics is formed by the power-electronic converters with turbines of Type B and C (in Figure 2.5).
- In some wind parks large power-electronic converters are part of the collection grid, mainly used for reactive-power compensations. These
converters are also sources of harmonics. Some wind parks are connected to the grid through an HVDC link. The emission into the grid would in that case be due to the grid-side converter.

In this thesis the measurements of harmonic emission are mainly from Type B and Type C variable-speed turbines.

The current at the terminals of a wind turbine with power electronic converter is non-sinusoidal, even if the voltage over the terminals is sinusoidal. The standard IEC 61400-21 [45] describes the harmonic emission measurement procedure for an individual wind turbine. However it focuses on the individual wind turbine rather than a wind park. The wind park emission needs to be evaluated by combining the harmonic emissions from individual wind turbines.

### 2.2.1 Distortion from individual turbines

Two main key-words are used throughout the thesis: emission and resonance. The emission in this work concerns the generated non-sinusoidal distortions included in the voltage or current waveforms. There are two types of emissions specified in the work. One is the emission from an individual wind turbine, where the wind turbine components act as a distortion source. The other one is the emission from a wind park. The harmonic source is from wind turbines or other power electronics in the wind park. The distortions in current at the collecting point of the wind park is the so-called wind park emission.

Concerning the electrical effect of the wind park, the resonance is a significant contributing factor. A capacitance associated with an inductance in a circuit forms a resonance circuit. Such a resonance circuit, if under-critically damped, will amplify voltage and / or current distortion at frequencies close to the resonance frequency. A resonance is characterized by two parameters: magnitude and resonance frequency. The magnitude is infinite when no resistance is present in the circuit. The resonance frequency is the main property of this oscillation: it is mainly determined by the circuit capacitance and inductance parameters.

Distortions with frequencies around the resonance frequency are amplified. Other distortions beyond the resonance frequency may be damped. So the emission from a wind park is determined by the emission from an individual wind turbine and by the resonances.
2.2.2 Transfer to the grid
The harmonics from individual turbines are one contribution to the emission of a wind park. However the different layouts and configurations of the wind park will produce resonances and thereby impact the total emission as well. The underground cables, which collect power from each wind turbine to the public grid, possess a significant shunt capacitance. For a number of reasons, some wind park is equipped with capacitor bank. In combination with the inductance from cables and the transformer, resonances are produced by these capacitances.

2.3 Mitigation of Wind Power Harmonics
As mentioned in Chapter 1, wind power harmonics, especially by the use of power electronics, have the potential to cause interferences to installations in the power system and end-users. Consequently there is a need to limit the harmonic voltage and current levels.

The effects (on harmonic emission) of the electronic power conversion system are dependent upon the state of the power converter and the prevailing grid parameters at the point of connection. So among the two elimination approaches as specified in [6,40], designing a low emission converter is one of the approaches. The second approach is to keep the emission low at the point of connection with the grid, which is typically done by means of installing harmonic compensation equipment either inside of the installation or at the terminals.

In the latter approach, passive circuit filters or active compensation can be applied to reduce the harmonics [6,40].
Chapter 3

Wind Turbine Harmonic Emission

3.1 Emissions from Individual Wind Turbines

3.1.1 Measurement requirements

The measurements in this work is based on the following standards with specified requirements. As mentioned in Chapter 1, IEC 61400-21 [45] specifies the harmonic measurement and analysis procedure for grid-connected wind turbines, especially those equipped with power electronic converters. Besides, standards IEC 61000-4-30 [1] and IEC 61000-4-7 [46] provide the measuring method on harmonic emissions. The spectrum is smoothed by introducing groups and subgroups for both harmonics and interharmonics, to improve the assessment accuracy which is due to the spectral leakage by the signal fluctuations.

The basic measurement window consists of 10 cycles of fundamental sinusoidal waveforms in a 50 Hz system or 12 cycles in a 60 Hz system (approximate 200 ms in time duration). The instrument used for the measurements in this work is sampling at a rate of 12.8 kHz (To be fully accurate: 256 times the power-system frequency which is tracked using a phase-locked loop). Applying the Discrete Fourier Transform (DFT) to the basic measurement window, it results in a 5 Hz spectrum resolution. Harmonic $G_{g,n}$ and interharmonic $G_{ig,n}$ groups at order $n$ are defined as (take a 50 Hz system for example):

$$G_{g,n}^2 = \frac{C_{k-5}^2}{2} + \sum_{i=-4}^{4} C_{k+i}^2 + \frac{C_{k+5}^2}{2}$$

(3.1)

$$G_{ig,n}^2 = \sum_{i=1}^{9} C_{k+i}^2$$

(3.2)
where \( C_k \) is the central component (i.e. the DFT component) with index \( k \) of the harmonic/interharmonic order \( n \) (\( k = 10 \times n \) in accordance with the measurements); thus the harmonic group \( G_{g,n} \) is derived from the 11 DFT components \( C_{k-5}, \ldots, C_{k+5} \) and and interharmonic group \( G_{ig,n} \) is from the 9 DFT components \( C_{k+1}, \ldots, C_{k+9} \).

Harmonic \( G_{sg,n} \) and interharmonic \( G_{isg,n} \) subgroups at order \( n \) are defined as (take a 50 Hz system for example):

\[
G_{sg,n}^2 = \sum_{i=-1}^{1} C_{k+i}^2 \quad (3.3)
\]
\[
G_{isg,n}^2 = \sum_{i=2}^{8} C_{k+i}^2 \quad (3.4)
\]

where the harmonic subgroup \( G_{sg,n} \) is derived from the 3 DFT components \( C_{k-1}, \ldots, C_{k+1} \) and and interharmonic subgroup \( G_{isg,n} \) is from the 7 DFT components \( C_{k+2}, \ldots, C_{k+8} \).

Note that in this work the harmonic order with integers represent harmonics, e.g. harmonics 1, 2, 3, \ldots; the others with half represent interharmonics, e.g. interharmonics 1.5, 2.5, 3.5, \ldots.

### 3.2 Characteristic Harmonics

#### 3.2.1 Principal characteristic harmonics by six-pulse rectifier

Wind turbines supply three-phase AC currents into the collection grid. The latter two types of state-of-the-art variable speed wind turbines as listed in Chapter 2, are equipped with power electronic converters (with a configuration: rectifier - DC link - inverter). Such converters transform the voltage and current from AC to DC (rectifier), and from DC back to AC (inverter). The inverter is normally on the grid side as the power flow is normally from the rotating machine to the grid. The six-pulse rectification, which is used in almost all the three-phase converters, is shown as in Figure 3.1.

Instead of diodes, power-electronic converters are equipped with switching technology such as IGBT or GTO. With the switching technology, the input three-phase AC voltage and current are transformed into DC by the switches working in turn. Six switches produce the DC voltage and current on the DC side under the three phase supply. A balanced three-phase supply then produces the DC output voltage as in Figure 3.2.
3.2 CHARACTERISTIC HARMONICS

The DC voltage is periodic with a period of one-sixth of the power system frequency (50 Hz). The voltage can thus be written as a DC component plus a 300 Hz component (6 times 50 Hz) plus harmonics of this component. Assume the input 3-phase voltages are sinusoidal. The theoretical DC component is thus expressed as:

\[ v_{DC}(t) = V_0 + \sum_{k=1}^{\infty} V_{6k} \cos(6k\omega_0 t + \phi_{6k}) \]  

(3.5)

where \( v_{DC}(t) \) the output DC voltage waveform as a function of time; \( V_0 \) the voltage of two phase joint point (approximate 0.8659\( V_{max} \)); \( V_{6k}, \phi_{6k} \) the amplitude and phase angle of this waveform; \( \omega_0 \) the radial frequency.

This voltage is the input voltage to the inverter. When a PWM-controlled inverter is used, the AC-side voltage of the converter consists of a low-frequency and a high-frequency component. The high frequency component contains the switching frequency. The low-frequency component consists of an ideal sine wave amplitude modulated by the DC voltage:

\[ v_{out}(t) = v_{DC} \times \cos(\omega_0 t) \]  

(3.6)

Equations (3.5) and (3.7) gives the following expression:

\[ v_{out}(t) = V_0 \cos(\omega_0 t) + \sum_{k=1}^{\infty} V_{6k} \cos(6k\omega_0 t + \phi_{6k}) \times \cos(\omega_0 t) \]

\[ = V_0 \cos(\omega_0 t) + \sum_{k=1}^{\infty} V_{6k} \cos((6k + 1)\omega_0 t + \phi_{6k}) + \sum_{k=1}^{\infty} V_{6k} \cos((6k - 1)\omega_0 t + \phi_{6k}) \]  

(3.7)
Figure 3.2: Three phase six-pulse input voltage and output DC voltage waveforms.

Equation (3.7) shows that, the harmonics on the grid-side of the inverter appear at orders $h = 6k \pm 1$, where $k = 1, 2, 3, \ldots$. These harmonic components are called “characteristic harmonics”, while the others are zeros under the balanced sinusoidal voltages, which are called “non-characteristic harmonics”.

As well, the current flow is shown as in Figure 3.1. Suppose that the three-phase input currents are sinusoidal. The current flow is thus under the following conditions:

- the current waveform is periodic with a 20 ms period (50 Hz system) for $i_a, i_b, i_c$;
- the positive ($i_1, i_3, i_5$) and negative ($i_2, i_4, i_6$) half cycles of flowing current are symmetrical;
- the three phase currents are balanced and with equal 120 degree fundamental frequency shift.

The resulted DC current is also a six-pulse waveform. Thus it results in characteristic harmonic components at orders $h = 6k \pm 1$, the same as that of the voltage.

The characteristic harmonics occur when the above three conditions are satisfied. And furthermore, interharmonics appear in the case that the first
condition is not satisfied; the even harmonics occur when the second condition is not kept [7].

### 3.2.2 Harmonic measurement

In this section, measurements of four types of wind turbine, mainly in terms of harmonic distortion, will be presented based on the measuring method in Section 3.1.1. The details of the four types of wind-turbine are presented in Table 3.1:

<table>
<thead>
<tr>
<th>Turbine type</th>
<th>Gear box</th>
<th>Generator type</th>
<th>Converter type</th>
<th>Nominal current</th>
<th>Nominal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nordex N90/2500kW</td>
<td>Yes</td>
<td>Asynchronous</td>
<td>IGBT</td>
<td>66 A</td>
<td>22 kV</td>
</tr>
<tr>
<td>Enercon E40/600kW×3</td>
<td>No</td>
<td>Synchronous ring generator</td>
<td>Enercon converter</td>
<td>104 A</td>
<td>10 kV</td>
</tr>
<tr>
<td>Vestas V90/2000kW</td>
<td>Yes</td>
<td>Asynchronous</td>
<td>IGBT</td>
<td>36 A</td>
<td>32 kV</td>
</tr>
<tr>
<td>Enercon E82/2000kW</td>
<td>No</td>
<td>SYNC-RT</td>
<td>Enercon converter</td>
<td>116 A</td>
<td>10 kV</td>
</tr>
</tbody>
</table>

Note that, the measurement of the second type of wind turbine was performed for three identical turbines connected to one LV/MV transformer, whereas the others were performed for single wind turbines. All four measurements were performed on the MV side of the turbine transformers.

These measurements have been performed with instruments Dranetz PX5 and PowerVisa, which are equipped with the same processing modules. The harmonic/interharmonic subgroups are computed and recorded in every 10-minute interval, using the frequency aggregation methods specified in the standard IEC 61000-4-7 and the time aggregation methods in IEC 61000-4-30. The measurements were performed continuously during a measurement period ranging from one week to one month, and performed separately for the four installations.

The recorded harmonic and interharmonic subgroups were sorted, and the 95 percentile value of each order of harmonic and interharmonic subgroups...
was computed to represent the harmonic and interharmonic levels for the corresponding wind turbines.

Applying the above steps, the 95% values of orders from 0 to 40 for each subgroup (both harmonics and interharmonics) are derived. The 95% value plots of harmonic current are seen in Figure 3.3 with subplots of the four turbine types: Figure 3.3 (a) Nordex N90, Figure 3.3 (b) Enercon E40, Figure 3.3 (c) Vestas V90, and Figure 3.3 (d) Enercon E82.

The four subplots show that the characteristic harmonics are dominating although different characteristic harmonics appear in different turbines. The main emissions are distributed in the lower harmonic orders, less than 20. Even though, each type of wind turbine has its own character that is discussed in the following paragraphs.
In Figure 3.3(a) (with turbine Nordex N90) harmonic orders 0.5, 2, 2.5, 5, 12, 12.5 and 13 are dominating. The characteristic harmonics 5 and 13 are apparent here. Emissions of non-characteristic harmonics, e.g. harmonics 0.5 and 2, are relatively high (compared to the characteristic harmonics), as well as harmonic orders higher than 20. The high levels of interharmonics 0.5 and 1.5 may be due to the fast variation with time of the 50 Hz component.

The emission of the second turbine type (Enercon E40) is seen as in Figure 3.3(b). The apparent broadband and narrow bands are seen in the 95% value plot. Also it shows the decreasing emissions along the orders up to 40. Significantly the characteristic harmonics 5, 7, 11, 13 and 17, by the six-pulse full-power converter, are clearly visible in the figure.

The other two figures, Figure 3.3(c) (Vestas V90) and Figure 3.3(d) (Enercon E82) present similar harmonic emissions with a similar trend and the dominating harmonics at 5.5th and 7.5th orders. However the emission levels are different due to the different rated currents as in Table 3.1.

Consequently it is concluded that, harmonic emissions differ among wind turbines.

