HARMONIC AGGREGATION AND AMPLIFICATION IN A WIND-PARK

Kai YANG Daphne SCHWANZ Math BOLLEN
Luleå University of Technology – Sweden
kai.yang@ltu.se daphne.schwanz@ltu.se math.bollen@ltu.se

ABSTRACT

This paper studies the harmonic emission in a wind park, using a current transfer function. The emission of an individual wind turbine has been measured during a period of a few weeks covering all output productions. The wind park harmonic emission is analyzed by the average spectrum at the collection point. The amount of emission of the wind park as a whole is modeled by a stochastic method, based on the Monte-Carlo Simulation. The measured harmonics at wind turbines have been analyzed and compared with the simulated overall emission at the collection point of the wind park. The results will be showed by graphs and some discussions will be made.

INTRODUCTION

The presence of alternative sources of energy in the global energy matrix is increasing every day. However, the use of such sources will impact the stability, reliability and voltage quality of the electric power system. The hosting-capacity approach is a way of quantifying this impact, which is not always negative and not always significant.

The frequency converters in wind power plants are sources of harmonic currents that can result in an increase of harmonic levels in the electrical power system. Several authors have discussed this issue [1], [2], [3], but the different aspects of this impact are still not fully understood and harmonic studies are needed before connecting these sources into the grid. Because of the increased regulation of the electricity sector, more attention is given to the study of harmonics. In the study of this topic related to wind parks there remains a need for more development, especially in harmonic aggregation and amplification or attenuation.

By using power electronics, the harmonic emission from a wind turbine is different from that generated by a conventional generator: interharmonics occur more likely with wind turbines; the emission from wind turbines is time-varying in a different way; etc.

Besides the emission from individual turbines, the total harmonic emission of a wind park is determined by aggregation between turbines and amplification due to resonances in the collection grid. These effects depend on the statistical characteristics of individual wind turbine harmonic current [4], the transfer functions of the collection grid [5], and on the emission from the individual turbines. These are very important input before able to study impacts of wind parks on the grid.

In this study by using a current transfer function, the harmonic emission of a wind park is analyzed. The amplification, attenuation and aggregation effects are also studied. And a stochastic method, based on the Monte-Carlo Simulation, is used to analyze the average spectrum at the collection point.

HARMONIC AGGREGATION AND AMPLIFICATION

The emission at the point of connection between the park and the public grid (PoC) is determined by:

- The emission from the individual turbines
- The contribution from the individual turbines to the emission at the PoC. When the contribution is higher than the emission at the turbine location this is called “amplification”, if it less it is called “attenuation”.

Harmonic Aggregation

Complex harmonics and interharmonics can be represented by vectors. The harmonics and interharmonics emitted by the park as a whole are the summation of all contributions from the individual turbines. The summation of two or more vectors depends on both magnitudes and phase-angles of the individual vectors [6].

Some studies have been developed about harmonic aggregation. In [7] a study about the summation of random phasors was performed. The problem is that a big number of vectors should be used for the method to be applied, although, the advantage is that little information is needed to use this method. In [8] an arithmetic sum is used for the combination of lower order harmonics and the root sum square for higher orders. In [9], an analysis based on the instantaneous value of a sum of sine waves was performed. However, no conclusive approach has been offered yet and research about this topic remains ongoing. As presented in [10], [11], and [12] the harmonic components are time-varying, and a statistical treatment must be used.

Some standards give recommendations to quantify the aggregation [13] [14]. In [13] the harmonic disturbances are quantified as a result of the vector sum of the individual components of each source as shown in (1). This is a general summation law that can be adopted for both harmonic voltage and current.

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \qquad (1)$$

Where U_h is the magnitude of the resulting harmonic voltage (order h), for the considered aggregation of sources, U_{hi} is the magnitude of the various individual emission levels (order h) to be combined and α is an aggregation exponent. This exponent varies with the harmonic order as can be seen in Table I.

