Evaluation of Power Quality Monitoring Systems in Offshore Wind Power Plants

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Abstract—The analysis of harmonic components measured in offshore wind power plants (WPPs) is shown in this paper. Harmonic analysis is a complex task and requires many aspects, such as measurements, data processing, modelling, validation, to be taken into consideration. The paper describes measurement process and shows sophisticated analysis on representative harmonic measurements from the Avedøre Holme WPP in Denmark. The nature of generation and behaviour of harmonic components is investigated and explained using various data analysis techniques. Some limitations of existing standards are emphasized and discussed in details. Based on measurements and data analysis it is shown that a general overview about WPP harmonic behaviour cannot be fully observed only based on single-value measurements as suggested in the standards but using more descriptive statistical methods.

Keywords- harmonic analyses, measurement devices, statistical analyses, wind power plant

I. INTRODUCTION

Offshore WPPs are being more and more popular in modern power systems [1], [2]. The interest in power quality has increased in WPPs from developers as well as system operators point of view. Therefore it is important to monitor/evaluate properly the quality of power supplied to consumers.

A. Background

The increasing number of distributed generation units with converters connected to the grid creates challenges in power quality assessment using commercial meters [3]. Such meters are designed based on already existing standards (e.g. IEC 61000-4-7;2002, IEC 61000-4-30:2009), however in some cases this can create limitations in appropriate power quality indices estimation. The paper will present analyses of measurements acquired at the point of common coupling by a sophisticated measurement system based on National Instruments solutions as well as commercial power quality meters.

B. Power Quality

The interest in the power quality of WPPs 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 [4]. 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 [5].

Analysis of such systems considers many aspects related to extended and accurate models, complex measurement campaigns and of course appropriate and more suitable data processing methods. It must be emphasized that there is no possibility to develop and validate accurate and extended models for harmonic studies without appropriate processed measurements. This became a crucial issue, especially if small changes in harmonic model development process are applied and signal processing begins to play a significant role [6].

II. METHODOLOGY

Harmonic measurements done simultaneously using the Elspec G44xx power quality monitoring device and National Instruments measurement system [7], [8] exclusively developed for power quality measurements will be analysed in this paper. The measurements were done at the point of common coupling of demonstration offshore WPP Avedøre Holme located in Denmark and connected to the distribution network at 10 kV voltage level.

The analysis takes into consideration various voltage and current harmonic components for different active power bins explaining their origin. The power quality evaluation process requires various data processing stages such as fundamental frequency detection, sample rate adjustment according to the detected frequency, discrete Fourier transform, phase lock, etc. The approach of sample rate adjustment is to adjust the finite orthogonal Hilbert basis in order to express each of frequency components in the Fourier space only by one vector from the Hilbert basis. However in estimation of harmonic spectrum from grid converters this sometimes can be a challenging task which will be shown in this paper [9].

Statistical analyses of different current and voltage harmonics measured by the two measurement systems (i.e.
Elpec power quality monitoring device and National Instruments data logging system) are analysed, compared and presented in the paper. The distribution of different harmonic components is graphically presented and statistics are calculated in order to provide sophisticated comparison [10].

III. MEASUREMENT SYSTEMS

Measurement process is one of the most important issues during WTG and WPP evaluation and requires careful approach. Accurate measurements of harmonic voltages and currents in offshore WPPS followed by proper data analysis are essential for harmonic emission evaluation. In harmonic measurements it is of great importance to specify appropriate measurement points and optimize data acquisition devices as well as sensors.

Measurement systems involving multiple devices often require accurate timing in order to secure event synchronization and correlation in long-term data acquisition. One of the ways to achieve this synchronization measurement units must synchronize their individual clocks in order share a common time base. In large offshore WPPs distributed clock synchronization becomes necessary. Distributed clock synchronization in WPPs requires devices synchronized to a GPS satellite because of significant distances between measurement units [8].

![Figure 1](image1.png)

Figure 1 Measurement system used for synchronization.

As presented in Figure 1 there are two synchronization possibilities: with reference clock and by means of phase-locked loop (PLL) synchronization. With the reference clock, the PXI 4472 device locks their frequency timebases – the inputs of their direct digital synthesis (DDS) chips, to the PXI_CLK10 (10 MHz) clock supplied by the PXI unit backplane. This is accomplished by using PLL. After a sync pulse is sent, which aligns the sample clock timebase on each device, the oversample clocks, and the analog-to-digital converters (ADCs). Finally, a shared start trigger is sent, which starts the acquisition and generation events on each device at the same instant. Another synchronization is just done by means of PLL which provides sufficient accuracy for harmonic measurements. Having an appropriate synchronization the GPS disciplined oscillator (GPSDO) is used to combine the good short term stability of the crystal oscillator with the excellent long term stability of the GPS signal. It assures that each acquired sample by all dispersed measurement unit will be synchronized together as presented in Figure 2.