The wind turbines are operating on different nominal currents. In order to compare the emissions of the four turbines, a percentage value (ratio) of the dominating harmonics and the nominal current is obtained as in Table 3.2. It is worth noticing that none of the frequency components exceeds 1% of the nominal current. The emission levels are relatively low, compared to measurements on domestic installations [47–49].

<table>
<thead>
<tr>
<th>Order</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>IH 0.5</td>
<td>0.662%</td>
</tr>
<tr>
<td>IH 1.5</td>
<td>0.433%</td>
</tr>
<tr>
<td>H 2</td>
<td>0.318%</td>
</tr>
<tr>
<td>H 5</td>
<td>0.397%</td>
</tr>
<tr>
<td>IH 12.5</td>
<td>0.353%</td>
</tr>
</tbody>
</table>

Table 3.2: Five highest emission levels (maximum of the three phases) of the measured wind-turbines (Abbreviations: harmonic - H; interharmonic - IH).

The second type of wind turbine with full-power converter apparently emits minimum among the four. Similarly in the four turbines, high emission at the orders 0.5 and 1.5 are apparently high around the fundamental components. And characteristic harmonics are the main emissions. Furthermore, turbines with same type of converters (Enercon E40 and E82) do not
have the same emission pattern.

### 3.2.3 Average spectra

The previous section applies the 95% value of harmonic and interharmonic subgroups of various 10-minute intervals to represent the harmonic levels. In this section, the emission is instead quantified by averaging the spectra over each 200 ms waveform, introducing the term “average spectrum”.

The average spectrum is derived from the square-root of the average squares summation from the series harmonics at each frequency:

\[
X_{\text{average}} = \sqrt{\frac{\sum_{i=1}^{N} X_i^2}{N}} \tag{3.8}
\]

where \(X_{\text{average}}\) and \(X_i\) are a spectrum at a specified frequency, the former average spectrum of the whole measurement and the latter single spectrum during a 200 ms, and \(i\) the index of each measured harmonic (at the specified frequency) from a 200 ms waveform during the whole measurement.

The four average spectra are shown as in Figure 3.4 with subplots of the four turbine types: Figure 3.4 (a) Nordex N90, Figure 3.4 (b) Enercon E40, Figure 3.4 (c) Vestas V90, and Figure 3.4 (d) Enercon E82.

Slightly Figure 3.4 makes some difference from that of Figure 3.3. This is reasonable due to the following reasons: the 95% value is obtained by the 95% largest value from sorted subgroup series (from minimum to the maximum value), whereas the average spectrum is obtained from average value at certain frequency from each 200 ms spectrum. One example of the difference is that, the ratio of the average value of harmonics 5 and 7 (as in Figure 3.4(a)) is a little larger than the ratio of the 95% value (as in Figure 3.3(a)).

Anyhow the average spectrum presents an average spectrum with 5 Hz resolution, which is of difference comparing to the 50 Hz of the 95% value. Thus for the weighted average spectrum at a specified frequency, there is less impact by the neighboring components. Whereas the components of 95% value might be grouped into high value by the neighboring high value components. An example is that, in Figure 3.4 (a) the high value components around the central component of harmonic 13 result in a high 95% value as in Figure 3.3 (a). Thus the average spectrum is a compensation for the details between two harmonic orders.

The four spectra, as in Figure 3.4, consist of a broadband over large parts of the frequency band associated with narrow band emissions at the characteristic harmonics.
Figure 3.4: Average spectra of the current. (a) Nordex N90. (b) Enercon E40 ×3. (c) Vestas V90. (d) Enercon E82.
Chapter 4

Harmonic Propagation and Transfer Function

4.1 Introduction

As mentioned in the previous chapters, wind power installations, especially those equipped with power-electronic converters, inject harmonics first into the collection grid and next into the public grid.

The relation between the emission from one turbine and the emission from the park as a whole is the subject of this chapter. This “propagation” from the turbines to the grid is determined by the structure and parameters of the collection grid. An important role in the propagation is played by harmonic resonances [4, 6, 7]. The resonance in some case may damp or amplify the waveform distortions from the harmonic sources. There are two types of resonances to be considered in the power system: parallel resonance and series resonance.

A parallel resonance occurs when the impedance of a capacitor and an inductor have the same absolute value in two parallel branches. The result is a very high impedance which amplifies harmonic currents. In case of a wind park, a parallel resonance results in high emission from the wind park into the public grid. Parallel resonances are a concern for all frequencies that are present in the emission from the individual turbines.

A series resonance occurs when a capacitor and an inductor have the same absolute value in a series branch. The result is a low impedance, which can amplify harmonic voltages. In case of a wind park a series resonance results in high harmonic currents being driven by the background voltage distortion in the public grid. This is only of concerns for frequencies present in the background voltage, in practice only the characteristic harmonics.
In [8, 9] the term “primary emission” and “secondary emission” are introduced. Primary emission is flowing from the wind park into the public grid, driven by the emission from the individual turbines. Secondary emission is flowing from the public grid into the wind farm. It is driven by all other sources of harmonics outside of the wind park. A parallel resonance amplifies the primary emission. A series resonance amplifies the secondary emission.

Because wind power generation works as a harmonic source injected into the power system, the parallel resonance is significant in the harmonic propagation study. Each wind turbine acts as a harmonic source in the collection grid. From the interface between the turbines and the collection grid harmonics propagate through the collection grid to the public grid. Resonances play an important role in this propagation. Finally the sum of the contributions from the individual turbines will be injected into the public grid.

The aim of this chapter is to study the harmonic current propagation, especially the resulted resonances, from the wind turbine connection to the public grid, by the certain configuration of wind park. A study model with the idea of transfer function is made. The impacts of different parameters of collection grid components are evaluated through the calculated model.

4.2 Theoretical Simulation

4.2.1 A wind park model

Suppose that, there is a wind park with a number of wind turbines, which are installed along the parallel underground cables. Each wind turbine is equipped with a turbine transformer to adjust the collection voltage level. A capacitor bank is installed to the main busbar. Through a substation transformer, the wind park is connected to the public grid. The configuration is shown as in Figure 4.1.

Suppose all the parallel cables have the same length $l_3$. A wind turbine associated with the turbine transformer (considered as a harmonic source) is located at the distance of $l_1$ from the busbar; and the cable length $l_2$ is connecting the remaining wind turbines along the same feeder; thus the total length of one cable is $l_3 = l_1 + l_2$.

4.2.2 Transfer function

In this study the transfer function is employed to characterize the impacts of harmonic current propagation from the wind turbine to the public grid.
Suppose that, the complex current from one individual turbine into the collection grid is represented as $I_t(\omega)$, with $\omega$, the angular speed. The “individual transfer function” $H_{tg}(\omega)$ from the individual wind turbine to the grid relates this current with its contribution to the (complex) current flowing into the public grid $\Delta I_g(\omega)$. The individual transfer function is thus expressed as:

$$H_{tg}(\omega) = \frac{\Delta I_g(\omega)}{I_t(\omega)} \quad (4.1)$$

The total complex current $I_g(\omega)$, from all ($N$) wind turbines in the wind park, flowing into the public grid is the summation of all the individual contributions (if the interactions among the wind turbines are ignored, and the wind farm is assumed to be a linear system):

$$I_g(\omega) = \sum_{t=1}^{N} \left( H_{tg}(\omega) \times I_t(\omega) \right) \quad (4.2)$$

In reality equation (4.2) cannot be used to calculate the final emission into the public grid, because magnitude and phase angle of the individual frequency components of the different turbines are not very well known. To obtain a more applicable expression, assumptions have been made that, the emission from each wind turbine is identical in magnitude but with random phase. With the consideration of the aggregation for random phase angles,
the square-root law can be applied to obtain the absolute value of the overall emission $I_{g}(\omega)$ from the individual transfer functions $H_{tg}(\omega)$ and the individual emission $I_{t}(\omega)$ of the turbines:

$$I_{g}(\omega) = \sqrt{\sum_{t=1}^{N} H_{tg}^{2}(\omega) \times I_{t}(\omega)}$$

(4.3)

Consequently the transfer function from $I_{t}(\omega)$ to $I_{g}(\omega)$ in equation (4.2) is called “overall transfer function”, which considers the aggregated current from the individual wind turbines. It is derived from the ratio of overall emission $I_{g}(\omega)$ and individual emission $I_{t}(\omega)$:

$$H_{g}(\omega) = \sqrt{\sum_{t=1}^{N} H_{tg}^{2}(\omega)}$$

(4.4)

Suppose all the individual transfer functions are identical, the overall transfer function is in that case:

$$H_{g}(\omega) = \sqrt{N} \times H_{tg}(\omega)$$

(4.5)

In order to obtain the transfer function for the studied wind park, a frequency-dependent cable model is a basic requirement. In [50] an incremental length model of a transmission line or cable is presented with consideration of the distributed character and of the frequency-dependence of the cable parameters. An equivalent circuit of a cable is obtained from the incremental model, as shown in Figure 4.2.

$$Z' = \frac{Z \sinh(\gamma L)}{\gamma L}$$

(4.6)

where $Z = z \times L$; $z = r + j\omega l$ the series impedance per unit length; $r$ the series resistance per unit [$\Omega$/m]; $l$ the series inductance per unit length per
phase [H/m]; $L$ the length of the cable, $\gamma = \sqrt{(r + j\omega l)j\omega c}$ the propagation constant.

And the equivalent shunt admittance per phase to neutral $Y'$ [S] is:

$$Y' = 2Y \frac{\tanh(\frac{\gamma L}{2})}{\gamma L}$$  \hspace{1cm} (4.7)

where $Y = y \times L$; $L$ the length of the cable; $y = j\omega c$; with $g$ the shunt conductance per unit length phase to neutral [S/m]; and $c$ the shunt capacitance per unit length phase to neutral [F/m].

Additionally the cable resistance is corrected as in [51, 52]:

$$R(f) = X_R(f) \times R$$  \hspace{1cm} (4.8)

where $R(f)$ is the correction factor obtained from equation (4.9) at frequency $f$, and $R$ the resistance at fundamental frequency.

The correction ratio $X_R$ for the resistance is:

$$X_R = \frac{\arcsin\left(\frac{r_{wire} - \delta}{r_{wire}}\right) \times r_{wire}^2}{-(r_{wire} - \delta)\sqrt{r_{wire}^2 - (r_{wire} - \delta)^2}/(2r_{wire} \times \delta)}$$  \hspace{1cm} (4.9)

where $r_{wire}$ is the radius of a single wire, $\delta$ the skin depth.

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$  \hspace{1cm} (4.10)

where $\rho = 1.68 \times 10^{-8}$ $\Omega$m is the resistivity of the copper conductor (from standard IEC 60287-1-1 [53]); $\mu = 1.256 \times 10^{-6}$ $\text{Hm}^{-1}$ the permeability of the conductor.

The transformer resistance, is an exponential function of the frequency expressed as:

$$R_T = R_{50} \times \left(\frac{f}{50}\right)^\alpha$$  \hspace{1cm} (4.11)

here $R_T$ the frequency-dependent resistance at frequency $f$; $R_{50}$ the resistance at 50Hz; $\alpha$ the skin-effect exponent.

With the above component models, the equivalent circuit for the wind park shown in Figure 4.1 is obtained as in Figure 4.3.

In the figure, $C_b$, represents the capacitor bank and $L_5, R_5$ represent the transformer model. Other components are obtained from the equivalent models of the wind park cables.
The transfer function is obtained as the ratio between the output current to the public grid and the input current from the wind turbine. The transfer function is then derived as:

$$
H_{tg}(\omega) = \frac{Z_{34}}{Z_{34} + j\omega L_5 + R_5} \times \frac{Z_{12}}{Z_{12} + Z_3}
$$

(4.12)

where the impedance $Z_{12}$ replaces the circuit elements $Y_1$ and $Y_2$, $Z_2$; and $Z_{34}$ replaces $C_b$, $Y_3$ and $Y_4$, $Z_4$.

High values of the transfer function occur when $|Z_{34} + j\omega L_5 + R_5|$ or $|Z_{12} + Z_3|$ reaches its minimum value.

### 4.2.3 Impact of resistance

A case study has been performed with a hundred-turbine wind park. The results of this case study are shown in Figure 2.6. Without capacitor bank present, two values of the transformer skin-effect component are considered: a low value $\alpha_{low} = 0.8$, and a high value $\alpha_{high} = 1.0$. Figure 4.4 and Figure 4.5 show the transfer functions for the low and high skin-effect exponents, respectively.

In the figures, left-top plots are the overall transfer function up till 50 kHz. The right-top ones are the absolute individual transfer functions of the ten wind turbine on one feeder. Because of the symmetrical configuration, these ten individual transfer functions represent the other nine feeders also. Left-bottom plots are the first individual resonances (of the ten individual transfer functions), and the right-bottom ones are the third individual resonances.

The peaks in the transfer functions represent the parallel resonances due to the maxima (4.12). These resonances are a significant concern of harmonic propagation.

The overall transfer function expresses the entire transfer from all the turbines to the grid. It is obtained as the aggregation of all the individual transfer functions. Those close individual transfer function resonances (in
frequencies) result in a single peak in the overall transfer function, e.g. the peak at around 1.5 kHz in both figures. Whereas the larger differences of individual transfer function resonances result in multiple peaks in the overall transfer function, e.g. the third resonances.

As seen in the two figures, the ten closer individual transfer functions result in about 8 times the maximum in the individual transfer functions. The larger difference of the third individual resonances results in around 4 times. In principal as in equation (4.5), all the equal individual transfer functions will make it 10 times the individual transfer function.

The resistance changed from low to high, as shown in Figure 4.4 and Figure 4.5, mainly results in: the first and the third resonances of both individual and overall transfer functions are damped. The individual transfer functions being damped to be almost half. Whereas the resonance frequencies remain almost the same. In contrast, the other resonances don’t change noticeably, e.g. the second resonances.