TABLE I SUMMATION EXPONENTS FOR HARMONICS IEC 61000-3-6

Harmonic Order	α
$h<5$	1
$5 \leq h \leq 10$	1.4
$h>10$	2

In [14], another approach is presented where the harmonic current is used to quantify the contribution of several harmonic sources at a point of common coupling (PCC), as defined in (2). This standard was developed for harmonics related to wind parks.

$$I_{hs} = \sqrt[\beta]{\sum_{i=1}^{N_f} \left(\frac{I_{h,i}}{n_i} \right)^{\beta}} \tag{2}$$

Where N_f is the number of harmonic sources connected at the PCC, $I_{h,i}$ is the magnitude of the h-th harmonic generated by the i-th source, and n_i is the transform relation of the i-th source. The β is the aggregation exponent used and its recommended values are shown in Table II.

TABLE II SUMMATION EXPONENTS FOR HARMONICS – IEC IEC 61400-21

Harmonic Order	β
$h<5$	1
$5 \leq h \leq 10$	1.4
$h>10$	2

Harmonic Amplification

Another contribution to the total emission of a wind park is the harmonic amplification due to resonances in the collection grid. At the resonance frequency, the impedance of a capacitance is the same in magnitude but opposite in phase as the impedance of an inductance. This results either in a very large or in a very small impedance. In both cases, the harmonic voltages and/or currents can be much larger in the network than with the sources, hence the term “amplification”. Harmonics exceeding a certain level have negative effects on network components and those levels can easily be exceeded because of the amplification [16]. According to [15], the most severe harmonic levels normally appear at the terminals the non-linear elements and their amplitude reduces with the increase of distance from its source. However, resonances can amplify harmonic levels at locations other than those terminals.

In wind park studies, this phenomenon was observed at several occasions. Some studies are presented for example in [16] and [17]. In [16], a study was performed for a 200 MW wind farm to illustrate the methods for harmonic resonance analysis. It was concluded that the details of the models had a minor effect on resonance orders but significant effect on the amplification of voltage distortion. In [17], the results were presented from a harmonic study for a planned offshore wind farm with 252 MW installed capacity. A mathematical transfer function method has been used in this study to improve accuracy of the harmonic study. It was observed that in the emission from the wind park (primary emission), the main effect is on the impedance close to the resonance frequency. It was also observed that the highest voltage harmonic emission occurs due to the resonance around this frequency.

CASE STUDY AND RESULTS

In this section the wind park modeling and the used methodology are described and the results are presented.

Wind Park Modeling

The emission into the grid is determined by the summation of the emission from individual turbines and the propagation from the location of those turbines into the grid [5]. From (3) we have the aggregated current at the point of connection, as a continuous function of frequency, and in (4) the total current from the *N* turbines into the public grid is expressed as a discrete transfer function.

$$I_{busbar}(f) = \sum_{n=1}^{N} H_{Tn}(f) \times I_{Tn}(f) \tag{3}$$

$$\begin{aligned} \overline{I}_{busbar}(f) = \sum_{n=1}^{N} \overline{H}_{T_{n,f}} \times \overline{I}_{T_{n,f}} = \overline{H}_{T_{1,f}} \begin{bmatrix} \overline{I}_{T_{1,f1}} \\ \overline{I}_{T_{1,f2}} \\ \vdots \\ \overline{I}_{T_{1,fM}} \end{bmatrix} + \\ \overline{H}_{T_{2,f}} \begin{bmatrix} \overline{I}_{T_{2,f1}} \\ \overline{I}_{T_{2,f2}} \\ \vdots \\ \overline{I}_{T_{2,fM}} \end{bmatrix} + \cdots + \overline{H}_{T_{N,f}} \begin{bmatrix} \overline{I}_{T_{N,f1}} \\ \overline{I}_{T_{N,f2}} \\ \vdots \\ \overline{I}_{T_{N,fM}} \end{bmatrix} \end{aligned} \tag{4}$$

Where, $H_{Tn}(f)$ and $I_{Tn}(f)$ are the effect of the current transfer from turbine *n* to the connection point [3].