In order to achieve that GPS synchronized triggering and GPS disciplined timebase were used. PXI-6682, PXI-6653, PXI-4495 and PXI-4472 were used in each of measurement locations in order to assure precise synchronisation and high quality (i.e. aliasing free, high resolution equal to 24 bits, suitable sample rate equal to 44.1kS/s/ch) data acquisition.

![Figure 2](image2.png)

Figure 2 Synchronization between PXI-4472 and PXI-4495 with filter delay compensation.

<table>
<thead>
<tr>
<th>Point</th>
<th>Input signal</th>
<th>Probe</th>
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<th>Accuracy</th>
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<td>±2% (+1%)*, loop center</td>
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<td>1Hz-1MHz</td>
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</tr>
</tbody>
</table>

A. Sensors evaluation

During the test measurements were done by inductive current transformers (CTs) and voltage transformers (VTs) which are permanently installed at the point of common coupling (PCC) and are used for power quality assessment by the Elspec G44xx monitoring. Simultaneously voltages and currents waveforms were measured using Rogowski coils and capacitive voltage dividers with sufficient bandwidth and tested in laboratory environment. The test was done in order to evaluate performance VTs and CTs during harmonic measurements.

From Figure 3 it can be seen that the inductive CTs and VTs are capable of measuring harmonics components within the third carrier group. Please note that this is only valid of transformers of this particular model. Unfortunately there is no requirement in the standards for metering and protection to provide bandwidth of measuring transformers by manufacturers.
Figure 3 Inductive current and voltage transformer bandwidth evaluation within the third carrier group, i.e. ~7500Hz.

IV. MEASUREMENT CAMPAIGN

Extended measurement campaign was performed at Avedøre Holme and appropriate data processing techniques were applied to carry out trustful harmonic evaluation. Avedøre Holme in the south of Copenhagen is a demonstration plant and allows testing wind turbine generators (WTGs) before they were implemented in large-scale offshore projects. One month of measurement gave a good overview about harmonic emission of a single WTG as well as the whole WPP. The WTG used in the offshore WPP is Siemens Wind Turbines SWT-3.6-120.

A. Wind power plant description

Avedøre Holme (see Figure 4) offshore WPP in the south of Copenhagen is a shared project between DONG Energy and Hvidovre Vindmøllelaug A/S. The two WTGs (M2 and M3) 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 accessibility to the offshore WTGs via a footbridge is the basic idea behind the project. This gives DONG Energy a unique opportunity to test and try out new WTG concepts, before they are implemented in large scale in offshore WPPs.

Figure 4 Avedøre Holme offshore WPP location

The SWT-3.6-120 is a variable-speed WTG 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 WTG. The WTG transformer is connected via a vacuum circuit breaker (VCB) to the MV network.

The measurement system was installed in all 3 WTGs as well as at the PCC as it is presented in Figure 5. The most important measurement location was at PCC and based on that measurement point it is possible to directly evaluate the WPP harmonic performance. Also at the same location, in most cases, commercial power quality meters are installed. Therefore the PCC was chosen to perform extensive measurement campaign leading, inter alia, to sophisticated comparison between two measurement systems, i.e. Elspec G44xx and the one based on National Instruments solutions.

Figure 5 Measurement points installed at Avedøre Holme.

V. RESULTS

Harmonic measurements done simultaneously using the Elspec G44xx power quality monitoring device and National Instruments measurement system will be analysed.

A simply way of harmonic components statistical analysis is histogram analysis. The distribution of harmonic data sets obtained by measurements and statistical indices like: mean, standard deviation, variance, skewness, kurtosis, min, max and %95 percentile are calculated [11], [12].

A. Measurements from Elspec

A quantitative analysis is done using the Elspec acquired measurements in order to point out which harmonics are generated by the WTG grid-side converter and which are harmonic background distortions from the grid.

As it can be seen from Figure 6 the 2nd harmonic increases with the increasing of the active power production level which provides some premises that this harmonic is caused mainly due to the converter operation.
In order to evaluate the 2nd harmonic contribution from WTGs also measurements from the LV circuit are analysed. In Figure 7 one can see that voltage is proportionally increasing with the WTG active power increase. It is also worth to mention that the 2nd harmonic is not power system characteristic harmonic therefore it is not expected to be seen in the grid.

The 5th harmonic presented in Figure 8 is characteristic for the power system, is simply a background harmonic which is present in the distribution network. The WPP operation can influence the power system characteristic harmonics by changing the equivalent network impedance. The network impedance can be changed by the number of generation units that are in operation and also by other system elements switching (e.g. transformers, power cables, compensation units, loads).