The impact by the resistance shows that, the frequency-dependance resistance has no impact on the resonance frequency, but damps some of the resonances.
4.2.4 Impact of capacitor size

The presence of a capacitor bank may change both resonance frequency and amplitude [54]. Suppose there are ten steps (0.1C to C) available for the size of the capacitor bank (C = 50 Mvar); each step will result in a different transfer function. The first resonance frequencies and amplitudes in the overall transfer functions are obtained for these 10 capacitor sizes as shown in Fig.4.6.

The resonance amplitudes decrease with increasing capacitor size. The amplitude in the overall transfer function is produced by the summation of the ten individual transfer functions. The closer individual resonances result in a higher resonance of overall transfer function. In contrast, the larger injected capacitor bank damps the overall transfer function. In general, Figure 4.6 shows a decreasing trend with frequency of the first resonance amplitudes in the overall transfer function.

4.2.5 Impact of cable length

The previous sections discussed the transfer functions with fixed cable length L. In this section the cable length is increased to 2L in step of 0.2L. Similarly the first six resonances (peaks of the apparent resonance group) of the overall
transfer function are shown in Figure 4.7 (frequency trend) and Figure 4.8 (amplitude trend):

As shown in Figure 4.7, the resonance frequencies become smaller with the increasing cable length. A longer cable length concentrates the resonances in a narrower frequency range.

The amplitudes of resonance are as shown in Figure 4.8. The first resonance amplitude shows a small decrease with cable length. The others show a more irregular decay. The irregular behavior is due to the multiple peaks making it difficult to decide what the amplitude actually is.

Figure 4.6: First resonances of overall transfer functions as a function of the capacitor size.
Figure 4.7: Impact of cable length on resonance frequencies of overall transfer function.

Figure 4.8: Impact of cable length on resonance amplitudes of overall transfer function.
Grid Impact

5.1 Emission Level of the Wind-Installations

5.1.1 Harmonic limits

The planning level is the level used by network operators as an internal design and operation value for voltage quality [7]. Among the number of planning levels, IEC 61000-3-6 [55] gives indicative planning levels in aspect of the harmonic distortions. The choice of planning level is an internal matter for the network operator. There is however an upper limit to the planning level: that is the maximum level of harmonic distortion allowed in the grid. In Europe, these maximum levels are typically set by a regulator or by law [56,57]. These levels are in most cases based on the so-called “voltage characteristics” set by the European standard EN 50160 [58]. This document gives the harmonic voltage limits up to harmonic order 25 as listed in the Table.5.1. It is applied in public networks up to 150 kV under normal operating conditions.

However, EN 50160 does not give the maximum-acceptable levels of interharmonics. Instead, the interharmonic compatibility levels are recommended in IEC 61000-2-2 [59]. In that standard the interharmonics are set to 0.3% of the nominal supply voltage.

5.1.2 Minimum short-circuit ratio

The short-circuit ratio is obtained by the ratio of fault current and the rated current. Here the minimum short-circuit ratio for harmonics and interharmonics is obtained from the harmonic current, the rated current, and the maximum voltage limits. The detailed derivation is initially introduced in [14], which is extended here by including interharmonics.
Table 5.1: Harmonic voltage limits in standard EN 50160

<table>
<thead>
<tr>
<th>Odd harmonics</th>
<th>Even harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not multiples of 3</td>
<td>Multiples of 3</td>
</tr>
<tr>
<td>Order $h$</td>
<td>Relative voltage</td>
</tr>
<tr>
<td>5</td>
<td>6%</td>
</tr>
<tr>
<td>7</td>
<td>5%</td>
</tr>
<tr>
<td>11</td>
<td>3.5%</td>
</tr>
<tr>
<td>13</td>
<td>3%</td>
</tr>
<tr>
<td>17</td>
<td>2%</td>
</tr>
<tr>
<td>19</td>
<td>1.5%</td>
</tr>
<tr>
<td>23</td>
<td>1.5%</td>
</tr>
<tr>
<td>25</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

Briefly the expression is obtained in the following steps:

Suppose that $U_{\text{nom}}$ and $I_{\text{nom}}$ represent the nominal fundamental voltage and current (phase to neutral). If the fault current is equal to $k \times I_{\text{nom}}$ the source impedance at fundamental frequency is equal to:

$$Z_1 = \frac{U_{\text{nom}}}{k \times I_{\text{nom}}}$$ (5.1)

The source harmonic impedance $Z_h$ is $h$ times fundamental impedance under the assumption that harmonic impedance is linearly increasing with frequency:

$$Z_h = h \times \frac{U_{\text{nom}}}{k \times I_{\text{nom}}}$$ (5.2)

The resulting distorted voltage due to a harmonic current $I_h$, is:

$$U_h = Z_h \times I_h = h \times \frac{U_{\text{nom}}}{k \times I_{\text{nom}}} \times I_h$$ (5.3)

The maximum voltage distortion is defined as:

$$U_{h,\text{max}} = \mu_{h,\text{max}} \times U_{\text{nom}}$$ (5.4)

The above equations give the expression of short-circuit ratio $k$. By using of the maximum voltage in equation (5.4), the minimum short-circuit ratio (or minimum fault level) is obtained:

$$k_{\text{min}} = \frac{h \times I_h}{U_h \times I_{\text{nom}}}$$ (5.5)
The voltage limit is in accordance with the standard EN 50160 for harmonic voltage limits, and IEC 61000-2-2 for interharmonic voltage limits. The minimum short-circuit ratios of the four listed turbine types, as in Table 3.1, are shown as in Figure 5.1, with subplots of the four turbine types: Figure 5.1 (a) Nordex N90, Figure 5.1 (b) Enercon E40, Figure 5.1 (c) Vestas V90, and Figure 5.1 (d) Enercon E82.

Figure 5.1: Minimum fault-level, to maintain the voltage distortion within the indicated limits. (a) Nordex N90. (b) Enercon E40 ×3. (c) Vestas V90. (d) Enercon E82.

The current harmonics and interharmonics are the 95% values as presented in the Figure 3.3. The figure presents the minimum short-circuit ratio of both harmonics and interharmonics up to order 25. The scale is set to be the same for all the four types of wind turbine.

The higher harmonic current, the stronger the system should be. Consequently it is the highest value of the minimum short-circuit ratio that sets the requirement on the system strength. From the figure it is obvious that those minimum short-circuit ratios are much higher for interharmonics than...
that of harmonics.

The interharmonic emission requirements are setting strict, so there may be a need to increase the compatibility levels to remove a possible barrier against the connection of new equipment [60].

5.2 Harmonic Variations with Time Duration

As mentioned in Chapter 3, the measurements of waveform distortion have been performed by several methods, for example 95% value and average spectrum. The emissions of wind turbines show strong variations when measuring over a longer time period. In one aspect it is due to the varying electricity production by wind conditions that are changing. In another aspect the dynamic characters of both wind turbine electronics and the collection grid may impact the emission. Additionally in Chapter 4, the impacts of a wind park configuration is a possible contribution.

![Harmonic and Interharmonic Groups duration [day] Harmonic Order](image)

Figure 5.2: Harmonic variations with time duration. (a) Nordex N90. (b) Enercon E40 ×3. (c) Vestas V90. (d) Enercon E82.
The measurements have been performed to present the harmonic variations of the four types of wind turbine in a continually measuring ranging from one week to one month, as seen in Figure 5.2 with subplots of the four turbine types: Figure 5.2 (a) Nordex N90. Figure 5.2 (b) Enercon E40 $\times$3. Figure 5.2 (c) Vestas V90. Figure 5.2 (d) Enercon E82.

The presented data are the recorded harmonic and interharmonic subgroups up to the order 50. The strength of harmonic emission is represented by the logarithm value (in order to distinguish the value difference), by using the color from the weakest (blue) to strongest (red). The x-axis is the measuring duration in days.

For all the four measurements, characteristic harmonics are apparent within the whole duration, even with the idle state of the wind turbine as the blue bars in the vertical direction, e.g. day 2, 5 and 10 in Figure 5.2 (a).

Within the time duration, the strong harmonic emission orders are variable, e.g. the emission around harmonic 13 in Figure 5.2 (a), the orders lower than 10 in Figure 5.2 (c) and Figure 5.2 (d). Additionally the increasing power generation (or the increasing current) results in higher harmonic emissions.

### 5.3 Measurements at Two Locations

![Figure 5.3: THD in Ampere. Red, green and blue lines are the measured three phases in the substation, while the black lines are the corresponding phases multiplied by the number of turbines (14).](image-url)

Measurements in over 10-days period have been performed in two locations inside one wind park, where 14 wind turbines are installed. One
measurement location is with an individual wind turbine, on the grid-side of the turbine transformer. The other measurement location with the point of connection to the public grid (in the substation) on the wind-park side of the transmission transformer.

Figure 5.4: TID in Ampere. Red, green and blue lines are the measured three phases in the substation, while the black lines are the corresponding phases with the individual wind turbine multiplied by 14.

Both Total Harmonic Distortion (THD) and Total Interharmonics Distortion (TID) are measured in the two locations. The THD and TID in volts (at both locations) follow the same pattern in the substation and with the individual wind turbine. However the THD and TID in Ampere make an apparent difference, which is shown in Figure 5.3 and Figure 5.4 respectively.

As the emission has only been measured for one of the 14 turbines, both THD and TID are multiplied by a factor of 14 to allow comparison with the total emission of the park. The wind turbine is idle during some days, during which the 14 times THD and TID are low.

The plot of the THD in Ampere (Figure 5.3) shows that the emission in the substation is less than 14 times the emission from the individual wind turbine. This is most likely due to aggregation between the different turbines. The TID in Ampere (Figure 5.4) shows the same trend: the emission in the substation is less than 14 times the emission of one individual turbine. The aggregation effect is clearly bigger for the interharmonic emission than for harmonics.
Chapter 6

Conclusion and Future Work

6.1 Conclusion

The variable speed wind turbines with power electronic are a source of harmonics in a wind park. Additionally the collection grid of the wind park, act as a channel through which harmonics propagate from the wind turbines to the public grid. The main work in this thesis consists of two parts: the harmonic emissions from the individual wind turbines, and the impacts of the collection grid on the propagation of those harmonics from the individual turbines to the public grid.

6.1.1 Emissions from Individual Turbines

Measurements from four types of wind turbine in different wind parks were analyzed and compared. The analysis and comparisons of the harmonic emissions are performed among the individual wind turbines. The similarities and differences from wind turbines have been addressed.

The measurements indicate that the emissions are low for the four types of commercial wind turbines. A distinction between characteristic and non-characteristic harmonics has been made. The emissions at characteristic harmonics are relatively low; while the emissions of non-characteristic harmonics are higher than normal, especially for the interharmonics. It is shown that there is a risk that limits are exceeded for certain interharmonics.

Additionally the emissions vary strongly with time, which has been illustrated by using a long-term spectrogram showing the various of the individual frequency components with time. This shows that the characteristic harmonics are present during the whole measurement period (of several days to weeks), even when the turbines are idle. The emissions vary with both
harmonic orders and strength. During period of high current (high power production by the turbine) the emission shows specific variations as well: an increase in intensity and a shift in frequency for the emission.

The impact on the grid is studied in terms of “short-circuit ratio” for all the four types of turbines. It is shown that the fault level requirement is set by the interharmonics. This is caused by relatively high emission at interharmonic frequencies, but also by the relatively low permissible voltage distortion at these frequencies.

6.1.2 Propagation through the Collection Grid

A study of the impact of the wind park configuration on the harmonic propagation has been performed. A mathematical model has been developed in which the transfer function for a linear system has been extended to an “overall transfer function”. The overall transfer function of a wind park quantifies the harmonic propagation transfer from the turbines to the public grid. Expressions have been derived for the transfer function in a wind-park model, including the impacts from the configuration components, i.e. underground cables, transformer and capacitor bank. The transfer function is applied to a 100-turbine park to study the effects of damping and amplification due to resonances in the collection grid.

The study shows that the amplification of harmonic emissions occurs due to the parallel resonances in which the capacitance from capacitor bank and the cables is involved. A sensitivity study reveals that the frequency dependent resistance of transformer has a large impact on the maximum transfer; the increase of resistance with frequency should be well known to obtain an accurate estimate of the transfer function around the resonance frequency. Increasing capacitance in the wind park installation reduces the resonance frequencies. Additionally the increasing cable length reduces the resonance frequency and damps the maximum amplitude of the overall transfer function.

Measurements have been performed at two locations inside the same wind park. These measurements reveal that the spectrum of the emission into the public grid shows a similar spectrum as the emission from an individual turbine. It is also shown that there is a significant level of aggregation between the individual turbines. The aggregation effect is bigger for the total interharmonic distortion than for the total harmonic distortion.
6.2 Future Work

The work presented in this thesis concerns the harmonic measurements of individual wind turbines and the study of propagation through a wind park. There are still a number of questions that need to be studied. The following lists some future work to resolve those remaining questions:

A further study is needed of the propagation from individual wind turbines to the public grid. A mathematical model has been developed in the first stage of the project. This model requires improvement especially on the parameter values.

- a more accurate aggregation effect among individual turbines;
- increase in series resistance with losses;
- impacts of the losses in the turbines.

This requires a combination of measurements and theoretical studies.

A second further work is the study of the combination of primary and secondary emission. Of special interest is the addition of primary and secondary emission in the complex plane. Also possible amplitude modulation of the current at the connection point to the grid is of interest and should be studied further. The main aim of this activity is to know what the harmonic current will be at the interface between the public grid and the wind park, in time domain as well as in frequency domain, due to the combination of harmonic sources inside and outside of the grid.

