Statistical Analysis and Comparison of Harmonics Measured in Offshore Wind Farms

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Abstract—The paper shows statistical analysis of harmonic components measured in different offshore wind farms. Harmonic analysis is a complex task and requires many aspects, such as measurements, data processing, modeling, validation, to be taken into consideration. The paper describes measurement process and shows sophisticated analysis on representative harmonic measurements from Avedøre Holme, Gunfleet Sands and Burbo Bank wind farms. The nature of generation and behavior of harmonic components in offshore wind farms clearly presented and explained based on probabilistic approach. Some issues regarding commonly applied standards are also put forward in the discussion. Based on measurements and data analysis it is shown that a general overview about wind farm harmonic behaviour cannot be fully observed only based on single-value measurements as suggested in the standards but using more descriptive statistical methods.

Index Terms—distribution estimation, harmonic analysis, harmonic measurements, statistical analysis, wind farm.

I. INTRODUCTION

OFFSHORE Wind farms (oWFs) equipped with more and more wind turbines (WTs) are being more popular sources of renewable energy in nowadays and future power systems. Incising number of WTs with advanced power electronic solutions in large offshore WFs introduces possibilities of power system stability and power quality improvements. However new technologies simultaneously create simultaneously new challenges to the industry in relation to understanding wind turbine complex behavior also from harmonic (e.g. generation, propagation, mitigation, stability) perspective.

Statistical approach in harmonic analysis in wind farms has been applied in few study cases [1], [2]. Some limitations due to the lack of representative data [1] or data processing techniques [2] have been observed and can drive to misleading conclusions. This paper reliably and really concerns probabilistic aspects of voltage and current harmonic emission in large offshore wind farms based on sufficient amount of appropriately processed measurements.

The paper also shows sophisticated statistical analysis on representative harmonic measurements from Dong Energy’s wind farms.

A. Probabilistic aspects in wind farms

Probabilistic approach of harmonic analysis in wind farms gives supplementary information in relation to harmonic assessment recommended in standards. Except one average value within certain power production levels stochastic modeling provides also information about probability of occurrence certain harmonic amplitudes and angles. In the standard about power quality measurements and assessment in wind turbines it is specified to measure and evaluate different harmonic levels depending on active power production. That is why it is also worth to use active power to stochastically model harmonic components.

Some interesting studies about probabilistic aspects of harmonic emission in large offshore wind farms were done in [3] where Monte Carlo approach was used in order to assess harmonic emission at the point of common coupling (PCC). Unfortunately some significant limitations affected a certain disagreement between simulations and measurements. One of the most important was lack of appropriate harmonic model of the grid form the transmission system operator. Another limitation was behind modeling assumption, i.e. it was assumed that all the current measured in wind turbines is generated by them. In this paper will be shown, base on sophisticated statistical analysis, that actually the harmonic current can flow into the wind turbine.

B. Power quality aspects

The interest in the power quality of WFs has increased as renewable energy sources become more important to face global environmental challenges, and the power industry grows with the trend of embedded and dispersed generation. Also, new technology being less tolerant to voltage quality disturbances, and the spread use of power electronic converters, contributes to the relevance of power quality [4].

Figure 1 SWT-3.6-120 installed at Avedøre Holme Offshore Wind Farm.

It is of major importance to assess the possible impact that WFs have on the power quality of a specific grid and specific wind farm system. For the wind farm developer an optimal assessment of harmonics means a cost-effective
design fulfilling the requirements [5] while from the
distribution system operator (DSO) and the transmission
system operator (TSO) perspective it is important in order to
supply adequate power quality to consumers. Therefore
there is a need to establish closer cooperation between wind
farm developers and transmission system operators in order to
provide reliable harmonic analysis solutions and tools.

II. MEASUREMENT CAMPAIGNS

Extended measurement campaigns were performed and
appropriate data processing techniques were applied to carry
out trustful harmonic evaluation. Three different wind farm
configurations were taken into account during
measurements. Burbo Bank with maximum output of 90MW
is one of the first offshore wind farms built in the uk, located
on the west coast. The total capacity of Gunfleet Sands
located on the east coast of the UK is 172MW. In both cases
measurement system was installed in different locations for
more than three months. Gunfleet Sands unlike Burbo Bank
has offshore substation and more extended mv cable
network. Avedøre Holme in the south of Copenhagen is a
demonstration plant and allows testing wind turbines before
they were implemented in large-scale offshore projects. One
month of measurement gave a good overview about
harmonic emission of a single wind turbine.

