Harmonic analysis of wind turbines including measurements, data analysis and modelling

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***Abstract*—Procedures and guidelines of harmonic analysis in wind turbines and wind power plants are shown in this paper. It is shown that harmonic analysis is comprised of measurements, data processing, data analysis and modelling. Only careful analysis can reveal the harmonic behaviour of wind turbines. Many aspects of harmonic analysis are described and explained based on real-life measurements. The paper summarises observations from wind power plant project development and cooperation between manufacturers and developers.**

***Keywords*—grid-side converter, harmonics; harmonic analysis; wind turbine**

I. INTRODUCTION

Wind power plants equipped with advanced power electronic solutions are becoming more and more popular in power systems [1]. Power electronic equipment in modern power systems is obviously a source of additional harmonic components not seen previously. On the other hand, the application of advanced and fast control in grid-connected power converters introduces possibility to controlling higher frequencies than the power system's fundamental frequency component [2]. Appropriately used power electronics can definitely improve the quality of power.

Harmonics were always of special concern in power system studies. In the past the power system comprised mainly of passive components with relatively linear operating range and synchronous generators. Harmonic analysis of such systems is the state-of-the art right now.

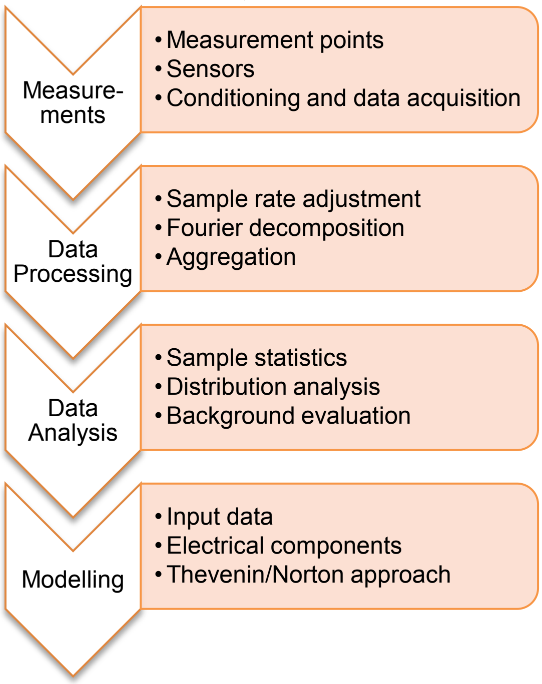
A. Harmonics in modern wind turbines

Renewable energy sources, in particular wind turbines, have become important elements in transnational electrical power systems. Power electronic equipment in modern power systems is obviously a source of additional harmonic components not seen previously.

Therefore, due to the modern power converters complexity, there is a high necessity to perform careful power quality evaluation including harmonic measurements, data processing, data analysis, and harmonic modelling of wind turbines. Appropriate harmonic assessment can be divided in several stages [3]:

- harmonic measurements,
- data processing,
- data analysis,
- model development.

Each of the stages is equally important in appropriate and accurate harmonic evaluation for wind turbines and wind power plants. Each of the stages introduces uncertainties which should be evaluated and should be at an acceptable level. Supplementary recommendations and requirements will be provided in this paper to already existing and applicable standards (i.e. IEC 61400-21, IEC 61000-4-7, IEC 61000-4-30) [4], [5], [6].



II. HARMONIC MEASUREMENTS

Measurements are an important element of the wind power plant and wind turbine evaluation process. In order to validate theoretical analysis and numerical simulations, measurements are required. The measurement equipment should be carefully adjusted in order to record harmonics of interest with acceptable accuracy and precision. The most important aspects of harmonic measurements, such as measurement conditions, sensors, signal conditioning and data acquisition, are briefly described and commented on in relation to existing standards in this section.

The harmonic measurements should be carried out during continuous wind turbine normal operation, i.e. fault free operation complying with the description in the wind turbine manual excluding wind turbine start-up and shutdown as described in IEC 61400-21.

Various operational modes could be taken into consideration. Please note that various operational modes can be characterised by different frequency response of the converter and consequently affect harmonic emission. Therefore it is recommended to take into consideration if the operation mode was changed during the measurement process.

It is also recommended to perform measurements during wind turbine standstill. This would be helpful in evaluating the harmonic background seen from the wind turbine. The wind turbine during background measurements should be invisible to the system to which it is connected, i.e. no harmonic current flow from or into the wind turbine is expected.

Also electromagnetic immunity of the measurement equipment should be secured, and appropriate electromagnetic compatibility tests in harsh wind turbine environment should be performed. Such tests would include data acquisition board open circuit measurements including cross-talk investigation, test of measurement cables/leads shielding and grounding in the wind turbine, DC-offset drift (systematic error) due to temperature variation, etc.