In this paper, a wind-turbine park model, as shown in Fig. 1, was used as a case study. These turbines have 3 MW rated power each, distributed uniformly over two linear feeders originating from the main busbar in the collection grid. The distance between neighboring turbines is 320 m. A single substation transformer is connected to a grid with a fault level of 800 MVA. The cable data are shown in Table III. Cables are modeled by Π model with frequency-dependent resistance with an attenuation factor of $\alpha_t = 0.6$ and a transformer frequency-dependent resistance attenuation factor of $\alpha_t = 1.0$.

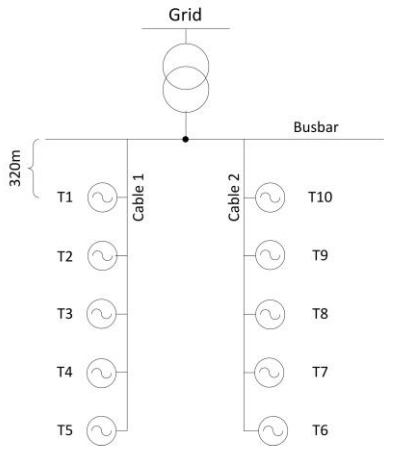

Fig. 1 Wind Park Configuration

TABLE III CABLE DATA

Cable	Resist. [Ω/km]	Induct. [mH/km]	Capacit. [μF/km]	Length [km]
1	0.13	0.356	0.25	1.6
2	0.13	0.356	0.25	1.6

Harmonic Currents Measurements

The harmonic currents were obtained by measurements during 8 days with the standard power quality instrument Dranetz PX5 at the medium voltage side of the turbine transformer of a 2 MW DFIG wind-turbine. The signals were decomposed using Fast Fourier Transform (FFT) resulting in a complex current. With this, the complex current spectra were obtained from the 1087 waveforms (200-ms), during the 8 days.

A chi-square goodness-of-fit test was performed to verify the uniform distribution of the phase-angles of the complex current. In this paper a “uniform” distribution means that the chi-square goodness-of-fit test passes with a 95 percent significance level; otherwise the distribution is classified as “non-uniform”. In Fig. 2 is presented the mean of the harmonic spectra (in 5-Hz resolution). It is observed that the components with non-uniform phase-angle (blue star mark) are mainly at integer harmonics especially at low frequency (<500 Hz), while those of the uniform phase-angle are at interharmonics. Furthermore, it was observed that the components around 2.3 and 2.4 kHz, which are related to the switching frequency of the turbine converter, are uniformly distributed (red dot mark).

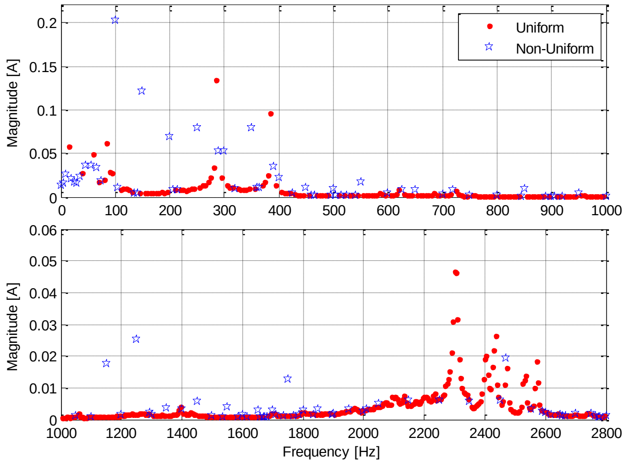

Fig. 2. Mean of Spectra up to 2.8 kHz, with Uniformly- and Non-Uniformly Distributed Phase-Angles

Model of Transfer Function

In this study, the resulting harmonic model for the transfer from one wind turbine to the grid of Fig. 1 is shown in Fig. 3.