All offshore wind farms where the measurements system
was installed are solely (Burbo Bank, Gunfleet Sands) or
partly (Avedøre Holme) owned by DONG Energy. The wind
turbines (WTs) used in the OWFs are Siemens Wind Turbines
SWT-3.6-120 (see Figure 2) or SWT-3.6-107 (see Figure 3).

A. Wind farm description

Avedøre Holme (see Figure 1) offshore WF in the south
of Copenhagen is a shared project between DONG Energy and Hvidovre Vindmøllelaug A/S. The two WTs (M2 and
M3 in Figure 2) are located less than 10 meters from shore
in a water depth of 0.5-2 meters. A location so close to shore
and easy access to the offshore WTs via a footbridge is
the basic idea behind the project. This gives DONG Energy
a unique opportunity to test and try out new wind turbine
concepts, before they are implemented in large scale in
OWFs.

Figure 2 Avedøre Holme offshore wind farm location.

The SWT-3.6-107 and SWT-3.6-120 are variable-speed
WTs utilizing full-scale frequency converters. The frequency
converter system comprises two converters (i.e. AC/DC
generator bridge and DC/AC network bridge) and a DC-link
decoupling the variable-frequency generator and the grid
frequency. There is a transformer (10/0.69 kV) to step-up
the voltage on each WT. The WT transformer is connected
via a vacuum circuit breaker (VCB) to the MV network.

Gunfleet Sands wind farm is located on the east cost of
the UK (see Figure 3) and consists of two phases, one with
30 wind turbines (Phase 1) and another with 18 turbines
(Phase 2). The wind turbines are connected in radials by
36 kV submarine cables. Each pair of radial is then
connected to the platform by one root cable. Two park
transformers (120 MVA, 132/33 kV) are placed in the centre
of the wind farm in the offshore substation. Each root cable
is connected in the substation to a MV busbar via a vacuum
circuit breaker. From the substation the electricity is
transmitted to shore via a 8.5 km long submarine cable
which comes ashore at Holland Haven and connects to the
Clacton substation at Cooks Green [6].

And Burbo Bank wind farm is located on Burbo Flats in
Liverpool Bay (see Figure 3). At its closest point, the site is
approximately 6.4 km from the Selfton coastline and 7.2 km
from North Wirral. The wind farm consists of 25 SWT-3.6-
107 variable speed wind turbines [7], each with rated
capacity of 3.6 MW. Burbo Bank is therefore capable of
providing a maximum output of 90 MW of electricity. The
wind turbine has a fully rated power converter IGBT-based
power electronic converter.

B. Measurement system installation

The measurement equipment consists of National
Instruments (NI) PXI-1033 chassis each comprising PXI-6682
timing and synchronization board with Trimble Bullet III
GPS antenna used to read precise GPS timestamp and PXI-
4472 dynamic signal acquisition (DSA) board with second-
order low-pass anti-aliasing filter [8] suitable for harmonic
measurements. The chassis is connected to an efficient
portable computer via ExpressCard laptop host capable to
achieve up to 110 MB/s sustained throughput.

In order to avoid problems, industrial solutions were used.
For example the LV voltage probes installed in the WT were
fitted to the terminals of the AC switchboard and in the
DC/AC converter terminals through fuses and 4mm standard
plugs. The MV voltage probes were built with standard
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methods is strongly dependent on origi

in this paper. The application of particular statistical

harmonic analysis. Some of them will be presented and used

were installed in the transformer. The

grid

dc/ac converter and dc-link of the WT. The

current probes were installed on the output terminals of the

grid-side converter, dc-link circuit and lv side of the WT

transformer. The lv voltage and current probes in the

were installed in the WT transformer side of the VCB.