A. Measurement conditions

According to IEC 61400-21 (7.1.2), the following test conditions are required.

– The wind turbine must be connected directly to the MV-network through a standard transformer with rated apparent power at least corresponding to the rated apparent power of the assessed wind turbine.

– The total harmonic distortion of the voltage including all harmonics up to the order of 50 must be less than 5% measured as 10min average data at the wind turbine terminals, while the wind turbine is not generating. Additionally, the harmonic background must be evaluated for each harmonic up to the 50^{th} harmonic. Please note that the requirement regarding the total harmonic distortion of the background does not consider variations of individual harmonic components, therefore each harmonic component should be evaluated during post-processing.

– The grid frequency measured as 0.2s (10 cycle) average data shall be within ±1% of the nominal frequency, and the rate of change of the grid frequency measured as 0.2s average data shall be less than 0.2% of the nominal frequency per 0.2s. It is good practise to measure the grid frequency during the test. In general, the frequency variation does not affect significantly the evaluation of the power system characteristic harmonics (i.e. linked with the power system fundamental frequency) if appropriate data processing methods are applied (i.e. resampling) [7]. Another issue is with the power converter characteristic harmonics for fixed switching frequencies which will also be measured and evaluated. This issue should be carefully investigated during data analysis, especially if the switching frequency is not locked to the power system fundamental.

– The voltage must be within ±10% of its nominal value measured as 10min average data at the wind turbine terminals. This voltage range is expected to be within the wind turbine continuous operation.

– The voltage unbalance factor must be less than 2% measured as 10min data at the wind turbine terminals. The voltage unbalance factor may be determined as described in IEC 61800-3:2004 (B.3).

– The environmental conditions must comply with the manufacturer's requirements for the instruments and the wind turbine.

Please note that the evaluation of test conditions is going to be performed during data post-processing. It is expected to perform continuously measurement and later, if required, exclude measurements that do not meet specified requirements.

B. Sensors

According to IEC 61000-4-30, the frequency response of a standard metering class VT depends on its type and the burden applied. With a high impedance burden, the response is usually adequate to at least 2 kHz, but it can be less. Thus, such transducers cannot be used for harmonic measurements. For higher frequency applications the IEC 61000-4-30 standard requires a capacitive voltage divider or pure resistive voltage divider [8]. Special purpose capacitor dividers can be obtained for measurements requiring accurate characterization of frequency components up to at least 1 MHz. Therefore, it is also suggested not to use VTs but voltage sensors based on capacitive voltage dividers. Of course, differential voltage sensors are even more recommended where it is possible (e.g. LV and MV differential voltage sensors) because they are characterised by higher electromagnetic immunity.

Also application of CTs for current measurements is not recommended due to the limited bandwidth. According to IEC 61000-4-30 standard metering-class, CTs are generally adequate for frequencies up to 2 kHz (phase error can start to become significant above this limit). For higher frequencies flexible Rogowski coils are recommended which are characterised by much better frequency response.

Of course, the rated values of all sensors (e.g. peak current, peak voltage) should be adjusted to maximum possible values in order to minimise uncertainties. Also the sensors output values (i.e. voltage or current) should be within an acceptable range for the signal conditioning equipment and for the data acquisition (DAQ) equipment.

For example, a DAQ device with 24-bit resolution is taken into consideration (e.g. PXI-4472), and a 32-bit sample size is returned during acquisition, e.g. signed integer (I32). If the full scale (FS) of the input signal acceptable by the DAQ is ±10 V, and the sensor FS output voltage is ±2.5 V (e.g. HIOKI 9279), the number of bits M_s=22 (see Eq. II.1). This means that 10 bits are unused (i.e. 2 bits from the DAQ resolution and 8 bits form I32).

The sensor accuracy is usually much smaller than the least significant bit (LSB) which should also be taken into consideration. Assuming the sensor has 1% accuracy, which means that measuring values with ADC LSB less than 25 mV are of great uncertainty, and the ADC performance with LSB of 1.2 μV is definitely not fully used.

$$M_S = \left\lceil \log_2\left(\frac{E_s}{Q}\right) \right\rceil \qquad \text{II.1}$$

where Q is the ADC resolution which can be expressed as

$$Q = \frac{E_{DAQ}}{N}$$

$$E_s = V_{S_{High}} - V_{S_{Low}}$$

$$E_{DAQ} = V_{DAQ_{High}} - V_{DAQ_{Low}}$$

$$N = 2^{M_{DAQ}}$$

where E_s is the FS voltage range of the sensor, E_{DAQ} is the FS voltage range of the ADC, $V_{S_{High}}$, and $V_{DAQ_{Hi}}$ are respectively the upper extremes of the sensor, and the ADC operating ranges, $V_{S_{Low}}$ and $V_{DAQ_{Low}}$ are respectively the lower extremes of the sensor and the ADC operating ranges, N is the number of voltage intervals, and M_{DAQ} is the ADC resolution in bits. The resolution of the converter Q indicates the number of discrete values it can produce over the range of analogue values and is equal to LSB voltage.