And a third further work is the development of methods for distinguishing between primary and secondary emission from a limited amount of measurements (limited duration, limited number of locations).
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Part II
Included Papers
Measurements of Harmonic Emission of Individual Wind Turbines

Kai Yang, Math H.J. Bollen and Mats Wahlberg

Submitted to *IEEE Transactions on Sustainable Energy*
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The layout has been revised.
Abstract

This work presents measurements of the harmonic emissions from three individual wind turbines. Measurements have been performed with 10-minute time resolution between one and several weeks. Frequencies up to a few kHz have been considered. Different methods are used to present and evaluate the characteristics of the emission, and a comparison is made among the three turbines. The current spectrum is a combination of narrowband and broadband, both of which increase with high power production. The narrowband and broadband indicate the emission characters of wind turbines. And the measurements show that converter type is not the dominating factor that determines the spectrum.

Keywords: Wind farms, wind energy, wind power generation, power quality, electromagnetic compatibility, power system harmonics, harmonic analysis, harmonic distortion.
A.1 Introduction

The increasing number of wind-power generators equipped with power-electronic converters makes that studies of their harmonic emission are needed [1–3]. The new technology making use of power-electronic converters offers various advantages, for example energy efficiency and flexibility in the power conversion. However power-electronic converters inject harmonics into the power grid [4,5].

Power-electronic converters with wind turbines are commonly six-pulse power-electronic converters. Such converters classically emit their main harmonics at the orders $6n \pm 1$, which are called “characteristic harmonics” [5]. All other emission is referred to as “non-characteristic harmonics”. The characteristic harmonics by far dominate in the emissions from non-controlled power-electronic converters, i.e. those using diodes or thyristors being switched at 50Hz.

Most power-electronic converters as part of wind turbines use active switching technology based on IGBTs or GTOs and switching patterns with a frequency significantly higher than 50Hz. Such converters enable current waveforms with much lower emissions. On the other hand, these new-developed large power-electronic converters are expected to generate components at other frequencies (“non-characteristic harmonics”), where especially the switching frequency is mentioned as a frequency at which emission is expected [6,7]. This “new type of emission” is a potential concern for the power system operators.

Studies have been performed after the harmonic emission from wind farms equipped with large power converters. Papers [8,9] perform a measurement on a small wind farm with three wind-turbines equipped with full-power converters. The analysis based on the harmonic subgroups reveals the emission character of the wind farm, as well as fault level requirements due to the emission. Papers [10,11] present measurements of the harmonic behavior of several types of individual wind turbines. Those measurements were performed at the power-converter output. The analyzed spectra show low harmonic emissions up to a few kilohertz. The analysis also shows that the non-integer harmonics are significant for the tested wind turbine.

This work is the continuing study with additional evaluation methods. The aim of this work is the analysis of the emission of a single turbine and the comparison between different turbines. The measurements were performed on several individual wind turbines (different modules in different wind farms) rather than measuring the emission of a complete wind farm. The variation of emission with time has been specifically studied.

Section A.2 introduces the details of the measurement method and the harmonic assessment method that has been used in the analysis. Section A.3 presents three ways of presenting the measurement results. Section A.4 evaluates the impact of the emission on the grid. Section A.5 presents the variations of harmonic emission with time. The conclusions from the work are presented in Section A.6.
A.2 Measurement Procedure

A.2.1 Measurement objective and instrument

Three individual wind-turbines were selected in the harmonic emission study as listed in Table A.1. The three modern wind-turbines equipped with power converters are connected to the public grid, as part of a wind farm, and their rated power is 2 or 2.5 MW.

<table>
<thead>
<tr>
<th>Turbine type</th>
<th>Gear box</th>
<th>Generator type</th>
<th>Converter type</th>
<th>Nominal current</th>
<th>Nominal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I 2.5 MW</td>
<td>Yes</td>
<td>Asynchronous double-fed</td>
<td>IGBT</td>
<td>66 A</td>
<td>22 kV</td>
</tr>
<tr>
<td>Type II 2 MW</td>
<td>Yes</td>
<td>Asynchronous double-fed</td>
<td>IGBT</td>
<td>36 A</td>
<td>32 kV</td>
</tr>
<tr>
<td>Type III 2 MW</td>
<td>Gearless</td>
<td>SYNC-RT</td>
<td>Full-power converter</td>
<td>116 A</td>
<td>10 kV</td>
</tr>
</tbody>
</table>

The three wind-turbines come from different manufacturers with different power conversion technologies. Type I and Type II employ gear-box on the mechanical power input side, together with an asynchronous double-fed generator on the electrical output side. IGBT technology is used for the frequency converter. Type III applies a gearless power input with synchronous generator, and is connected to the power grid through a full-power converter.

Measurements with the wind-turbines were performed individually at the secondary side (medium-voltage grid side) of the turbine-transformer as seen in Fig. A.1. Both voltage and current were recorded.

![Figure A.1: Monitor position of the single turbine measurement inside the windpark.](image)

As shown in Fig. A.1, the power quality monitor performs the measurement at the point of connection of the turbine transformer to the collection grid in the windpark.
farm. Consequently the equivalent nominal line-to-neutral voltage and current at
the monitor locations are provided in the Table A.1.

The monitor used for the measurements is a standard power quality monitoring
type Dranetz-BMI Power Xplorer. The build-in module performs a power quality
analysis based on the standards IEEE 1159 [12], IEC 61000-4-30 [13] Class A and
EN 50160 [14]. The three-phase voltage and current waveforms were recorded by
the monitor through the conventional voltage and current transformers, with a
sufficient accuracy for the frequency range up to few kHz [15].

A.2.2 Harmonic assessment methods

The IEC standard 61400-21 [16], which stipulates the harmonic current measure-
ment procedure of a wind-turbine equipped with power electronic converter, has
been complied with during the testing at least for one week. The waveform was
continuously acquired every 10 cycles of the power-system frequency at 50 Hz (ap-
proximately 200 ms) with a sampling frequency of 256 times the power-system
frequency (approximately 12.8 kHz) by the monitor. The Discrete Fourier Trans-
f orm has been applied using a rectangular window on the 10 cycles, which results
in a 5 Hz frequency resolution. According to IEC 61000-4-7, the harmonic groups
(as in (A.1) and subgroups (A.2)) and interharmonic groups (as in (A.3) and sub-
groups (A.4)) are obtained with the method of grouping by the summation of
neighboring frequency components.

\[
G_{g,n}^2 = \frac{C_{k-5}^2}{2} + \sum_{i=-4}^{4} C_{k+i}^2 + \frac{C_{k+5}^2}{2} \quad (A.1)
\]

\[
G_{sg,n}^2 = \sum_{i=-1}^{1} C_{k+i}^2 \quad (A.2)
\]

\[
G_{ig,n}^2 = \sum_{i=1}^{9} C_{k+i}^2 \quad (A.3)
\]

\[
G_{isg,n}^2 = \sum_{i=2}^{8} C_{k+i}^2 \quad (A.4)
\]

where \(G_{g,n}\) and \(G_{ig,n}\) are the harmonic group and interharmonic group, \(G_{sg,n}\) and
\(G_{isg,n}\) the harmonic subgroup and interharmonic subgroup.

The first 200 ms waveforms (for each 10-minute interval) of the voltages and
currents are stored by the instrument with the above-mentioned sampling fre-
frequency of about 12.8 kHz, as well as using the aggregation of harmonic and inter-
harmonic subgroups (up to order 40) from the 10-cycle waveforms.
A.3 Measurement results

A.3.1 95 Percentage value

In engineering the 95% level is commonly used to quantify the severity of a phenomenon from a series of statistical data. The remaining 5% is thought to be extreme values, which are in that case excluded from the evaluation. The 95% value is used extensively in the European voltage characteristics standard EN 50160 [14]. That standard also excludes short-duration deviations, by averaging over a 10-minute interval.

Consequently the 95% value is employed in this study, to represent the harmonic current level from a series of measured 10-minute values. The measured harmonic and interharmonic subgroups every 10 minutes are obtained for at least one week of monitoring. The 10-minute values for each harmonic and interharmonic order are sorted from minimum to maximum by the following expression:

\[ X_1 < X_2 < \cdots < X_i < \cdots < X_N \] (A.5)

The index \( i \) of harmonic current \( X_i \) is used to find the 95% value from the whole data series of length \( N \), by using the expression \( i \approx 95\% \times N \). The 95% value evaluation method is applied to each harmonic and interharmonic subgroup up to order 40.

The 95 percentage values of harmonic and interharmonic emissions of the three individual wind-turbines are presented in Fig. A.2. The overall emissions of the three turbines are mainly present with harmonic orders less than 15, and are significantly lower for higher frequencies. As seen in the figure, for the same turbine the emission is somewhat different in the three phases for those components with a higher emission, while the emission is balanced for components with a lower emission. Examples of unbalance are, the 5\textsuperscript{th} harmonic and the components around the 13\textsuperscript{th} harmonic in Type I, harmonics at orders less than 7 in Type II, and the 5\textsuperscript{th} harmonic in Type III. The characteristic harmonics of the six-pulse convertor are clearly visible, especially the 5\textsuperscript{th} and 7\textsuperscript{th}.

In Type I, the interharmonics (0.5 and 1.5) around the fundamental are highest. The harmonics 5 and 13 and the interharmonics 12.5, 13.5 are further dominating in the emissions. The emissions at the orders higher than 15 show a broadband character.

When interpreting the emission levels it is important to realize that the nominal current of Type I is 66 A, which makes that the emissions for each component are less than 1%. This is significantly lower than the emission from commercial customers [17].

In Type II, emissions up to the order 7.5 are visible. The harmonics at the three phases are more unbalanced than the interharmonics. The interharmonics 5.5 and 7.5 dominate in the emission. And the emissions increase with frequency from order 35. This will be presented in the forthcoming evaluation of the spectrum.
In Type III, the emission is distributed similarly as for Type II. Harmonic 5 and interharmonics 5.5 and 7.5 are dominating, next to which are the even harmonics 2, 6 and 8 clearly visible. Similar as in Type II, the interharmonic 5.5 and 7.5 are higher than the harmonics 5 and 7. And the harmonics increase again starting around order 35. The rated current of Type III is 116 A, which is larger than Type II of 36 A.

### A.3.2 Average Spectrum

The common evaluation method for quantifying the waveform distortion is by using the spectrum obtained from the Discrete Fourier Transform (DFT) applied to the time-domain waveform. The spectrum contains the magnitudes and the phase angles of each frequency component, where the frequency resolution depends on the window length. Applying the DFT to a 200 ms windows results in a 5 Hz frequency resolution. This should be compared with the resolution of about 50 Hz when presenting the results as harmonic and interharmonic subgroups.

The power-quality instrument used records the waveforms with a window length of 200 ms every 10 minutes. The spectrum of such a "basic measurement..."
"window" presents only the phenomena that occurred during the 200 ms window over which spectrum was taken. Any variations outside of that window are not part of the spectrum. However, the emissions are likely to vary with time, i.e. the harmonic distortion will not be the same for every 200 ms window during the running of the wind-turbine. In this section, the average over all spectra obtaining during the measurement period of at least one week has been used to represent the emission over the whole period. The average spectra for the three turbines are shown in Fig. A.3.

![Graph showing average spectra of three individual turbines](image)

**Figure A.3:** The average spectra of the three individual wind-turbines.

Comparing the evaluation methods in this and in the previous section, it can be concluded that the overall emissions in absolute values are only a bit lower when using the average than in the 95% value plot presented in Fig. A.3. The method presented in this section provides an averaging from the whole measured range, while the 95% value picks the higher level for evaluating.

When comparing the average spectrum Fig. A.3 with the 95% value Fig. A.2, the dominating components are more or less the same as well as the trend of the broadband emission. The main difference is the ratio between the magnitude of the dominating components. For example, in Type I the average value of harmonic 5 is much larger than the average value of harmonic 13, whereas the 95% values of harmonic 5 and 13 are similar. And as well as in Type III, the ratio of the average value of harmonics 5 and 7 is a little bit larger than the ratio of the 95% values.
There may be two potential reasons for the differences. One is due to the different evaluation methods used: the average spectrum weights all the data in sense of the magnitudes, while the 95% value considers the representations by a statistical methodology which exclude the extreme values. The other reason may be due to the grouping, where the final harmonic emission is grouped with the emission at neighboring components especially frequencies with broadband and narrow band are present at the same time, for example harmonic 13 in Type I and harmonics 5 and 7 in Type III.

Almost the same for the three types of wind-turbines, the spectra consist of a combination of broadband and narrow band components. The emissions in Type I consist of a broadband component around the fundamental frequency and a narrow band around harmonic 13. There are narrow bands present around harmonics 5 and 7 in both Type II and III.

By presenting the spectrum from the 200 ms windows, instead of harmonic and interharmonic subgroups, a higher frequency resolution is obtained and more narrow-band components are visible. Several harmonic narrow-band components for frequencies up to several hundred Hz are visible in the spectra for Type I and II, as seen in the first and third sub-plots in Fig.A.4. In the frequency range from 1 kHz to 2.5 kHz, the emissions from the non-harmonic frequencies are relatively high (second sub-plot in Fig.A.4).

![Figure A.4: The zoomed spectra of wind-turbine Type I and II from 0 to 1 and from 1 to 2.5 kHz. Note the differences in vertical scale.](image-url)
As seen in the third sub-plot of Fig.A.4, the average spectrum presents higher narrow-band amplitudes at 275 Hz and 285 Hz (around interharmonic 5.5 and 7.5) than that at 200 and 300 Hz. They are in consistence with the results obtained from the analysis of the 95% values.

The other obvious phenomenon visible in Fig.A.4 is the presence of broadband emissions with superimposed narrowband components around 2.5 kHz in both Type II and III. These emissions are most likely due to the switching of the wind-power conversion system. The frequency range from 1 kHz to 3 kHz of Type II is shown in more detail in the fourth sub-plot of Fig.A.4.