III. STATISTICAL METHODS

Various statistical methods can be successfully used in

harmonic analysis. Some of them will be presented and used

in this paper. The application of particular statistical

methods is strongly dependent on origin and nature of

analyzed harmonic components. Also it is of great

importance to use appropriate data processing techniques

also depending of analyzed harmonic components

behavior[8].

A. Central limit theorem

In general central limit theorem in probability theory

states conditions under which the mean of a sufficiently

large number of independent random variables are

approximately normally distributed. It has to be emphasized

that considered random variables should be with finite mean

and variance[9].

Let random sample (e.g. harmonic components)

size n is a sequence of independent and

digitally distributed random variables with expected value

E[X1] = μ and variance Var[X1] = σ². Now let average

sample of these random variables is

\[
S_n = \frac{1}{n}(X_1 + X_2 + \cdots + X_n) = \frac{1}{n} \sum_{i=1}^{n} X_i
\]  

(1)

Then according to Lindeberg-Lévy central limit theorem

as n approaches infinity the asymptotic distribution of S_n is

normal with mean μ and variance1/n σ²[10]. Formal

formula is the following (denotes convergence in distribution)

\[
\sqrt{n}(S_n - \mu) \xrightarrow{D} N(0, \sigma^2)
\]

(2)

It is worth to emphasize that the true strength of the

theorem is that S_n approaches normality regardless of the

shapes of the distributions of individual X_i’s. That is also

why it is expected to observe normally distributed harmonic

components from measurements due to the fact that

estimated harmonic components based on measurements

and data processing are an average value within the

analyzed window[11].

The most significant it is affected by an application of

Fourier transform on time-varying harmonic components

and averaging within certain period which is necessary in

long-term harmonic measurements. In IEC 61000-4-7 and

IEC 61000-4-30 standards about harmonics measurements

and power quality measurements respectively[12],[13] it is

recommended to apply Fourier transform on 10-cycle

rectangular window. High frequency components can

change significantly their magnitude within this period and

averaging is unavoidable and at first glance can provide

misleading estimation.

B. Signal stationarity

On the other hand if one considers sufficiently large

number of samples (and their sample averages) the

asymptotic distribution is expected to be the same normal if

averaged random variables are independent and identically

distributed. One can note that as long as signal stationarity is

assumed in analysis the asymptotic distribution should be

the same for all observations. General definition of a

stochastic process stationarity is that its joint probability

distribution does not change when shifted in time or space.

Consequently this means that parameters such as the mean

and variance, if they exist, also do not change over time or

position[14].

By removing any trend or slow variation from the time

series using resampling non-stationary data blocks can be

transformed to stationary. Sometimes even if resampling is

applied the stationarity test may not be passed. This is due to

fact that there are also frequency components not

synchronised with the grid frequency which show higher

variation after resampling. Normally in voltage and current

waveforms comprise more integer multiple frequencies of

the nominal one and resampling should improve analysed

data series. Stationarity test results on resampled and not-

resampled data are compared in[8]. It can be seen there that

frequency variation after resampling exists only for sideband

frequencies of the carrier signal and is smaller but on a

certain level. Therefore the application of resampling can

improve or make worse time-series depending on analyzed

harmonic components origin (e.g. generated by pulse-width

modulation).

C. Histogram analysis

Histogram analysis is one of the first steps in quantitative

statistical analysis of harmonic components. It is used to

roughly assess the probability density function of a given

dataset by depicting the frequencies of observations

occurring in certain ranges of values. In practice histogram

is nothing else than graphical representation of analyzed
data showing visual impression of its distribution.

D. Kernel smoothing

Kernel density estimation is a nonparametric technique

for probability density function estimation. Knowledge

about probability distribution of analyzed harmonics can be

extensively used in comparison of the same frequency

components from different data sets (e.g. different wind

turbines, measurement points in a wind farm) as well as be

applied in modeling of harmonic sources. Additionally

description of harmonics from its probability distribution

perspective provides better overview about harmonic

phenomena and power quality.