C. Signal conditioning

According to IEC 61000-4-7, frequencies outside the measuring range of the instrument must be attenuated so as not to affect the results. To obtain the appropriate attenuation, the instrument may sample the input signal at a frequency much higher than the measuring range. For example, the analysed signal may have components exceeding 25 kHz, but only components up to 2 kHz are taken into account. An anti-aliasing low-pass filter, with a 3 dB frequency above the measuring range must be provided. The attenuation in the stop-band must exceed 50 dB. In modern data acquisition devices for harmonic/vibration measurements the anti-aliasing filter are added by default with much better attenuation capability. The input low-pass filter is also recommended by IEC 61400-21.

It is recommended to apply a low-order (e.g. second-order) Butterworth filter, which is characterised by a flat pass band which reduces measurement uncertainty within the measurement system bandwidth. Together with the low-order low-pass filter an oversampling process during data acquisition is recommended in order to limit aliasing within the relatively wide transition band of the low-order filter. It is recommended to use the same analogue anti-aliasing filter (low pass filter) which should have the same frequency response in all voltage and current inputs in order to prevent phase errors.

D. Data acquisition

According to IEC 61000-4-7, the window width must be 10 (50 Hz systems) periods with rectangular weighting. Hanning weighting is allowed only in the case of loss of synchronisation. Application of the Hanning window to minimise spectral leakage is always connected with additional uncertainties. Therefore, it is recommended to perform measurements without synchronisation and later adjust the sample rate during post-processing and all the time apply the rectangular window.

Also according to IEC 61000-4-7 the time window must be synchronised with each group of 10 cycles according to the power system frequency of 50 Hz. However, in that case only harmonic components linked with the power system frequency will be properly estimated. In power systems where with more than only one driving frequency (e.g. power system fundamental frequency and carrier signal fundamental frequency) and where such driving frequencies are not linked between each other (i.e. non-integer frequency ratio), window synchronization will affect significant spectral leakage. Hence, sample rate adjustment during post-processing is required and sophisticated single tone detection algorithm is required [9].

The data acquisition unit should be kept within the ambient temperature range specified by the manufacturer. The temperature variation regarding calibration uncertainties cannot exceed limits specified by the manufacturer. According to IEC 62008 [10], to compensate for environmental effects and maintain measurement accuracy, an analogue-to-digital converter in the data acquisition board may be able to self-calibrate. Self-calibration does not require any external connections to the data acquisition board. Instead the data acquisition board contains all the hardware required to adjust its own measurements.

The sample rate according to IEC 61400-21 is required to be of at least 2 kS/s/ch for the voltage and current signals. For measurement of sideband harmonics (higher frequency components) the minimum sample rate must be at least 20 kS/s/ch. Such sample rate will allow recording harmonic components generated by switching power converters [11].

III. Data processing

In this section it is shown that there are various aspects such as grouping, sample rate adjustment, aggregation which are not exhaustively described in already existing standards. Accordingly, supplementary requirements are described in this paper of special concern in connection with wind turbine harmonic evaluation and modelling.

According to IEC 61000-4-7, additional operations on the raw data, such as smoothing and weighing, are described. However, it is not recommended, as it may cause additional uncertainties in harmonic assessment, especially for high-frequency components. Fourier decomposition and possible grouping should be applied during off-line data processing. On the other hand, only adjacent interharmonics grouping as a contribution to harmonics is recommended.

Please note that the Fourier transform analysis assumes that the signal is stationary. Meanwhile, the signal magnitude (voltage or current) of the power system may fluctuate, spreading out the energy of harmonic components to adjacent interharmonic frequencies. To improve the assessment accuracy of the signal, the spectrum components of the Fourier decomposition must be grouped including only adjacent/neighbouring spectrum components (i.e. ±5Hz) according to Parseval theorem (see IEC 61000-4-7 for more details).

In the IEC 61000-4-7 standard, it is also mentioned that all interharmonics can be considered in harmonic assessment which is not recommended. This approach can be only reasonable if one would assume that all interharmonics are only affected by data processing errors (i.e. spectral leakage), which in most cases is a too strong assumption and can lead to overestimation of emission levels.