A.3.3 Percentage emission

As mentioned in the Section A.3.1, the 95% value of a statistical data set is often used for representing the harmonic emission. In Section A.3.2 the emission was expressed in Ampere. To compare harmonic emissions from different wind-power installations, which different properties (for example, the rated current or the voltage level), the percentage emission level is a better indicator.

Here it is important to distinguish between the emission as percentage of the fundamental current and as a percentage of the rated current. The fundamental current varies strongly with time and using this as a reference often results in very high values for the relative emission during periods of low production. In this section, we have used the emission as a percentage of the rated current.

The ratio of the 95% value of the emission and the rated current of one individual turbine, is used to quantify the emission level, by both comparing with other turbines or with the recommended limits (by the related contents of different harmonic orders).

Fig.A.5 shows the percentage of each harmonic and interharmonic component for the three individual wind-turbines, and the five frequency components with highest emission. For each frequency component, the maximum of the corresponding three phases has been used. The results are listed in Table A.2 for the three individual wind turbines.

<table>
<thead>
<tr>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td>Percentage</td>
<td>Order</td>
</tr>
<tr>
<td>IH 0.5</td>
<td>0.662%</td>
<td>IH 1.5</td>
</tr>
<tr>
<td>IH 1.5</td>
<td>0.423%</td>
<td>H 2</td>
</tr>
<tr>
<td>H 2</td>
<td>0.318%</td>
<td>H 5</td>
</tr>
<tr>
<td>H 5</td>
<td>0.397%</td>
<td>IH 5.5</td>
</tr>
<tr>
<td>IH 12.5</td>
<td>0.353%</td>
<td>IH 7.5</td>
</tr>
</tbody>
</table>
From the view of the high individual harmonics, none of the components exceed 1% of rated current. Type II has a higher emission level than the other two types. Interharmonic 5.5 is slightly more than 0.9% of the rated current. And the other apparent harmonic components in the lower orders are around 0.5%, which are also higher for Type II than for the other two types.

A.3.4 Analysis of the presentation methods

In general, there is a higher emission with Type II, in terms of the individual harmonic components. The emission for each turbine is shown to have a character distinguished from the others, by the use of different conversion technology.

By the use of the 95% value, the emission characteristics are presented for each turbine type. The characteristic harmonics and the non-characteristic harmonics are clearly visible. By the use of the average spectrum, more details of the narrow-band components are visible. The broadband also shows the characteristics of the wind-turbines. The percentage chart reveals the differences in emission level between the turbines.
In Section A.3 the spectrum of the individual turbines was presented in terms of harmonic and interharmonic subgroups for the current. The operator of the electricity network to which the turbines are connected is responsible for maintaining the voltage harmonics below certain limits. The voltage harmonic due to a given current emission depends on the background harmonic distortion and the source impedance at the harmonic frequencies.

Harmonic voltage limits are different for different frequencies and the harmonic source impedance varies with frequency as well. The magnitude of the harmonic and interharmonic groups in the current is thus not directly a quantifier for the impact of the harmonic emission on the grid. A method for quantifying the impact on the grid has been developed in [18].

The method is based on the short-circuit ratio and proceeds as follows.

The short-circuit current is assumed to be \( k \) times the rated current of the emitting device, in this case the wind turbine. Suppose that \( U_{nom} \) and \( I_{nom} \) represent the nominal fundamental phase-to-neutral voltage and current.

The source impedance \( Z_h \) at harmonic \( h \), is frequency dependent and this frequency dependence is strongly dependent on the location. The source impedance does however show a general increasing trend with frequency for lower harmonics. It is assumed here that this linear increase continues also for higher harmonic orders, so that the impedance at harmonic order \( h \) is equal to \( h \) times the fundamental impedance:

\[
Z_h = h \times \frac{U_{nom}}{k \times I_{nom}} \quad (A.6)
\]

The distorted voltage is obtained by multiplying the emission by the source impedance:

\[
U_h = Z_h \times I_h = h \times \frac{U_{nom}}{k \times I_{nom}} \times I_h \quad (A.7)
\]

Assume that the maximum-permissible voltage harmonic distortion is equal to:

\[
U_{h,max} = \mu_{h,max} \times U_{nom} \quad (A.8)
\]

The above three equations give an expression for the minimum fault ratio \( k \):

\[
k_{min} = \frac{h \times I_h}{\mu_{h,max} \times I_{nom}} \quad (A.9)
\]

The harmonic voltage limits are set by the local energy regulator, by national characteristics set by the standard EN 50160 [14] as in Table A.3, are often used [19,20].

For interharmonics, no limits are given in EN 50160. Instead the interharmonics compatibility levels equal to 0.3% of the nominal supply voltage are used in accordance with IEC 61000-2-2 [21]. The overall similarity between compatibility levels and voltage characteristics makes that this is an acceptable approach.
Table A.3: Harmonic voltage limits in standard EN 50160

<table>
<thead>
<tr>
<th>Order $h$</th>
<th>Odd harmonics</th>
<th>Even harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not multiples of 3</td>
<td>Related voltage</td>
<td>Multiples of 3</td>
</tr>
<tr>
<td>5</td>
<td>6%</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>5%</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>3.5%</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>3%</td>
<td>21</td>
</tr>
<tr>
<td>17</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.5%</td>
<td></td>
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</tbody>
</table>

The highest of the 95% values of the three phases for each harmonic or interharmonic subgroup is used as emission level in the minimum fault level computation. The minimum fault levels of harmonics and interharmonics are obtained up to order 25 with the same scale for the three individual turbines, as shown in Fig.A.6. The higher the minimum fault level, the more difficult it will be for the network operator to maintain the voltage level below the limit.

In practice the requirement on the grid is set by the highest minimum fault level. However, the value for each individual component can be used to quantify the impact of this component on the grid. The higher the value of the minimum fault level is, the bigger the impact of the harmonic on the grid.

The interharmonics normally require a much higher fault level than the neighboring harmonics in all the three wind-turbine types as shown in Fig.A.6. The resulting higher requirement on the interharmonics is due to the high emissions of the interharmonics, for example, interharmonics 12.5, and 13.5 in Type I; interharmonics 5.5 and 7.5 in both Type II and III, but also due to the low permissible voltage levels for interharmonics.

The minimum fault level is relatively low in the lower frequency range for Type I. But they are high after harmonic 12. This is due to the broadband emission present over the whole frequency range, in combination with the harmonic impedance assumed to be linear increasing with the frequency. The high requirements for harmonics towards order 25 are therefore likely to be somewhat inflated. A specific study is needed at every location to decide what the actual requirements are for that location.

On the other hand, the high minimum fault level for the interharmonics is also due to the strict interharmonic voltage limits of 0.3% of the nominal voltage. The strict limit produces the high fault level by using of small limit in the denominator of the Eq. (A.9).

Apart from the high values for interharmonics 5.5 and 7.5, the impact of the
wind turbines on the grid is low to moderate.

A.5 Emission Variation with Time

In the previous sections the emission of the wind turbine was presented by means of one value for each frequency component. The emission does however vary with time. The differences between the average and the 95% values that were shown earlier, already illustrate this variation with time. A further study has been conducted of the variations of emission with time; and these variations are presented in the form of a so-called “long-term spectrogram” [22]. The long-term spectrogram for Type I is shown in Fig.A.7: the frequency (in multiples of the power-system frequency of 50 Hz) is shown along the vertical axis. The horizontal axis in the spectrogram presents the time duration of the whole measurement in days. The time resolution is 10 minutes: the spectrum has been calculated from 200-ms measurement windows obtained every 10 minutes. The strength of the emission, i.e. the amplitude of the harmonic component for the corresponding time instant is represented through a logarithmic color scale. The “warmest color” (red) corresponds to highest emission and the “coldest” (blue) corresponds to the lowest emission.
By applying the above idea, the spectrograms of the three wind-turbines are obtained as in Fig.A.7, Fig.A.8 and Fig.A.9 respectively for Type I, Type II and Type III.

Each turbine shows its own pattern of emission and variation with time. However in general, the dominating emission components remain similar for each of the three turbines. For example, for Type I the harmonic 5 and the emission around harmonic 13 are present; interharmonics 5.5 and 7.5 dominate during the whole measurement for Type II and III.

During the measuring, wind-turbines were occasionally idle without production. These idle periods are visible from the low value for the power-system component in the current (the mainly red horizontal band towards the bottom of the spectrograms). Note that there remains some power-system component present even during the idle periods. For all three turbines, the broadband components in the spectrum are absent during the idle periods. Some of the narrowband components remain present. The resulting blue vertical bands are especially visible for Type I. Examples of idle periods are day 2, 5 and 10 in Type I, day 3 in Type II and day 1 in Type III. While the characteristic harmonics, 5, 7, 11 and 13 are always visible without weakening much even when the turbines are idle.

During production of significant amounts of power (when the fundamental component gets dark red in the spectrogram) the spectrum changes character. For Type I, a broadband emission appears covering the whole frequency band. Also does the spectrum show a strengthening and broadening of the thirteenth harmonics and the appearance of stronger emission band around order 35.

For Type II, the spectrogram shows a whole range of components with different

![Figure A.7: The emission duration of the Type I wind-turbine.](image-url)
<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Duration (day)</th>
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<tbody>
<tr>
<td>2</td>
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<td>50</td>
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Figure A.8: The emission duration of the Type II wind-turbine.

Time behavior. Harmonics, 23, 25 and 37 shows a rather irregular behavior, but without any obvious correlation with the fundamental component. During periods of high production, emission appears for order 5.5 and 6 as well as for 7.5 and 8, while at the same time harmonics 5 and 7 are not impacted. During these same periods, the spectrogram shows higher levels around order 12 and 15, as well as between order 45 and 50.

Type III clearly shows less broadband emission than the other two turbines. The characteristic components (5, 7, 11 and 13) are also here present and rather independent of the fundamental component. During periods of high emission broadband components appear again for orders 5.5 and 6 as well as 7.5 and 8, like for Type II. Also low order harmonics (0.5, 1.5 and 2) are strengthened during periods of high production.

### A.6 Conclusion

The paper presents the individual wind-turbine measurements with several methods. The current spectrum from a wind turbine shows a combination of narrowband and broadband components. Narrowband components appear especially with characteristic harmonics and mainly for lower-order harmonics.

Both narrowband and broadband components show variations with time. The variations are biggest for broadband components where increased levels are observed for higher levels of production. As a result several interharmonics and other non-characteristic frequency components show high values during periods...
with high wind-power production. The common point of the tested individual wind-turbines is that, the characteristic harmonics are apparent in the emissions. Even though, the overall emission levels are relatively low for the tested wind turbines.

The measured emissions of the turbine types differ from each other. The dominant harmonics and their amplitudes are identified. The relatively high emission above 1kHz in Type I is unexpected, because it is beyond the assumption that, harmonic impedance is linearly increasing with frequency which may reduce the harmonic current.

The switching frequency is clearly visible in the spectrum, mainly in the form of a broadband frequency component. This component is far from the dominant component when considering the whole spectrum, but it is a dominant frequency component above 1 kHz.

On the aspect of the minimum fault level study, the impact of the emission on the grid is low for characteristic harmonics, but significant for certain interharmonics. Based on the planning level, those compatible levels seem strict to limit the interharmonic voltages. A potential limits need to be set up in a suitable level.

The variative spectrograms show the emission dynamics. Except the increasing of broadband components during the high production, the idle state indicates the less changing characteristic harmonics in the whole time duration.

Harmonic studies in the neighborhood of wind-power installations should be alert for increased levels of non-characteristic harmonics (voltages as well as currents) during periods of high wind-power production.

Type I and Type II are both double fed. However the spectra of Type II
and Type III are most similar. This is somewhat unexpected. Because Type I and Type II use the same technology, one would expect the spectra to be similar. So type of converter (double fed or full power) is not the dominating factor that determines the spectrum.


Paper B

Propagtion of Harmonic Emission through A Wind Farm

Kai Yang and Math H.J. Bollen

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The layout has been revised.
Abstract

This paper introduces a model for the propagation of harmonic emission from wind turbines to the public grid. An overall transfer function has been defined by combining the transfer functions from each individual wind turbine to the grid. The model includes the structure of the wind farm, the aggregation among individual wind turbines, the high-frequency behavior of cables, and the increase of the damping with frequency. The model has been applied to a 100-turbine wind farm and the impacts of several parameters have been studied. It has been shown that the difference in transfer between individual turbines has a reducing effect on the maximum emission. It has been also shown that the increase of damping with frequency requires further study.

Keywords: Wind farm, wind power generation, power quality, propagation, power system modeling, sensitivity analysis.
B.1 Introduction

Wind power gains an increasing interest in many countries [1]. Thanks to its contribution to reduced carbon-dioxide emission and its reducing costs, a huge amount of wind power has being installed recently and further large increases are expected [2].

Modern wind power generation technology, introduces also some challenges to the power system, e.g. harmonic emission [2–5]. Inside a wind farm, a wind turbine associated with power-electronics is a typical harmonic source [6]. These wind turbines produce the main harmonic emission of the wind farm.

When studying the harmonic emission from a wind farm, two separate issues should be considered: the harmonic emissions from individual wind turbines and the propagation from the individual wind turbines through the wind farm to the public grid. The former harmonic emission from an individual wind turbine has been discussed by numbers of papers, e.g. [7–11]. The impact of the wind farm on the propagation has not been studied specifically, but harmonic resonances have been studied in a number of papers [12–15]. The parallel resonance is the one that has the main impact on the emission of the farm. The parallel resonance makes that the emission into the grid is several times higher than would be expected from the emission of the individual turbines. The role of the wind-farm layout in this amplification has not been studied yet.