A good example where probability distribution estimation can be beneficial is harmonic emission

assessment of a wind turbine. It is described in IEC 61400-

21 standard[15] concerning measurements and power
quality assessment in wind turbines. The standard predicts measurements of 10-minute harmonic current generated by a wind turbine for frequencies up to 50 times the fundamental frequency of the grid [16], [17]. It has to be emphasized that the most popular standard concerning measurements and power quality assessment of grid-connected wind turbines refers only to current harmonic components.

IV. RESULTS COMPARISON

A. Statistical approach

In order to distinguish which harmonics are generated directly by the voltage source converter and which are simple the harmonic background measured at the ac terminals of the power converter, a quantitative analysis is carried out. As it can be seen from Figure 4 and Figure 5 the phase-to-phase RMS voltage is around 690 V when the WT converter is turned off. If the voltage is around 790 V the grid-side converter is in operation. The value of the RMS voltage measured and the grid-side converter AC terminals varies depending on modulation index.

![Harmonic voltage and current scatter plot against voltage RMS value.](image)

Figure 4 Harmonic voltage and current scatter plot against voltage RMS value.

When the grid-side converter is in operation the distorted background voltage affects harmonic current flow (Figure 4). This current is measured by the converter control system and transformed into SRF. In order to reduce voltage background harmonic distortions, the converter needs to adjust command signal depending on harmonic voltage distortions by cancelation of oscillations in the dq frame. That is why the measured voltage waveform to some extend is free of baseband harmonics affected by the grid even if there harmonic current is still flowing.

On the other hand from Figure 5 it can be seen that there is no $h_2$ harmonic distortions present in the grid voltage when the converter is turned off. The harmonic current flow during production in this case is only affected by the grid-side converter. It can be also seen that no spectral leakage affects the data processing results because the voltage of $h_2$ is equal exactly to zero when the WT is shutdown even if the fundamental frequency is still significantly high.

B. Sideband harmonic components

Sideband harmonics generated by the wind turbine grid-side converter are affected by the modulator. The frequency of sideband harmonic components is above the converter control bandwidth. Therefore sideband harmonic components are considered to be characteristic harmonics from power electronics perspective. Please note that the frequency of carrier group harmonic components is dependent on two variables: power system fundamental frequency and carrier signal fundamental frequency. If the modulation ratio $m_f = f_c / f_o$, where $f_o$ is the power system fundamental frequency and $f_c$ is the carrier signal fundamental frequency, is not an integer number sideband harmonic components frequency is not an integer multiple of the power system frequency [18]. Thus such harmonic component cannot be considered as harmonics from power system studies point of view.
It is important to mention that sideband harmonic components are dependent on the modulation index $M$ of the fundamental component in the command signal (see Figure 6) as well as amplitude $M_h$ of injected harmonic components into the command signal. Both relationships are nonlinear and are strongly dependent on nonlinear nature of Bessel functions of the first kind \cite{19, 20}.

Assuming if a harmonic component is dependent on voltage fundamental harmonic it is not surprising that the harmonic component is only a little dependent on power production. In grid-connected wind turbines not only the fundamental voltage amplitude affects the active power level but also the angle and the grid voltage level as it was presented previously. Of course it is not possible to provide active power control only by changing the angle. Therefore grid-side converter voltage has to be increased if more active power is expected to be pushed to the grid.

Based on Figure 7 one can see that there is quite scattered linear relation between both active and reactive power and the voltage fundamental component. This also explains why sideband harmonic components are also dependent on active and reactive power, and not only on the output voltage. From Figure 7 it can be seen that different power production can be achieved for the same fundamental voltage magnitude. This is affected by possible grid-side converter voltage angle shift in relation to the grid voltage. That is also why scatter plots of both active and reactive power are significantly dispersed. It allows thinking about random harmonic generation for different power production levels.

In Figure 8 one can see that sideband harmonics generated by the grid-side converter modulator are multimodal data sets (i.e. statistical distribution is with multiple peaks). It can be seen that distributions are a mixture of at least two different unimodal normal distributions. The harmonics are distributed within relatively small range (i.e. small standard deviation) which can be due to uncertainties affected by measurement system and calculation method precisions as well random nature of harmonic generation by the grid-side converter. As it was shown earlier the harmonic magnitude is correlated with active power production of the wind turbine. Therefore one can say that different distributions are due to changes in the modulation index.