Also in the same standard it is stated that harmonics above 2000 Hz in the output of the raw Fourier decomposition (DFT) must be grouped in bands of 200 Hz, beginning at the first centre band above the harmonic range. The centre frequencies, for example, can be 2100 Hz, 2300 Hz, 2500 Hz designates the band. Unfortunately, this approach cannot be successfully applied in measurements of power converters where sideband harmonics in the carrier groups are situated much closer in the spectrum (i.e. every f_o, where f_o it the power system fundamental frequency). It is recommended to apply grouping for frequencies above 2000 Hz in the same was as below 2000 Hz (i.e. only the adjacent interharmonics should be considered in the grouping). If appropriately performed data processing significantly reduces spectral leakage, the grouping can be even omitted.

A. Sample rate adjustment

In IEC 61000-4-7 it is stated that before application of DFT, the samples in the time window are often weighted by multiplying them with a special symmetrical function (i.e. windowing function). Nevertheless, for periodic signals and synchronous sampling, it is preferable to use a rectangular weighting window which multiplies each sample by unity.

The synchronous sampling can be obtained in two possible ways: before data acquisition (on-line) and after data acquisition (off-line). The comparison of different resampling algorithms is presented in Figure 1. The most optimal interpolation algorithm for harmonic processing is spline [3].

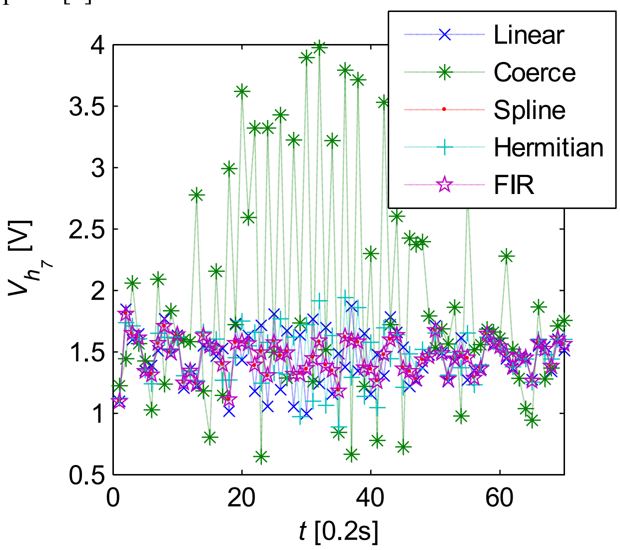


Figure 1 Comparison of various interpolation techniques of measurements from the converter terminals.

It is recommended to perform sample rate adjustment during off-line processing. For harmonic components which are multiple integers of the power system, frequency the sample rate should be adjusted to the power system fundamental component. However, for harmonic components that are multiple integers of the carrier frequency, the sample rate should be adjusted to the carrier fundamental component. In case of sideband harmonics within each of carrier groups, the sample rate can be adjusted separately for each sideband harmonic component or just resampled to the carrier fundamental component. Fourier decomposition of sideband harmonics if the window is synchronised to the carrier signal fundamental frequency can be slightly affected by spectral leakage because sideband harmonics are dependent on the power system fundamental frequency and the carrier signal fundamental frequency [7].

B. Fourier decomposition

According to IEC 61000-4-7, IEC 61000-4-30, and IEC 61400-21 the basic measurement time interval for parameter magnitudes (supply voltage, harmonics, interharmonics and unbalance) must be a 10-cycle time interval for a 50 Hz power system. Each of 10-cycle intervals must be decomposed in frequency domain using DFT. In Fourier decomposition it is assumed that the waveform is a stationary time-series [12]. Nonetheless, in real life this this is not always the case. Therefore various stationarity tests (e.g. reverse arrangement test) can be performed before the Fourier decomposition, and results, where the stationarity assumption is violated, should be flagged. If the harmonic content is changing within the specified 10-cycle interval, the Fourier transform would cause averaging and according to the central limit theorem (CLT) changes in the harmonic distribution.

In order to estimate harmonic components, the rectangular window should be precisely synchronised to their waveform length in order to avoid spectral leakage. In some cases, the switching frequency (f_c) is not linked with the power system frequency (f_o). Therefore, during post-processing, the rectangular window synchronization should be evaluated separately for baseband and sideband harmonics and adjusted, if needed.

It is recommended to lock the baseband harmonics phase to the fundamental voltage harmonic of the first phase. In many cases, the estimated phase of the sideband harmonics cannot be locked to the fundamental frequency, because it is dependent on phases of the power system fundamental frequency (θ_o) as well as the carrier signal fundamental frequency (θ_c) [13].