Figure 8 shows the statistical distribution of harmonics generated by the convertor. The distribution presents at least two peaks which it means that is a multimodal data set. The harmonics are distributed within relatively small range which is also proved by the small standard deviation value (s=0.44). The nature of multimodal histogram of the 2nd harmonic current can be caused by changes in the short-circuit impedance of the power system to which the WPP is connected.

Figure 9 presents the statistical distribution of the 5th harmonic current values. The data set is also a multimodal data set with two peaks, but this time the standard deviation is higher, 1.08. For the 5th harmonic data set estimated skewness is positive (\(g_1=0.28\), but the difference to zero (which is the skewness value for a normal distribution) is the same like for the second harmonic current data distribution presented in Figure 9. (\(g_1=-0.27\)).

Interesting results regarding harmonic measurements using Elspec commercial power quality meter are presented in Figure 11. Due to the spectral leakage the estimated magnitude sometimes can be even equal to zero. Therefore data processing algorithm of the commercial power meters can sometimes give wrong results. Similar behaviour is expected to be seen also in grid-connected converters with random or hysteresis modulation. This creates new challenges in terms of power quality evaluation in modern power systems.
**B. Measurements from National Instruments**

Statistical distributions corresponding to harmonic currents values from National Instruments measurements are presented in Figure 12 and Figure 13. In order to make a comparison, between the results obtained by Elspec G44xx commercial power quality meter and National Instruments measurement system, the same harmonic currents are presented, i.e. the 2\textsuperscript{nd} and 5\textsuperscript{th} harmonics.

Interesting observation is that the disturbances in the higher frequency range are typically not linked to the power system frequency $f_0$ but are due to active controllers that operate at a certain switching frequency $f_s$ which tends to produce power system characteristic harmonics only under ideal operation conditions (i.e. $f_s=nf_0$, where $n$ is integer). This provides some limitations to measurement methods introduced in the IEC 61000-4-7 standard where window synchronization based on phase-locked loop is suggested. Furthermore, sample rate adjustment based on window synchronization can even give wrong results and lead to misinterpretation of calculated data.

Figure 14 shows WTG grid-side converter sideband harmonic components measured at PCC. In Figure 14(a) it can be clearly seen that the harmonic component is affected by spectral leakage caused by sample rate adjustment, i.e. rectangular window synchronization to $f_s$. Without the synchronization the estimated harmonic is much more accurate as can be seen in Figure 14(b). However in IEC 61000-4-7 also possible grouping is mentioned which can...
improve a little the outcome as is presented in Figure 15(a) in comparison to Figure 15(b).

C. Comparison

Analysing the distributions and the statistical indices calculated for the measurements data sets acquired with both measurement systems (i.e. Elspec Investigator and National Instruments) it can be seen that the min values for Elspec are zero and for National Instruments are different to zero. This is due to the lossy compression and connected to that a tolerance value (threshold) of the Elspec G44xx measurement devices which consider all the values lower than this tolerance to be zero.

Elspec measurements data set for 2nd harmonic current has skewness and kurtosis values lower than National Instruments data set which means that the distributions are closer to a normal distribution. The same conclusion is valid also in the case of 5th harmonic.

Comparing Figure 10 and Figure 13 is important to emphasize that the algorithm of the power quality meter uses lossy compression which also determines estimated magnitudes. Estimated harmonic components are assumed to be insignificant and they are assumed to be zero if the values are lower than a certain threshold depends on measured waveform distortion and maximum allowed database storage capacity per month.

However comparing the histograms of the 2nd harmonic from Figure 9 and Figure 12 as well as histograms of the 5th harmonic from Figure 10 and Figure 13 it can be seen that the overall distribution of both harmonics is similar from both measurement system. Even lossy compression does not affect significantly the harmonic estimation however the measurement system developed based on National Instruments technology gives higher harmonic values in all cases giving more conservative harmonic estimation.

VI. SUMMARY AND CONCLUSIONS

The paper provides a comparison of different monitoring systems designed for harmonic measurements. Simultaneously it shows limitations of commercial power quality meters in harmonic monitoring in WPPs with modern grid-connected converters.

The paper provide recommendations and guidance regarding power quality monitoring at the point of common coupling in WPPs as well as emphasizes a need for further standards development.

Statistical analyses of harmonic measurement data sets are useful for harmonic understanding and the calculation of indices like mean, variance, skewness, kurtosis gives more information about the data distribution.

Spectral leakage is an issue in the case of commercial power quality meters due to the fact that these are doing a sample rate adjustment with the power system variation frequency.

VII. REFERENCES