In Figure 9 it is possible to observe how non-parametric estimation of probability density function is dependent on number of observations. Another aspect of estimation is associated with a problem if actually measured observations of harmonic components are representative dataset. In the figure one can see that the estimation does not change significantly the probability density function. In this particular case the initial dataset size of the 51st sideband harmonic components is equal to 1190 observations. The
initial dataset does not contain representative data to estimate the probability distribution, but if the length of analyzed harmonic series is more than 10 times bigger (i.e. 11900 observations and more), the estimation gives comparable results.

It was mentioned that there is a certain dependency of sideband harmonic components on power production levels. Simultaneously their nature can be considered as random because the estimated sideband harmonic component magnitude can be the same for different power production levels (i.e. power production also dependent on phase angle of the fundamental component and not only on the magnitude). Therefore the harmonic dataset can be divided into smaller subsets depending on different production levels. Please note that according to central limit theorem one expects to observe different (i.e. be means of mean and variance) normally distributed random variables.

In order to specify appropriate active power ranges a series of goodness-of-fit hypothesis tests are performed. This provides by means of sophisticated statistical methods to verify conclusions derived from first glance of Figure 8. Due to the fact the one expects to estimate normal distributions both two-sample as well as single sample goodness-of-fit hypothesis test can be carried out.

In case of two-sample goodness-of-fit tests (e.g. Kolmogorov-Smirnov (K-S) [21], Ansari-Bradley (A-B) [22]) the null hypothesis $H_0$ states that two independent random samples, $X_1$ and $X_2$, are drawn from the same underlying continuous population. Taking into consideration single sample goodness-of-fit hypothesis test (e.g. Lilliefors' (l) [23], Chi-square (Ch), Jarque-Bera (J-B) [24]) the null hypothesis considers normal distributed population and states that a random variable $X$ is normally distributed with unspecified mean and standard deviation. In some cases (e.g. single sample Kolmogorov-Smirnov goodness-of-fit hypothesis test) it is possible to test null hypothesis if a random variable $X$ is distributed according to a standard normal distribution $X \sim N(0,1)$.

Table 1 Results of different goodness-of-fit tests in case of sideband harmonics generated if the wind turbine has high output power.

<table>
<thead>
<tr>
<th>Power Output $P$</th>
<th>Goodness-of-fit test</th>
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<tr>
<td></td>
<td>K-S</td>
</tr>
<tr>
<td>$&gt; 0.55P_n$</td>
<td>1</td>
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<tr>
<td>$&gt; 0.75P_n$</td>
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<tr>
<td>$&gt; 0.86P_n$</td>
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<td>$&gt; 0.95P_n$</td>
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Table 1 presents test results for different output power levels. It can be seen that separated dataset fits normal distribution for active power level in range $P \in (0.87P_n, P_n)$. The sideband harmonic components are generated during approximately full power production. The tests return the logical value 1 if they reject the null hypothesis at the 5% significance level, and 0 if they cannot reject the null hypothesis $H_0$.

In Figure 10 one can see that it is possible to fit Gaussian curve to the sideband harmonic component distribution measured during high production ($P > 0.87P_n$).

The fitted curve in Figure 10 is bell-shaped Gaussian function which is a probability density function of the normal distribution

$$f(x|\mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where parameter $\mu$ is the mean and $\sigma^2$ is the variance. Please note that he distribution with $\mu = 0$ and $\sigma^2 = 1$ is called the standard normal distribution. For this particular dataset sample mean $\bar{x}$ is equal to 167.3191, sample variance $s^2$ is equal to 3.6199, sample skewness $g_1$ is equal to -0.0791, and sample kurtosis $g_2$ is equal to -0.2005. In case of normal distribution skewness and kurtosis are equal to 0 and 0 respectively. Mean value is any real-valued number ($\mu \in \mathbb{R}$) and variance is any positive real-valued number ($\sigma^2 > 0$).