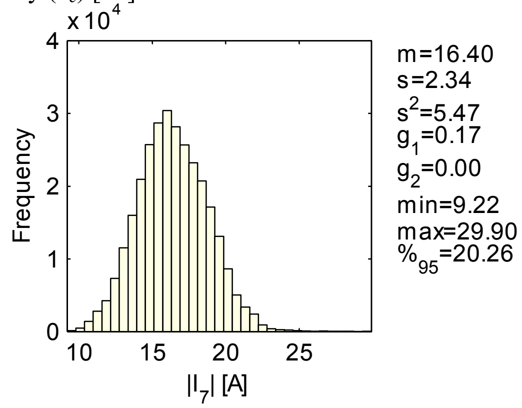


Figure 2 Baseband (7th) harmonic current magnitude measured at LV in the wind turbine: harmonic current significantly affected by the background distortions.

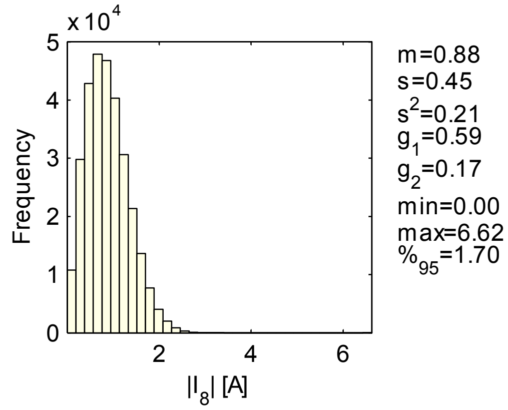


Figure 3 Baseband (8th) harmonic current magnitude measured at LV in the wind turbine: harmonic current of low amplitude.

Figure 2 and Figure 3 show harmonic magnitude estimation by application of DFT. It is easy to see that the distribution is affected by the harmonic background, harmonic level as well as measurement uncertainties. Please note that m, s, s^2, g_1, g_2 correspond to sample mean, sample standard deviation, sample variance, sample skewness, and sample kurtosis, respectively.

C. Aggregation

Different aggregation methods are presented and analysed in this part. One harmonic aggregation method taken directly from IEC 61000-4-30 can be expressed as presented below. Please note that the harmonic angle is not taken into consideration.

$$G_h = \sqrt{\frac{1}{n}\sum_{i=1}^{n} G_{i,h}^2} \qquad \text{II.2}$$

where $G_{i,h}$ is the h-th harmonic frequency bin from the estimated spectrum from each of i-th 10-cycle waveforms and G_h is the aggregated h-th harmonic magnitude (gain).

According to IEC 61000-21, the 10-min averages of each frequency band (i.e. each sub-grouped harmonic, interharmonic and higher frequency current component) must be calculated for each 10 min time-series, and subsequently the maximum 10 min averages of each frequency band in each 10 % power bin must be reported. However, it is not specified how the averages should be calculated. One of the possibilities is to calculate averages for the magnitude and phase separately and later evaluate the results. Probably this approach was assumed during the standard development, because it does not mention the harmonic phase. The harmonic magnitude can be obtained in the following way

$$G_h = \frac{1}{n}\sum_{i=1}^{n} G_{i,h} \qquad \text{II.3}$$

Meanwhile, similar aggregation can be made by using complex numbers

$$G_h = \left|\frac{1}{n}\sum_{i=1}^{n} G_{i,h} e^{jP_{i,h}}\right| \qquad \text{II.4}$$

where $P_{i,h}$ is the estimated phase of the h-th harmonic components of the i-th 10-cycle waveform.

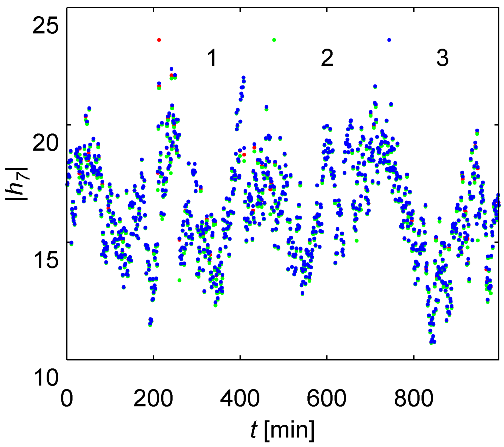


Figure 4 Comparison of the 7th harmonic current magnitude aggregation measured at LV in the wind turbine: 1(red) – magnitude separately averaged (IEC 61400-21), 2(green) – complex numbers averaging, 3(blue) – square root of the arithmetic mean of the squared magnitudes (IEC 61000-4-30).