A wind farm consists of an underground cable network, typically with a radial configuration, to which the wind turbines are connected through turbine transformers. The underground cable network, known as the collection grid, is connected to the public grid (at transmission level for large wind farms) through the “grid transformer” or “transmission transformer”. Several books introduce modeling of these components over a wider frequency range [16–18].

In this paper the propagation of the harmonic emission through the collection grid will be studied in details. The component models introduced in the above-mentioned books will be applied to general model of a wind farm. Section B.2 extends the existing concept of transfer function to the new concept of “overall transfer function” linking the emission of the individual turbines with the emission from the wind farm as a whole. Section B.3 provides the component models with consideration of a wider frequency range. Section B.4 presents the results from a case study with the impacts of different wind farm parameters on the propagation. The conclusions of the work are summarized in Section B.5. The details of the used model have been provided in Appendix B.6.
B.2 Transfer function

B.2.1 Individual transfer function

Suppose the complex current from one individual turbine into the collection grid is $I_t(\omega)$, with $\omega$, the angular speed ($2\pi$ times the frequency). The “individual transfer function” $\mathcal{H}_{tg}(\omega)$ from an individual wind turbine to the grid relates this current with its contribution to the (complex) current flowing into the public grid $\Delta I_g$:

$$\Delta I_g(\omega) = \mathcal{H}_{tg}(\omega) \times I_t(\omega) \quad (B.10)$$

where the index $tg$ represents the transmission from a wind turbine ($t$ the index of a turbine) to the public grid.

Thus the individual transfer function $\mathcal{H}_{tg}(\omega)$ is obtained by the ratio between the two complex current: the individual complex current flowing into the public grid $\Delta I_g(\omega)$ and the complex current from the individual wind turbine $I_t(\omega)$.

Alternatively, the individual transfer function can be interpreted as the emission from the wind farm into the public grid when the emission from all other turbines would be zero.

$$\mathcal{H}_{tg}(\omega) = \frac{\Delta I_g(\omega)}{I_t(\omega)} \quad (B.11)$$

The individual transfer function $\mathcal{H}_{tg}(\omega)$ from one wind turbine to the public grid is a measure of how much the collection grid amplifies or damps the emission from this turbine. In case the amplitude of the transfer function is less than one, the collection grid damps the emission; if it is more than one, the collection grid introduces an amplification of the emission.

The total complex current $I_g$, from all the ($N$) wind turbines, flowing into the public grid is the summation of all the individual contributions (if the interactions among the wind turbines are ignored, and the wind farm is a linear system):

$$I_g(\omega) = \sum_{t=1}^{N} \left( \mathcal{H}_{tg}(\omega) \times I_t(\omega) \right) \quad (B.12)$$

B.2.2 Overall transfer function

Equation (B.12) holds general and could in theory be used to calculate the total emission of the wind farm. In practice the expression has limited applicability because magnitude and phase angle of the individual frequency components are not very well known. To obtain more applicable expressions some additional assumptions have been made.

It has been assumed that the emission from each wind turbine is identical in magnitude but that, the phase angles are random. With the consideration of
the aggregation for random phase angles, the square-root law can be applied to obtain the absolute value of the overall emission $I_g(\omega)$ from the individual transfer functions $H_{tg}(\omega)$ and the individual emission $I_t(\omega)$ of the turbines:

$$I_g(\omega) = \sqrt{H_{tg}^2(\omega) + H_{tg}^2(\omega) + \ldots + H_{tg}^2(\omega)} \times I_t(\omega) \quad (B.13)$$

Consequently the overall transfer function is the product of the aggregated current into the public grid and the current from an individual wind turbine:

$$H_g(\omega) = \frac{I_g(\omega)}{I_t(\omega)} \quad (B.14)$$

$$= \sqrt{H_{tg}^2(\omega) + H_{tg}^2(\omega) + \ldots + H_{tg}^2(\omega)} \quad (B.15)$$

Thus the overall transfer function $H_g(\omega)$ from all wind turbines to the public grid is a measure of how much the collection grid amplifies or damps the emission from individual turbines.

Suppose all the individual transfer functions are identical, the total emission of the wind farm is in that case:

$$I_g(\omega) = \sqrt{N \times H_{tg}(\omega)} \times I_t(\omega) \quad (B.16)$$

and in the same way:

$$H_g(\omega) = \sqrt{N \times H_{tg}(\omega)} \quad (B.17)$$

Under the assumption that all individual transfer functions are the same, the overall transfer function is $\sqrt{N}$ times the individual transfer function. It will be shown later on in this paper that this assumption is not generally valid. In the studies presented below, the differences between the individual transfer functions are considered.

### B.2.3 General wind farm model

Consider the general wind farm lay-out shown in Fig.B.10. This wind farm consists of $N$ feeders of equal length, all originating from the main busbar supplied from the public grid through one or more transmission transformers. The individual transfer function is, in this model, the transfer from the grid-side of the turbine transformer to the grid-side of the transmission transformers (i.e. to the public grid).

From the wind turbine, there is a cable with length $l_1$ connecting to the transmission transformer, and a cable with length $l_2$ connecting the remaining turbines along the same feeder. There are another $N - 1$ cables connected to the same busbar in the wind farm, each with a length equal to $l_3 = l_1 + l_2$. A capacitor bank is installed to the main busbar.
Figure B.10: Transfer model for a general wind farm.

Figure B.11: Equivalent circuit of the transfer through the general wind farm.

An equivalent circuit of the transfer from the wind turbine to the public grid is obtained for the general wind farm in Fig. B.10, and shown in Fig. B.11. The cable is modeled as a circuit with a series impedance and two shunt capacitances (see more details in Section B.3.1). The transformer is modeled as the series connection of a resistance and an inductance. The detailed parameters of the equivalent circuit are given in Appendix B.6.

To obtain the individual transfer function as defined in Section B.2.1 to additional impedances, $Z_{12}$ and $Z_{34}$, are introduced according to the following expressions:

$$Z_{12} = Y_1 || (Y_2 + Z) \quad (B.18)$$

$$Z_{34} = (\frac{1}{j\omega C_b} + Y_3) || (Y_4 + Z_4) \quad (B.19)$$

where $Z_A || Z_B$ indicates the parallel connection of the impedances $Z_A$ and $Z_B$. The
impedance $Z_{12}$ (left parallel component) replaces $Y_1$ and $Y_2$, $Z_2$, and the impedance $Z_{34}$ (right parallel component) replaces $C_b, Y_3$ and $Y_4, Z_4$.

The individual transfer function is obtained with the above simplification, as:

$$H_{tg}(\omega) = \frac{Z_{34}}{Z_{34} + j\omega L_5 + R_5} \times \frac{Z_{12}}{Z_{12} + Z_3} \quad \text{(B.20)}$$

The absolute value of the individual transfer function reaches a high value when the absolute value of $|Z_{34} + j\omega L_5 + R_5|$ or of $|Z_{12} + Z_3|$ reaches its minimum. These high values of the transfer function correspond to the resonances. Which the former expression indicates that the minimum impedances of transformer (as shown in Fig.B.11) and the right parallel component determine certain resonances, and the latter expression indicates that the minimum impedances of cable $l_1$ and the left parallel component determine the other resonance frequencies. Looking in further detail at the parameters that impact these two groups of resonances, the following can be concluded:

- Resonances due to cable to which the turbine is connected; minimum of $|Z_{12} + Z_3|$;
- Resonances due to all other cables and the transmission transformer; minimum of $|Z_{34} + j\omega L_5 + R_5|$.

### B.3 Component Models

#### B.3.1 Cable model

In the classic cable model there are four parameters: the series resistance, the series inductance, the shunt capacitance and the shunt conductance. All these parameters are a function of the frequency. The frequency dependence of inductance and capacitance can normally be neglected; the conductance is normally considered equal to zero. At any non-zero frequency, the current density distributes non-uniform over the conductor cross-section. This distribution depends strongly on the frequency. This is known as the skin effect.

As a result of this frequency dependence, the series resistance needs to be corrected. Reference [19, 20] has introduced the correction method for resistance with skin-effect and “skin depth” of a cable. The skin depth $\delta$ is a function of frequency, and defined as follows:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \quad \text{(B.21)}$$

where $\rho = 1.68 \times 10^{-8} \, \Omega m$ is the resistivity of the copper conductor (from standard IEC 60287-1-1 [21]); $\mu = 1.256 \times 10^{-6} \, Hm^{-1}$ the permeability of the conductor.

A correction ratio for the resistance is obtained as follows:
\[
X_R = \left\{ \arcsin \left( \frac{r_{\text{wire}} - \delta}{r_{\text{wire}}} \right) \times r_{\text{wire}}^2 \right. \\
- \left. \frac{(r_{\text{wire}} - \delta) \sqrt{r_{\text{wire}}^2 - (r_{\text{wire}} - \delta)^2}}{2r_{\text{wire}} \times \delta} \right\} (B.22)
\]

where \( r_{\text{wire}} = 0.0113 \text{ m} \) is the radius of a single wire, for a wire with cross-section area 400 mm\(^2\).

The corrected resistance is obtained as:

\[
R(f) = X_R(f) \times R
\]

where \( R(f) \) is the correction factor obtained from (B.22) at frequency \( f \), and \( R \) the resistance at fundamental frequency.

When take into account the cable parameters in the equivalent circuit of Fig.B.11, it is important to realize that for higher frequencies they are not lumped, but distributed uniformly through the length of the cables. It is shown in [22] that a lumped model can give incorrect results when studying harmonic propagation for higher frequencies. In [22] the cable is modeled through a number of lumped Pi-circuits. In [23] an incremental length model of a transmission line or cable is presented with consideration of this distributed character and of the frequency-dependence. An equivalent circuit of a cable is obtained from the incremental model, as shown in Fig.B.12.

\[
Z' = Z \frac{\sinh(\gamma L)}{\gamma L} \quad \text{(B.24)}
\]

---

**Figure B.12: Equivalent circuit of a transmission cable**
where \( Z = z \times L \), \( L \) the length of the cable, \( \gamma = \sqrt{(r + j\omega l)j\omega c} \) the propagation constant.

And the equivalent shunt admittance per phase to neutral \( Y' \) [S] is:

\[
Y' = 2Y \frac{\tanh(\frac{\gamma L}{2})}{\gamma L}
\]  
(\( B.25 \))

where \( Y = y \times L \), \( L \) the length of the cable.

The propagation constant is obtained on the assumption that the losses in the dielectric are neglected (i.e. \( g = 0 \)). Using this cable model the series inductances and the shunt capacitances become frequency dependent. The method has also been employed in paper [22]. Together with the frequency-dependent resistance, as provided in [20] and presented in Section B.3.1, the complete cable model is available with frequency dependency for all parameters. Note that the cable is modeled by means of a small number of lumped elements, but that the distributed character of the parameter is fully included by adjusting the values of these elements.

### B.3.2 Transformer model

As mentioned in the equivalent circuit, each transformer is modeled as the series circuit with an inductance \( L_5 \) and a resistance \( R_5 \), as in Fig.B.11.

The equivalent resistance of the transformer has to be frequency-dependent in harmonic penetration studies. In this study it has been assumed that the resistance is an exponential function of the frequency \( f \). The resistance at frequency \( f \) is:

\[
R(f) = R_{50} \times \left( \frac{f}{50} \right)^\alpha
\]  
(\( B.26 \))

where \( \alpha \) is the skin effect exponent for the transformer resistance.

### B.4 Case Study

#### B.4.1 Wind farm model

A studied layout of a wind farm is designed as in Fig.B.13. In the wind farm, one hundred wind turbines (WT) of 3MW each, are installed along ten parallel underground cables. Each cable connects ten wind turbines with a consistent distance of \( L = 320 \text{ m} \) between two neighboring turbines.

The one hundred wind turbines have been connected to a 4200 MVA and 110 kV public grid through two 110/30 kV, 250 MVA and 12\% transmission transformers in parallel. The \( X/R \) ratio of the transmission transformers is 12. The inductance of each transformer is derived as 1.4 mH, and the resistance 0.11 m\( \Omega \).

In this case study a number of capacitor sizes have been considered: 10 MVar, 25 MVar and 50 MVar as well as the case without capacitor bank.
The generator symbol in the figure represents a wind turbine associated with a turbine transformer at the collection point to the collection grid. All the wind turbines are supposed to be identical in this case study.

### B.4.2 Low and high resistances

In this study case, no capacitor is present and two values of the skin-effect component of the transformer are considered: a low value $\alpha_{\text{low}} = 0.8$, and a high value $\alpha_{\text{high}} = 1.0$. Fig.B.14 and Fig.B.15 show the transfer functions for the low and high skin-effect exponents, respectively.

In the figures, the left-top plots show the overall transfer function (of the 100 wind turbines) up till 50kHz. The right-top plots are the absolute value of the individual transfer functions from ten wind turbines to the public grid; these ten turbines are located along the same cable. Because of the symmetry assumed here, the transfer functions are the same for turbines connected to the other cables. The left-bottom figures show the first resonances of the ten individual transfer function, and the right-bottom ones are the third resonances.

Peaks in the transfer functions, represent the resonances due to the maxima in (B.20). These resonances are strongly impacted by the wind farm configuration; some of these impacts will be discussed below.

The overall transfer function expresses the entire transfer from all the turbines to the grid. This function is obtained as a consequence of the aggregation of all the individual transfer functions. Individual resonances close together in frequency
result in a single peak in the overall transfer function. This is the case for the first resonance around 1.5 kHz in this case. A larger frequency difference between the individual transfer function resonances results in multiple peaks in the overall transfer function. This is the case e.g. for the second and third resonances (around 8 and 10 kHz). It produces the case that, in certain frequency range there is a group of peaks in the overall transfer function.