C. Baseband harmonic components

Baseband harmonics are affected by different and many factors. One of the most crucial is the harmonic background distortion which is always present to certain extend during wind turbine operation. Therefore prediction and analysis of baseband harmonic components is more time consuming and complex. Not infrequently it is difficult or even impossible to gather information about harmonic background and frequency dependent characteristic of the system to which the wind turbine is connected. In such cases harmonic analysis and assessment results is of great uncertainty and can provide misleading conclusions. It is also worth to emphasize that various wind turbines can differently interact with the plant changes and background distortions. Such variety implies significant difficulties in deterministic modeling of wind turbines and consequently wind farms.

The 2nd harmonic which is only generated by the converter (as seen from Figure 5) therefore it is relatively easy to distinguish that this particular baseband harmonic component is generated directly by the voltage source converter and is not affected by the harmonic background. Due to the fact that this harmonic does not exist in the background distortions the harmonic current is flowing from the wind turbine into the grid and its value is mainly affected by the plant impedance.
As it is expected the 2\textsuperscript{nd} harmonic is also almost linearly (see Figure 11) dependent on the fundamental voltage. Previously it was shown that this particular baseband harmonic component is not present in the background which means that is only generated by the wind turbine. Therefore might be considered as a power converter characteristic harmonic which is not affected by the grid conditions.

Also in Figure 12 it is possible to see that the estimated probability density function indicates multimodal probability distribution with at least local peaks. A series of estimated curves also proves that the 2\textsuperscript{nd} harmonic is described by a representative dataset at least for lower magnitudes, i.e. applicable statistical analysis can be performed.

It is possible to specify appropriate power production levels to model stochastically also the 2\textsuperscript{nd} harmonic. This can be done in the same way as it was performed in case of the sideband harmonic component. According to various nonparametric as well as parametric goodness-of-fit tests appropriate active power brackets were specified and are presented in Table 2.

Another more complex example of baseband harmonics is related with existing in the background harmonics. The most significant are non-triple odd harmonics such as 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th} and 13\textsuperscript{th}. These are also observed in measurements and the most interesting from analysis perspective. In case of such harmonic components it is of great importance to have an overview of existing in the grid distortions and how the grid-connected converter interacts with it.

From Figure 13 one can see that it is complicated to measure background harmonics. This case is even more complicated in existing wind power systems. Measurements of harmonic background should be carried out when a certain wind farm is disconnected. This can be done only in case of some grid tests or maintenance which is not so frequent in commercial projects. Therefore to avoid unwanted losses in terms of money it is much better to carry out measurements of background distortions before wind farm commercial operation. Please note that even no producing wind farm but connected at the point of common coupling can significantly change impedance at that point and thus also expected harmonic distortion.

Knowing that harmonic current in case of power converter non-characteristic harmonics (e.g. 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th}, etc.) is also affected by the harmonic background one can conclude that also harmonic voltage will change at the wind turbine output terminals. Therefore it is much complicated to analyze power converter non-characteristic harmonics. Harmonic current measured during wind turbine production is presented in Figure 14.
Based on measurement data it can be concluded that baseband voltage harmonics are strongly affected by the grid. Therefore their dependence on either active or reactive power is minor. This dependence is even less significant if harmonic measurements are carried out in other places than at the grid-side converter AC terminals. In case where harmonic generation is dependent on many properties statistical approach of harmonic description becomes even more important. Unfortunately in such analysis more extended measurements are required thus long-term offshore measurements were carried out.

**D. Harmonics in offshore wind farms**

It can be expected that background distortions should be much lower at wind turbines output terminals in large offshore wind farms. Potential distortions from various nonlinear loads such as rectifiers should not be observable. Earlier it was mentioned that wind turbine harmonic emission can be analyzed taking into consideration harmonic dependence on output power. Therefore commonly taken approach in standards is understood. It was presented that actually grid-connected converter characteristic harmonics are strongly correlated with the wind turbine voltage. And due to the fact that wind turbine active power is controlled mainly by the angle probabilistic approach of harmonic generation can be applied. In large offshore wind farms where many wind turbines are connected together via the collection grid harmonic emission is of great uncertainty. In this case it is difficult to discuss about harmonic dependency on power production.