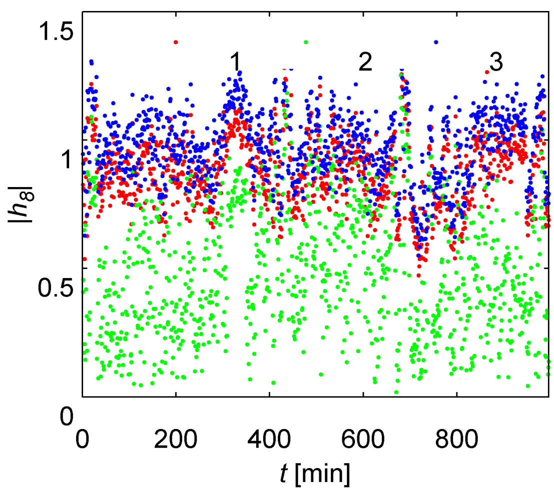


Figure 5 Comparison of the 8th harmonic current magnitude aggregation measured at LV in the wind turbine: 1(red) – magnitude separately averaged (IEC 61400-21), 2(green) – complex numbers averaging, 3 (blue) – square root of the arithmetic mean of the squared magnitudes (IEC 61000-4-30).

In Figure 4 it can be seen that the harmonic aggregation technique does not affect harmonic amplitude estimation in case of significant harmonic components. On the other hand, in Figure 5 it can be seen that in case of harmonics with significant measurement uncertainty (i.e. amplitude close to the measurement system accuracy) amplitude estimation may vary, depending on different aggregation techniques. It actually can be seen that the complex numbers averaging are probably the most appropriate due to the randomness of the phase angle.

Separate aggregation of phase and magnitude and complex numbers aggregation should give the same results for correctly measured stationary signals. However, it was observed that for really low harmonic components (i.e. within the measurement system uncertainty), it is difficult to estimate the harmonic phase. Therefore, separate aggregation (averaging) of magnitudes and phases provides more reliable results. The angle can be aggregated in the following way.

$$P_h = \frac{1}{n}\sum_{i=1}^{n} 1 e^{jP_{i,h}} \qquad \text{II.5}$$

On the other hand, for harmonics of significant uncertainty and affected by significant measurement errors, it may be an advantage to perform aggregation of complex values (i.e. including amplitude and angle).

Various aggregation techniques are possible, nevertheless, it is recommended to calculate average according to IEC 61400-21. It is recommended to separately aggregate the harmonic magnitude and the harmonic phase. However, for harmonics of low value complex, numbers averaging would be better in order to reduce uncertainties.

The 10-cycle values are then aggregated over 3 additional intervals:

– 150-cycle (3 s) interval for 50 Hz nominal,
– 10 min interval,
– 2 h interval.

In some applications, other time intervals (e.g. 10 sec, 1 min) may be useful. These other time intervals, if used, should be obtained with the same aggregation method (e.g. a 1-min time interval, if used, should be implemented using a method that is analogous to the 10-minute aggregation method).

Please note that the phase angle aggregation is not specified in any of the standards. Therefore, for sophisticated harmonic analysis another aggregation approach is required taking into consideration magnitude as well as phase aggregation. The aggregation process can be performed by separate averaging of the estimated magnitude and the estimated phase.

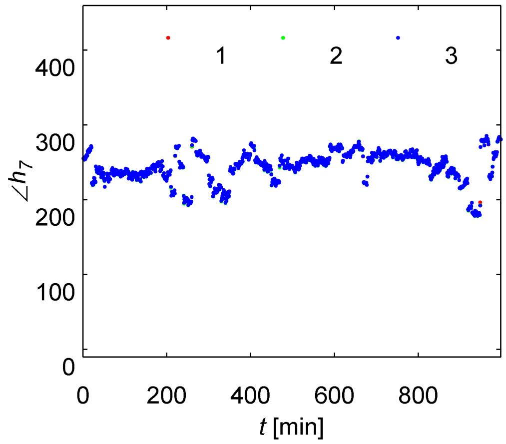


Figure 6 Comparison of the 7th harmonic current phase angle aggregation measured at LV in the wind turbine: 1(red) – phase separately averaged (arithmetic mean), 2(green) – complex numbers averaging, 3(blue) – complex numbers averaging (unity vectors).

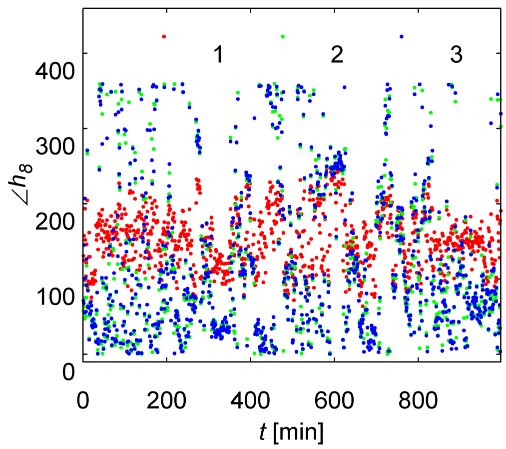


Figure 7 Comparison of the 8th harmonic current phase angle aggregation measured at LV in the wind turbine: 1(red) – phase separately averaged (arithmetic mean), 2(green) – complex numbers averaging, 3(blue) – complex numbers averaging (unity vectors).