When the peaks in the individual transfer functions are further away from each other in frequency, the maximum of the overall transfer function becomes smaller. For the first resonance, the maximum in the overall transfer function is about 8 times the maximum in the individual transfer functions; for the third resonance this is only about four times. When the individual transfer functions are all equal, the overall transfer function is 10 times ($\sqrt{100}$) the individual transfer function. The difference in individual transfer function for individual turbines, thus results in additional aggregation and lower peaks in emission.

The change from low frequency-dependence (low skin-effect exponent $\alpha_{low}$) to the high frequency-dependence ($\alpha_{high}$) shows the impact of damping at the first resonances (both in individual and overall transfer functions) and in the third resonances. The other resonances remain almost the same. One example is given in Table B.4 for the second resonance.

In Table B.4 the second resonance of turbine 10 is not shown because its indi-
individual transfer function does not show a maximum in this frequency range. For the other nine turbines the resonance frequencies remain the same and almost the resonance amplitudes show only very small changes.

For the high frequency-dependence case, the first resonances from both the individual and overall transfer functions are reduced to approximate half, compared to the low frequency-dependence case.

The amplitudes of the third resonances are strongly impacted by the frequency-dependence, as shown in Table B.5.

The skin-effect exponent changing from $\alpha = 0.8$ to $\alpha = 1.0$ results in reducing of the third resonance amplitudes to be almost half. The resonance frequencies remain the same.

These simulation results show that the frequency-dependent resistance has no impact on the resonance frequency, but it strongly damps some of the resonance amplitudes.

**B.4.3 Resistance sensitivity analysis**

As discussed in the previous section, the skin-effect exponent impacts the first and the third resonance amplitudes. This impact is further quantified here by varying the exponent over the range from $\alpha = 0.8$ to $\alpha = 1.0$. The resonance amplitude as a function of the skin-effect exponent is shown in Fig. B.16.
Table B.4: The second resonance frequencies (F[kHz]) and amplitudes ($A_{\text{low}}$ and $A_{\text{high}}$) for low ($\alpha = 0.8$) and high ($\alpha = 1.0$) frequency dependencies.

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>7.81</td>
<td>8.09</td>
<td>8.23</td>
<td>8.205</td>
<td>8.07</td>
<td>7.89</td>
<td>7.72</td>
</tr>
<tr>
<td>$A_{\text{low}}$</td>
<td>1.615</td>
<td>8.216</td>
<td>16.29</td>
<td>23.38</td>
<td>22.5</td>
<td>12.12</td>
<td>9.102</td>
</tr>
<tr>
<td>$A_{\text{high}}$</td>
<td>1.613</td>
<td>8.209</td>
<td>16.28</td>
<td>23.36</td>
<td>22.48</td>
<td>12.11</td>
<td>9.095</td>
</tr>
</tbody>
</table>

This figure confirms the conclusion from the previous section that the amplitude of the first resonance of the overall transfer function decreases significantly with increasing skin-effect exponent. This holds for the first as well as for the third resonance frequency. For an accurate estimation of the magnification at the resonance frequency, it is thus important to know accurately how the transformer impedance increases with frequency.

B.4.4 Wind farm with capacitor bank

Section B.4.2 presents the transfer functions without capacitor bank connected to the collection grid. The transfer functions for low frequency-dependence is shown in Fig.B.14. For the same condition, a 50 Mvar capacitor bank is connected. The resulting transfer function is shown in Fig.B.17.

The presence of the capacitor bank results in a shift of resonance frequencies and also in a reduction of resonance amplitudes. The first resonance frequency shifts from around 1500 Hz to around 500 Hz. Most of the other resonances are no longer visible; only a resonance around 8 kHz remains.

For a large capacitor bank, as in this study, the main peak in the transfer functions is due to the parallel resonance between the capacitor bank and the transformer inductance. Cable inductance and capacitance have only minor impact. The result is that the individual transfer functions are very similar (bottom left plot in Fig.B.17) and that the overall transfer function is close to 10 times the amplitude of the individual transfer functions.
Table B.5: The third resonance frequencies (F[kHz]) and amplitudes (A_{low} and A_{high}) for low (\alpha = 0.8) and high (\alpha = 1.0) frequency dependencies.

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>10.41</td>
<td>10.44</td>
<td>10.47</td>
<td>10.49</td>
<td>10.52</td>
<td>10.55</td>
<td>10.58</td>
</tr>
<tr>
<td>A_{low}</td>
<td>24.37</td>
<td>13.76</td>
<td>2.523</td>
<td>17.86</td>
<td>30.06</td>
<td>30.88</td>
<td>27.66</td>
</tr>
<tr>
<td>A_{high}</td>
<td>14.27</td>
<td>8.32</td>
<td>1.401</td>
<td>10.85</td>
<td>16.57</td>
<td>17.62</td>
<td>17.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>T8</th>
<th>T9</th>
<th>T10</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>10.61</td>
<td>10.64</td>
<td>10.67</td>
</tr>
<tr>
<td>A_{low}</td>
<td>27.93</td>
<td>26.58</td>
<td>26.13</td>
</tr>
<tr>
<td>A_{high}</td>
<td>16.55</td>
<td>15.8</td>
<td>15.23</td>
</tr>
</tbody>
</table>

B.4.5 Impact of capacitor size

Previous section presents the resonance changes due to the presence of a 50 Mvar capacitor bank. Suppose there are ten steps available for the size of the capacitor bank, each step will result in a different transfer function. Thus the impacts on the harmonic emission will be different. The first resonance frequencies and amplitudes in the overall transfer function are obtained for these 10 capacitor sizes as shown in Fig.B.18.

The resonance amplitudes decrease with increasing capacitor size. The amplitude in the overall transfer function is produced by the summation of the ten individual transfer functions. The closer individual resonances result in a higher resonance of overall transfer function. In contrast, the larger injected capacitor bank damps the overall transfer function. In general, Fig.B.18 shows a decreasing trend with frequency of the first resonance amplitudes in the overall transfer function.

As specified in the previous section, the increasing injected capacitance results in lower first and third resonance frequencies. It makes the third individual resonances shifting to the lower frequencies. However the second individual resonance frequencies are fixed. From the capacitance step 0.1C to C, certain resonances are much excited by the overlap of second and third resonances. Example with 0.3C capacitance injected, wind turbine T5 has a resonance with amplification 1722 at 8.065kHz; and with 0.8C capacitance, wind turbine T7 reaches amplitude 508.8 at 7.72kHz. In the case of 0.8C capacitance, the other wind turbines reach the individual resonance at 7.72kHz.
Figure B.16: Maximum of the overall transfer function versus the skin-effect exponent.

B.4.6 Impact of cable length

The model in the earlier examples considers a cable length of $L = 320$ m between two neighboring wind turbines. By changing the cable length, the transfer functions change also. Suppose the cable length increases to $2L$ (640 m) in step of $0.2L$; the first six resonance frequencies are shown as in Fig.B.19. Note that, each resonance is picked from each resonance group. The resonance of the overall transfer function is a group or summation of the ten individual resonances; only the first resonance has only one peak.

The six resonance frequencies as a function of cable length are shown in Fig.B.19. The resonance frequencies decay with cable length. A longer cable length concentrates the resonances in a narrower frequency range.

The amplitudes of these resonances as a function of the cable length are shown in Fig.B.20. The first resonance amplitude shows a small decrease with cable length. The others show a more irregular decay. The irregular behavior is due to the multiple peaks making it difficult to decide what the amplitude actually is.

B.5 Conclusion

This paper has introduced a model for the propagation of harmonic emission from the individual wind turbines in a wind farm to the public grid. The model uses the existing concept of transfer function to relate the emission from one individual turbine with its contribution to the total emission of the wind farm.
For a general wind farm model an analytical expression has been obtained for
the individual transfer function. This expression includes structure of the wind
farm, the high-frequency behavior of the cables, and the increase of the cable and
transformer resistance with frequency. It is shown that the resonance frequencies
in the individual transfer functions fall into two groups: those related to the cable
feeder to which the turbine is connected; those related to the other cables in the
wind farm, any capacitor banks, and the transmission transformer.

The aggregation between turbines is included by assuming equal magnitude
but random phase angle for the emission for the individual wind turbines. A so-
called “overall transfer function” is introduced and an expression is derived for its
relation with the individual transfer functions.

The individual and overall transfer functions have been calculated for a 100-
turbine wind farm and the impact of several parameters has been studied. It is
shown that the difference in transfer between individual turbines has a reducing
effect on the maximum emission. Maxima at different frequency in the individual
transfer functions results in a broad maximum or in multiple maxima in the overall
transfer function. The result is that the maximum value of the overall transfer
function is lower than in case all individual transfer functions are equal. More
equal individual transfer functions are obtained by a more symmetrical collection
grid and by the addition of a capacitor bank. In the latter case the capacitor bank dominates the individual transfer functions and the differences become small. It is also shown that the higher-frequency peaks in individual transfer function are more different than the lower-frequency peaks. Further studies are needed on the impact of different wind-farm parameters on the maxima of the overall transfer function, especially for higher frequencies.

The maximum of the overall transfer function is strongly impacted by the speed with which the transformer resistance increases with frequency. The frequency-dependence of the transformer resistance is not very well known and further research is needed to obtain realistic frequency dependencies.

An important conclusion from the study presented in this paper is however that the emission from the wind farm, beyond the first resonance frequency, is likely to be small.

B.6 Appendix

The parameters in Fig.B.11 are related to physical element as follows:

- $Y_1$, the left-half shunt admittance according to the transmission cable model, which involves the cables of length $l_1$ and $l_2$;
- $Y_2$, the right-half shunt admittance of cable length $l_2$;
- $Z_2$, series impedance of the cable length $l_2$;
- $Z_3$, series impedance of the cable length $l_1$;
- $Y_3$, the right-half shunt admittance of the cable length $l_1$ and the left-half shunt admittance of the other cables except the cable to which the turbine under consideration is connected;
- $C_b$, the capacitor bank connected to the main busbar;
Figure B.19: Impact of cable length on resonance frequencies of overall transfer function.

$Y_4$, the right-half shunt admittance of the other cables in the wind farm;
$Z_4$, the series impedance of the other cables in the wind farm;
$L_5$, the inductance of the transformer, any lines and cables on primary side of the transformer and the inductance of the grid.
$R_5$, the resistance of the transformer, any lines and cables on primary side of the transformer and the resistance of the grid.
Figure B.20: Impact of cable length on resonance amplitudes of overall transfer function.
Bibliography


Measurements at two different nodes of a windpark

Kai Yang, Math H.J. Bollen and Mats Wahlberg

Accepted at 2012 IEEE Power and Energy Society General Meeting
Abstract

This paper presents measurements of power quality, with emphasis on voltage and current distortion, simultaneously at two locations in the same windpark, located in northern Sweden. Both harmonics and interharmonics components are considered in the study. Similarities and differences between voltage and current distortion are presented in this paper and possible explanations are discussed. One of the conclusions is that there is no simple relation between voltage and current distortion in a windpark.

Keywords: Power Distribution, Wind farms, Wind energy, Wind Power Generation, Power Quality, Electromagnetic Compatibility, Power System Harmonics.
C.1 Introduction

Windparks are normally equipped with underground cables to connect windturbines and other installations. Those underground cables and other components inside the windpark with certain impedance have an impact on the voltage and current, especially at harmonic frequencies [1–3].

The factors would be a significant reason that produces harmonic resonances in the windpark [4]. Around those resonances, the harmonic emissions would be amplified a lot, which would be harmful to the installations inside or outside of the windpark.

The shunt capacitance associated with those underground cables together with the inductive part of the source impedance results in parallel resonance [2]. The operational state of other windturbines and of, for example, cables and transformers, can significantly impact the harmonic resonance frequency [5]. This makes the emission in the windpark uncertain in a predictable range with the certain windpark parameters.

Due to the different transfer function from one node to the public grid, the behavior of different nodes inside one windpark is expected to be different from each other [4]. Furthermore based on the background distortion and the distortion from the windpark, voltage and current emissions could show different behavior as well.

This work presents measurements at two locations inside one windpark located in northern Sweden. The aim of this study is to describe and understand the different behavior inside the same windpark. The measurements were performed on the same medium voltage level in the collection grid using conventional voltage and current transformers, and Dranetz power quality monitor according to the standard IEC 61000-4-30 [6].

Section C.2 of the paper presents the measurement setup used for this work; section C.3 to section C.6 present the measurement results, emphasizing the different behavior at two locations inside the same windpark.

C.2 Measurement Setup

The measurements were performed with two Dranetz power quality monitors, one was of type PowerVisa and the other one was of type PX5. Both instruments used the same standardized processing modules, allowing for a direct comparison of the results. Conventional voltage and current transformers were used for the measurements, which are of sufficient accuracy for harmonics up to few kHz [1].

The location of the monitors is shown in Fig.C.21. The PowerVisa monitor was installed in the substation on the MV side of the HV/MV grid transformer (Monitor 1 in the figure). The 14 windturbines in the part are connected to this bus by five medium voltage cables with a total length of about 40 km. RMS voltage/current together with their harmonic/interharmonic groups were recorded over
every 10-minute interval according to IEC 61000-4-7 [7]. Also the total harmonic
distortion (THD) and the total interharmonic distortion (TID) were recorded over
the same 10-minute intervals.

Figure C.21: The drawing of the monitor distribution inside the windpark.

At the same time the PX5 monitor measured at one of the windturbines with
the same settings as the PowerVisa monitor (Monitor 2 in the figure). The length
of the cable between the location of monitor 2 and the main busbar is about 5 km.
Both measurements simultaneously lasted for around 11 days during winter.

The parameters of the windpark are shown in Table C.6.