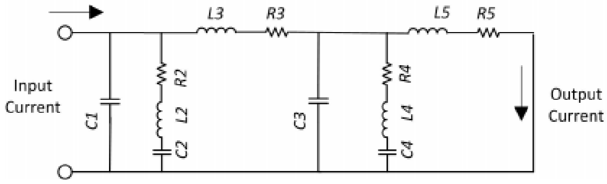

Fig. 3 Model for the Transfer from One Wind Turbine to the Grid

Where, L_2, L_3, L_4 and L_5 are the series inductance, C_2, and C_4 are the shunt capacitance, and R_2, R_3, R_4 and R_5 are the series resistance. Furthermore, in this figure, C_1 and C_3 are the left-half and right-half capacitance of turbine cable and the left-half capacitance of the rest of the cable, respectively. In this figure, analyzing the circuit, the current flows from a turbine to the busbar through a part of one feeder, by R_3 and L_3, in parallel with the rest of the feeder, using R_2, L_2 and C_2; and in parallel with the other feeder, by R_4 and L_4; and, finally, in series with the transformer (R_5 and L_5) to the grid.

With this, using impedances, the transfer function from the turbine to the grid $H_{tg}(\omega)$ is obtained as a function of the frequency ω, as shown in (5).

$$H_{tg}(\omega)=\frac{Z_{34}}{Z_{34}+j\omega L_5+R_5}\times\frac{Z_{12}}{Z_{12}+(j\omega L_3+R_3)+\dfrac{Z_{34}\times(j\omega L_5+R_5)}{Z_{34}+(j\omega L_5+R_5)}} \qquad (5)$$

Where, Z_{12} is the combination of R_2, L_2, C_2 and C_1 and Z_{34} is the resulting impedance of L_4, C_4 and C_3.

From each wind turbine, a graphic showing the transfer function was developed, as shown in Fig. 4. In this figure only five turbines were presented, but this is valid for the

10 turbines analyzed. With this figure, it was observed a resonance at 1.585 kHz with maximum transfer of 16.49, the same for all turbines, which means that a harmonic from the turbine will be amplified to 16 times into the grid at this frequency. Furthermore, it was observed that the transfer function is around unity below the resonance frequency and decaying towards zero above the resonance frequency. Above a few kHz the contribution of the emission from individual turbines to the emission of the park is small.

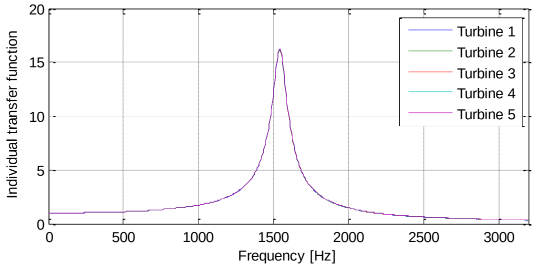

Fig. 4. Transfer functions from five wind turbines (on one feeder) to the public grid.

Harmonic Aggregation and Amplification

In this paper, the Monte-Carlo method, a stochastic model, was used to estimate aggregation effects in a wind park. As input to the model, the 1087 measured complex currents are used. The emission from each individual turbine is obtained by taking a random sample from the 1087 complex currents. Ten different values, for each frequency component, are obtained in that way for the 10 turbines. The emission of the park is obtained by applying the discrete function of the complex harmonic current, applying (4) to the sampled spectra. The process is repeated 100,000 times resulting in 100,000 complex currents at the point of connection. The average of the magnitudes of these complex currents is used as the emission of the park; for each of the frequency components. In Fig. 5 and Fig. 6 some analyses were developed. In [6], similar results were obtained for other turbines.