Possible grouping of the spectral components must be performed according to IEC 61000-4-7 with restrictions specified above.

IV. Data Analysis

Important issues related with data analysis are taken into consideration in this section. It is shown how statistical analysis can be beneficial in measurement data assessment and preparation for model development and validation.

A. Statistical analysis

According to IEC 61000-4-30, the first objective of statistical analysis is to compress a large number of measured values and the second objective is to compute power quality indices for benchmarking, either on one specific point or for a whole network. However, there are no specific guidelines regarding statistical analysis, and it is simply stated that a suitable statistical analysis method must be chosen for the data. Different statistical methods may be selected, depending on the power quality parameter and measurement objectives [14].

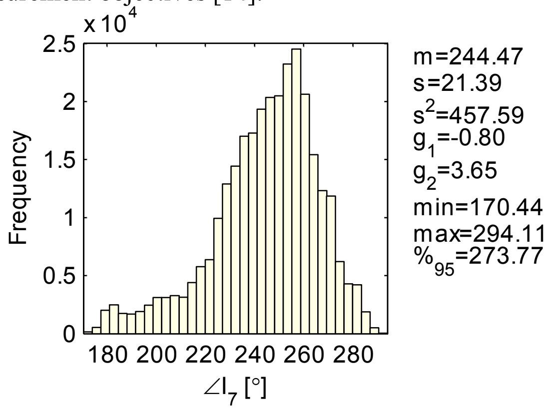


Figure 8 Baseband (7th) harmonic current phase measured at LV in the wind turbine: harmonic current phase within relatively narrow range.

In Figure 8 and Figure 9 it can be seen how easily the phase angle can be estimated for significant harmonics and how poorly the phase angle can be estimated for harmonics of high uncertainty. Thus, for harmonic where the phase angle is almost uniformly distributed, it is better to use aggregation based on complex numbers averaging. Phase angle estimation corresponds to amplitude estimation in Figure 2 and Figure 3.

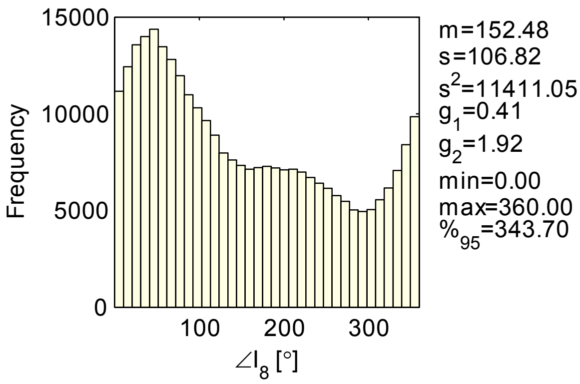


Figure 9 Baseband (8th) harmonic current phase measured at LV in the wind turbine: badly estimated harmonic current phase.

Calculation of min, max and mean values can give an overview about measured harmonics. However, without knowledge of their distribution, it is impossible to evaluate the emission and consider such values as representative indices. If the distribution is skewed with a long right tail, it is recommended to consider 95% instead of the maximum value. According to IEC 61000-4-30 and ETR 122, calculation of 95% is also recommended. Also information about the standard deviation would be beneficial. Please note that the harmonic phase distribution should be even more carefully evaluated before any aggregation is applied. This is absolutely crucial for harmonics of low amplitude. From Figure 10 can be seen how the distribution is affected according to the CLT by simple averaging.

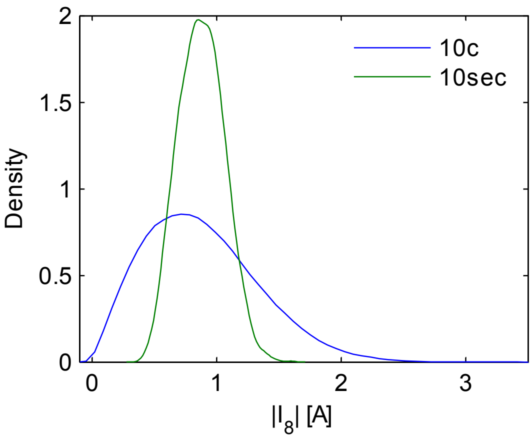


Figure 10 Kernel density estimation of harmonic current measured at LV in the wind turbine before (10c) and after (10sec) aggregation based on the arithmetic average.