<table>
<thead>
<tr>
<th>Number of turbines</th>
<th>Rated power per turbine</th>
<th>Nominal current</th>
<th>Nominal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>2500 kW</td>
<td>66 A</td>
<td>22 kV</td>
</tr>
</tbody>
</table>

C.3 RMS Voltage and current

RMS voltage and current at the two measuring locations were recorded by the
two Dranetz instruments over every 10-minute interval. The total measurement
period lasted for about 11 days. As a comparison, the three phases were recorded at both locations, and the corresponding RMS voltage or currents were presented in the same charts.

C.3.1 RMS voltage.

The RMS voltages at the two locations are shown in Fig.C.22. In the figure, red, green and blue lines represent the three phase-to-neutral voltages in the substation, while the black lines in the same chart represent the corresponding voltages with the turbine.

![Figure C.22: RMS voltage versus time. Red, green and blue lines are the measured voltages in the substation, while the black lines are the corresponding voltages with the turbine.](image)

The figure shows that the RMS voltage in the substation was slightly lower than that with the turbine. The difference is about 100 volts. The higher voltage with the turbine is due to the active power flow from the turbine to the substation and due to the reactive power produced by the medium-voltage cables. As the difference in voltage magnitude is rather constant, the latter effect is likely the dominating one.

C.3.2 RMS current.

The RMS current as a function of time is shown in Fig.C.23. The RMS current from the individual windturbine was multiplied by 14 (the number of turbines in the park) to allow for a better comparison with the RMS current in the substation. Comparing Fig.C.22 with Fig.C.23 shows that the variations in RMS voltage are strongly related to the variations in RMS current. From this we conclude that the
variations in RMS voltage are mainly driven by the variations in current for all turbine together.

From Fig.C.23 and Fig.C.22 we conclude that the voltage variations are mainly due to the variations in active power flow from all turbines together. This active power flow gives a voltage drop mainly over the HV/MV grid transformer. The reactive power produced by the cables gives a voltage rise between the substation and the turbine location.

Figure C.23: RMS current duration. Red, green and blue lines are the measured three phases in the substation, while the black lines are the corresponding phases with the individual windturbine with 14 times RMS current.

The current at the substation is the sum of the currents from the individual turbines. When all turbines produce the same current, the total current is 14 times the current from one individual turbine. With this in mind, we can distinguish three different states from C.23: the current from the individual turbine is zero; the total current is about 14 times the current from the individual turbine. In the first case, the individual turbine is disconnected. In the second case all turbines produce about the same amount of power. In the third case the turbine at which the measurement is performed is producing more than the average turbine, probably due to the main substation, so that for certain wind directions this turbine will shield other turbines.

Different from the RMS voltage, the three phases of the RMS current did not show any significant difference. From this it can be concluded that the cause of the voltage unbalance must be found outside of the wind park.

Generally around the peak current as the current in the substation, the individual windturbine contributed a higher current than the average level, while other time, it produced more or less similar as the average level. Additionally, around day 5 and day 10, this turbine produced nothing as it was switched off.
C.4 Harmonic and interharmonic distortion

C.4.1 Total Harmonic Distortion (THD)

The THD in volts, during the 11-day measurement period, is represented in Fig.C.24. Note that the THD is expressed in volts (and in the next section in Ampere) not in percent of the fundamental.

![Figure C.24: THD in volts. Red, green and blue lines are the measured three phases in the substation, while the black lines are the corresponding phases with the individual windturbine.](image)

The THD in volts follows the same pattern in the substation and with the individual windturbine. A possible explanation for this is that the main harmonic voltage drop takes place over the grid transformer and not over the cables, the same as was shown earlier for the voltage drop at power-system frequency. An alternative explanation could be that the source of the harmonic voltage distortion lies outside of the windpark.

Also the THD in Ampere is shown in Fig.C.25. The THD in Ampere of the windturbine has been multiplied by 14 so as to make a comparison possible with the THD of the current at the substation. Comparing Fig.C.25 with Fig.C.24 shows that the variations in THD in volts shows a reasonable correlation with the variations in THD in Ampere. From this it is concluded that at least part of the harmonic voltage distortion in the MV collection grid is due to the emission from the turbines.

In general, the 14 times THD in Ampere of the individual windturbine is a bit higher than that of substation except when the turbine is in the idle state around day 5 and day 9. Between the middle of day 6 and the middle of day 8 the power from the 14 turbines is about 14 times the power from the single turbine. It seems reasonable to assume that all turbines are in production during that period.
and that they all produce about the same amount of power. Most likely they also produce about the same amount of emission. The THD of the current at the substation is however somewhat less than 14 times the THD of the current with one substation. In other words: there is some aggregation effect. The effect is small but non-negligible.

### C.4.2 Total Interharmonic Distortion (TID).

The waveform distortion at interharmonic frequencies is quantified here by the parameter Total Interharmonic Distortion (TID). The TID in volts is shown in Fig.C.26.

The same as the THD in volts, the total interharmonic voltage distortion with the turbine follows the same pattern as that in the substation, still a little higher when zoomed into the detailed figure. This is explained by the fact that the harmonic voltage drop is mainly over the grid transformer, not over the MV cables. The TID in volts is especially high during periods with high current RMS in Fig.C.23.

The TID in Ampere is shown in Fig.C.27. The TID in Ampere of the individual turbine has again been multiplied by a factor 14.

Comparing this figure with Fig.C.26 shows that the TID in Ampere in the substation is strongly correlated with the TID in volts. We already concluded for the THD that the voltage distortion was due to the emission from the turbines. Here we draw the same conclusion for the interharmonics.

TID voltage versus TID current is shown in Fig.C.28. The substation TID
Figure C.26: TID in volts. Red, green and blue lines are the measured three phases in the substation, while the black lines are the corresponding phases with the individual windturbine.

voltage is strongly correlated to the TID current. Even for zero TID voltage a non-zero TID current remains. To explain this the individual interharmonic currents need to be studied separately.

For the measurements with the turbine location, two states can be distinguished. During the "idle state" (almost straight line close to the vertical axis) a small TID current is presented that is proportional to the TID voltage. Our conclusion is that the current is driven by the voltage in this case. During the non-idle state, a non-linear relation between TID voltage and TID current is visible. The interharmonic voltage distortion is due to the current emission from multiple turbines. Also the interharmonic spectrum is not the same for different amounts of produced power and individual interharmoni components vary independent from each other.

The strong correlation between the substation TID voltage and TID current is expressed by correlation coefficients of the three phases, listed in Table C.7.

Table C.7: Correlation coefficient of TID voltage verses TID current in the substation.

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>0.9981</td>
<td>0.9962</td>
<td>0.9967</td>
</tr>
</tbody>
</table>

The behavior of the TID is different from THD in Ampere: 14 times the TID in Ampere is almost twice that in the substation, as seen in the figure. There is a clear aggregation effect, much bigger than for the THD. The most commonly ventilated explanation for this is that the phase angles of the different emission
Figure C.27: TID in Ampere. Red, green and blue lines are the measured three phases in the substation, while the black lines are the corresponding phases with the individual windturbine with 14 times TID in Ampere.

sources are different so that the magnitude of their sum is less than the sum of their magnitudes. For fully random phase angles the emission from $N$ turbines would be $\sqrt{N}$ times the emission from one turbine.

C.5 Voltage and current spectra

To obtain representative spectra of voltage and current, the 95 percentage value of harmonic and interharmonic group were used, for both current and voltage. The method has been introduced in [8–10]. The 95 percentage values were obtained from the harmonics and interharmonics recorded every 10 minutes during the 11 days. Both 95 percentage value of harmonic and interharmonic were plotted in a spectrum to obtain a whole picture of the emission.

C.5.1 Spectra at substation.

The voltage spectrum measured at the substation is shown in Fig.C.29.

Overall the voltage distortion is low. The dominating harmonics and interharmonics are 5th, 7th 12.5th 13th and 13.5th. The interharmonic 12.5th, being the highest, has a value of about 0.5% of the nominal voltage. The spectrum shows relatively high levels of even harmonics, at least compared to the levels of odd harmonics. Interharmonic 12.5 and 13.5 show a high level that is distinguishable in the figure.

The 95 percentage current spectrum in the substation is shown in Fig.C.30.
Overall the current distortion at the substation is low. For a rated power of 14 times 2.5 MW, the rated current is 920 A at 22 kV. The highest harmonic current component of around 4 A thus corresponds to less than 0.5% of rated. In the 95 percentage current spectrum in the substation the dominating harmonics remain 5th, 7th, and 13th. Next to that two interharmonic component 12.5 and 13.5, reach similar values. Also here we see relatively high levels of even harmonics below the emission peak around harmonic 13 and a broadband spectrum that remains more or less constant at least up to 2 kHz.

C.5.2 Spectra at individual turbine.

The 95 percentage voltage spectrum at the individual windturbine is shown in Fig.C.31.

The voltage spectrum with the individual turbine shows, compared to the voltages spectrum at the substation, a much similar presence of harmonic emission. Similarly interharmonics 12.5 and 13.5 are much strong with the turbine as in the substation. The harmonic voltage components show very similar levels in the substation as with the turbine. This holds for even as well as for odd harmonics. Above the emission peak around harmonics 13, the levels of harmonics and interharmonics become very similar. The difference might be explained because harmonic and interharmonic groups are calculated over a different bandwidth.

The 95% current spectrum of the individual windturbine is shown in the Fig.C.32.

When comparing the current spectrum for one turbine with the spectrum for the whole park (measure at the substation, C.30) the amplitude of the current
should be multiplied by 14, as there are 14 turbines in the park. For the fifth harmonic the current at the substation is about 10 times the current for one turbine. The reduction could be explained as an aggregation effect due to random variations in amplitude and phase angle of the fifth harmonic current. For harmonic 13 and for interharmonics 12.5 and 13.5 the current at the substation is about 20 times the current for one turbine. This amplification can only be explained through a parallel resonance as described in [4, 5]. The size of the amplification cannot be determined because there is both an amplification and a cancelation effect. The very high emission peak in the substation is due to high emission from individual turbines at these frequencies in combination with a parallel resonance.

By comparing the current spectra, one can also observe that harmonic 7 and 11 are much lower for one individual turbine than for the substation. A possible explanation here is that these harmonics mainly originate from the sources outside of the windpark.

C.6 Individual harmonics

In this windpark, the dominating emission from both windturbine and substation are harmonic 5, 7 and 13, as well as interharmonic 12.5. In this section, the emissions will be studied in detail by presenting time duration in the measurement.

Firstly the RMS voltage with harmonic 5, 7, 12.5 and 13 in both substation and windturbine are presented in Fig.C.33 and Fig.C.34.

The variations with time are very similar at the two locations for harmonics 5, 7 and 13. There is no relation between those harmonics and the RMS voltage. The level of interharmonic 12.5 is about the same high with the turbine as that at the substation. Variations in the different frequency components are not strongly related, but interharmonic 12.5 and harmonic 13 show some correlation.
The RMS current with H5, 7, 12.5 and 13 in the substation and in the individual windturbine are shown in Fig.C.35 and Fig.C.36.

Harmonic 5 and 7 have a similar magnitude in the substation (1 to 3 A); but with the individual turbine harmonic 5 is about twice as high as harmonic 7. This again points to a different origin of these two harmonics. Interharmonic 12.5 and harmonic 13 have similar magnitude, both at the substation and with the individual turbine.

Harmonic currents 5 and 7 were high whenever the RMS current is high, but there are also other influencing factors.

Another apparent issue is that, the interharmonic 12 came up especially high around day 9. This makes the suspicious that normally this frequency emission is not excited, without the resonance frequency moved to 12th interharmonic. The resonance would be produced by the operation of the windpark, example, certain windturbines were running at the same time, and with certain power production.

C.7 Conclusion

Measurements of harmonic voltage and current distortion were performed during an 11-day period at two nodes inside one windpark, to study the different behavior inside the same windpark. The two nodes were the MV bus in the main substation and on MV side of a turbine transformer, i.e. close to an individual turbine.

The spectrum of the current from the individual turbines showed a combination of harmonic and interharmonic components. An emission peak was visible around harmonic 13. This kind of spectra have also been measured for turbines at other locations [8–10]. The measurements presented in this paper show that a similar spectrum is present at the substation, i.e. for the windpark as a whole.
Overall the emission is very low, the total harmonic distortion (THD) is less than 1% of the rated current; a bit lower at the substation than for the individual turbine. The total interharmonic distortion (TID) is about the same.

The amplitude of the harmonic and interharmonic currents at the substation are expected to be less than the sum of the contributions from the individual turbine due to cancelation and other aggregation effects. However in this case some harmonic currents were higher than expected, most likely due to a parallel resonance. Further studies are needed to quantify this amplification effect and to separate it from cancelation and other aggregation effects.

The levels of harmonic voltage and currents in a windpark are determined by a range of phenomena: emission by individual turbines; cancelation and other aggregation effects between turbines; current amplification through parallel resonances; background voltage distortion; and harmonic current driven by the background distortion in combination with series resonances. All this makes it difficult to predict harmonic levels but also to interpret measurements.
Figure C.32: 95% current spectrum measured with the individual wind turbine.

Figure C.33: RMS voltage with harmonic 5, 7, 12.5 and 13 in the substation. Unit in [V].
Figure C.34: RMS voltage with harmonic 5, 7, 12.5 and 13 in the individual turbine. Unit in [V].

Figure C.35: RMS current with harmonic 5, 7, 12.5 and 13 in the Substation. Unit in [A].
Figure C.36: RMS current with harmonic 5, 7, 12.5 and 13 in the individual turbine. Unit in [A]. Note the difference in vertical scale compared with the previous figure.


[7] IEC 61000-4-7, Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.