In Fig. 5, using the Monte-Carlo results, the spectrum of the harmonic current from one individual turbine (input) and for the wind park as a whole (output) is presented. The factor 10 difference in scale is to compensate for the number of turbines. In this figure, it was observed that the spectrum for the lower-order harmonics is about the same for the individual turbine and for the park; this means that the emission, in percentage of rated power, is the same for the park as a whole as for the individual turbines. For interharmonics there is a lower emission for the park as a whole than for the individual turbines. The emission around 1.55 kHz is amplified for broadband and narrowband due to resonances in the collection grid. Also, for frequencies above about 1.75 kHz, the emission from the park is again smaller than ten times the emission from one turbine.

It was also observed a different aggregation between harmonics and interharmonics. This is very clear in the frequencies 285 Hz and 385 Hz. These are dominating the spectrum of a single turbine, however, for the whole park analysis this is not the case.

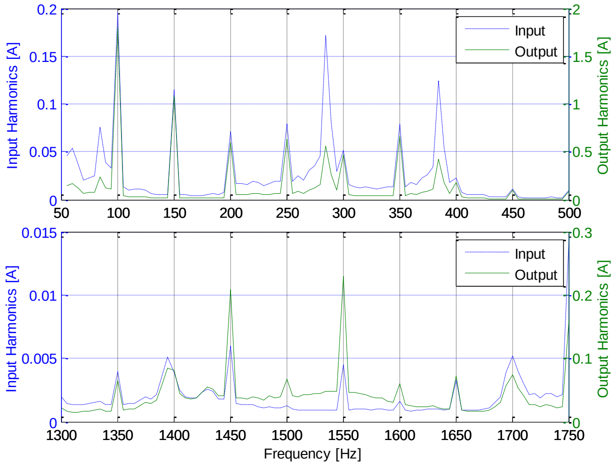

Fig. 5. The Input and the Output Current Spectra, Note the factor 10 difference in scale between input and output.

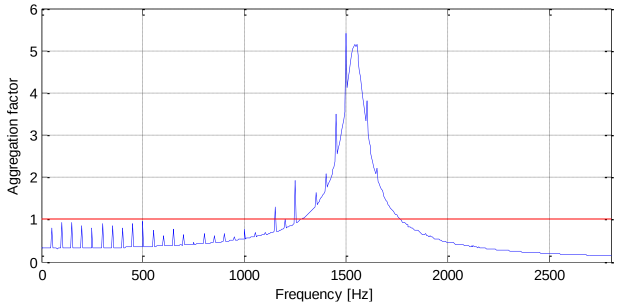

Fig. 6. Overall Transfer Function at the Point of Connection

In Fig. 6, it was presented the results for the impact of aggregation and collection grid using the overall transfer function. This is defined as the ratio of the emission from the park into the public grid and ten times the emission from an individual turbine. In this analysis it was also observed the difference in overall transfer function between interharmonics and harmonics up to about 1650 Hz. Integer multiples of the fundamental frequency aggregate less (i.e. the resulting emission is higher) than other frequencies. The lowest overall transfer function below the resonance peak is obtained at interharmonics in the low frequency range. The value is around 0.316, according to the square-root rule as a function of the number of turbines, square root of ten in this example.

CONCLUSIONS

In this paper the harmonic emission of a wind park, with 10 wind turbines, was analyzed. The amplification, attenuation and aggregation effects were studied and a stochastic method, based on the Monte-Carlo Simulation, was used to analyze the average spectrum at the collection point.

A uniformity test was applied to the distribution of the phase angle for all frequency components and it was observed that interharmonic components have uniform distribution and harmonic components have non-uniform distribution.

About the aggregation, using Monte-Carlo simulation, it was discovered that, for this case study, the aggregation is different for low-order harmonics, high-order harmonics and interharmonics. For low-order harmonics the aggregation is closest to linear addition and the overall transfer function is up to about 500 Hz. For harmonics above about 1.5 kHz it is close to the random-phase-angle model. And for interharmonics the aggregation is identical to the one assuming random-phase-angle.

For future work is needed to verify the assumption made for calculating the overall transfer function. Also, it is needed to use measurements with longer time windows and studies including primary and secondary emission. The studies should be repeated for other wind turbines and other wind parks.

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