In the IEC standard [15] about measurements and assessment of power quality is stated that it is up to the wind turbine supplier to define the wind turbine terminals to be at the LV or HV side of the transformer. Normally power quality measurements are done at the LV because it more convenient. It is assumed that changing the transformer from one output voltage to another is not expected to cause the wind turbine to behave differently with respect to power quality. Please note that usually D_y,1 type transformers are used to separate zero sequence components between the wind turbine power circuit and the wind farm collection grid.

In Figure 15 one can see that measured sideband harmonic current tends to be normally distributed in measurements from large offshore wind farms (i.e. Burbo Bank, Gunfleet Sands) and its nature is specified even by small datasets. In contrast in Avedøre Holme, which is small offshore wind farm, sideband harmonic current is significantly affected by external network impedance variation.

**Figure 16** Harmonic voltage and current measured at wind turbine 38 LV terminals in Burbo Bank.

**Figure 17** Harmonic voltage and current measured at wind turbine F9 LV terminals in Gunfleet Sands.

Harmonic current and voltage measured at each individual wind turbines comprising a small piece of large offshore wind farms are presented in Figure 16 and Figure
17. As expected background distortions seen from the grid-side converter are much lower at Gunfleet Sand and therefore also the harmonic current flowing into the wind turbine is also much lower.

V. CONCLUSIONS AND DISCUSSION

A comprehensive comparison of voltage and current harmonics base on probability distribution estimation and appropriate statistics calculation (e.g. mean, variance, probability density function, etc.) is presented. Results are clearly compared using solid statistical techniques and extensively discussed. All similarities and differences are described and explained in details.

Nonparametric probability density function estimation based on kernel smoothing for different number of observations is presented. It gives an overview if a certain harmonic distribution tends to vary depending of the dataset size. If above certain length of the measured harmonic dataset there are no significant changes in the estimated probability density function one can assume the measurements were performed long enough. Thus analysis of the dataset would provide good overview about analyzed system from harmonic perspective.

Nowadays sideband harmonic components are not emphasized enough. Baseband harmonic are nowadays mainly of interest based on traditional power system harmonic studies. However more and more power electronic converters are installed in modern power systems. They are mainly generating harmonics due to pulse-width modulation. Such harmonic components are affected by two driven frequencies (i.e. power system fundamental frequency and carrier signal fundamental frequency). Therefore such harmonic components can be not integer multiple of the power system fundamental frequency. Please note that wind turbines provided by different manufacturers can introduce different modulation techniques and thus different harmonic spectrum. Such diversity can affect different harmonic phenomena at higher frequencies level (e.g. presence of frequencies below the power system fundamental in a DC-link circuit).

Actually in separated modern power systems (e.g. offshore wind farms with internal AC network connected to the grid through HVDC solution) with many grid-connected converters sideband harmonic components can be more important since baseband components emission is limited.

A. Standards

Another interesting aspect observed during the analysis is about IEC 61400-21 standard [25] concerning measurements and power quality assessment in WTs. The standard predicts measurements of 10-minute harmonic current generated by a WT for frequencies up to 50 times the fundamental frequency of the grid [16], [17]. It has to be emphasized that the most popular standard concerning measurements and power quality assessment of grid-connected WTs refers only to current harmonic components. Based on measurements and simulations it is presented in the paper that a general overview [5] about the WT behavior cannot be fully observed only based on harmonic current analysis. Additional harmonic voltage at the converter terminals and background distortion measurements are required.

According to mentioned above IEC 61400-21 standard [26] the WT during tests is connected to a certain external network which also introduces a certain level of background distortions. In the standard it is only stated that measurements which are clearly influenced by grid background noise shall be excluded. There are no specific guidelines how to assess the impact harmonic background. In the paper it is described that the background can have extremely significant impact on harmonic current flow even if it is not directly affected by the WT. Therefore dealing only with current measurements without sophisticated knowledge about its origin can provide misinterpretation and misleading power quality assessment.

VI. ACKNOWLEDGMENT

The Industrial Ph.D. project “Harmonics in Large Offshore Wind Farms” is supported by the Danish Ministry of Science, Technology and Innovation, project number 08-044839.

The measurement campaign in offshore wind farms was sponsored by DONG Energy’s SIDER3.6 R&D project.

VII. REFERENCES


VIII. BIOGRAPHIES

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