B. Harmonic background distortion

In IEC 61400-21, it is stated that the total harmonic distortion of the voltage including all harmonics up to the order of 50 must be less than 5% measured as 10 min average data at the wind turbine terminals, while the wind turbine is not generating. The total harmonic distortion of the voltage may be determined by measurement prior to testing the wind turbine.

It is known that the harmonic background level can cause problems in harmonic emission evaluation of the wind turbine. Therefore, it is recommended to evaluate harmonic background distortions when the wind turbine is not producing (standstill or disconnected). The wind turbine should be invisible to the network to which it is connected during background distortions evaluation. It means that there should not be any harmonic current flowing either from or into the wind turbine (i.e. open circuit). From Figure 11 it can be seen that the background voltage (V_{RMS} is only from the background and is around 390 V) is higher than the harmonic voltage generated by the converter (V_{RMS} is around 460 V due to sideband harmonics). Thus, the harmonic current seen in Figure 2 is actually flowing into the wind turbine. This demonstrates that the harmonic assessment approach presented in IEC 61400-21 is inappropriate.

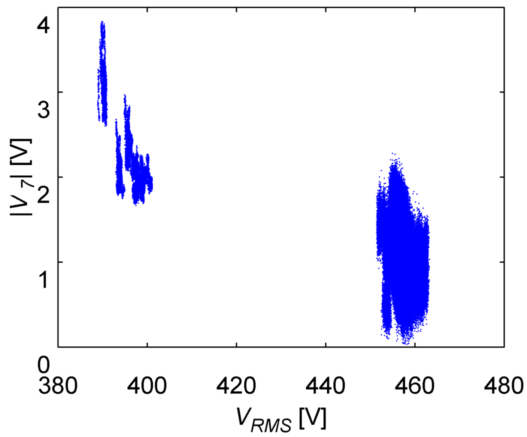


Figure 11 Harmonics background evaluation at wind turbine converter terminals. The 7th harmonic is higher when the wind turbine is not producing (true V_{RMS} equal to around 390 V) than wnen the wind turbine is procucing (V_{RMS} equal to around 460 V).

In order to evaluate which harmonics are affected by the grid and which are purely generated by the wind turbine, statistical analysis can be helpful. Please note that for harmonics of low magnitude, which are within the measurement system uncertainty, the determination of the phase angle might be problematic. Therefore, additional statistical analysis is recommended to specify harmonics origin and nature.

V. MODEL DEVELOPMENT

Nowadays, there is a lack of appropriate wind turbine model descriptions for harmonic analysis purposes in standards. Such models have been available from at least one manufacturer of wind turbines (i.e. Siemens Wind Power) for a number of years. These models represent the converter in a wind turbine as a number of Thévenin equivalent circuits representing the harmonic emissions from the converter at particular harmonic frequencies. These models have been applied extensively in harmonic assessment studies for large wind farms. As the models appear to provide a more accurate representation of such converters and the models are of a sufficiently simple structure to make them applicable in harmonic assessment studies, it is recommended to develop wind turbine harmonic models based on a Thévenin – or similarly Norton – approach. The authors are aware of work being done on describing these models and verification methods in other still unpublished work. Harmonic emission models need to be based on actual measurements either via directly deriving the models from measurements or by subsequent verification of the models based on measurements. Figure 5 and Figure 10 show that various aggregation techniques can affect the measurement results, and this should therefore be taken into consideration when developing or evaluating such models.

If the grid-side converter is built of multiple parallel converter units to accommodate a higher phase current rating (which is the case for most modern wind turbines equipped with full rating power converters), it is insufficient to measure the harmonic voltages and currents at a single of these units as the low level controls of such converters can cause the modulated voltages to differ between the individual units.

In model development it is important to use measurements which can describe the grid-side converter harmonic behaviour accurately. The total main reactor current and the voltage at the turbine low voltage AC terminals is the most obvious choice as these include the total behaviour of the turbine in a single three phase measurement of current and voltage at the turbine terminals which is more or less equivalent with the present descriptions in standards. Unfortunately this entails that the main reactor – and therefore its parameter uncertainties – are included in the representation of the converter (i.e. Thévenin impedance) thereby reducing the overall accuracy in the derivation of the model.

Provided the fact that most modern wind turbines equipped with full rating power converters are built of multiple parallel converter units on each phase, it is recommended to base the model development and possible verifications thereof on current measurements conducted at the grid side of the converter main reactor.

If the purpose of the measurements is to better understand the operation of the converter, additional measurements can be conducted at the terminals of one or more of the individual converter units as this would allow for the tolerance of the main reactor to be removed from the model and the emissions from such a module – disregarding the inter-module cancellation of harmonics – can be evaluated.

Based on the results presented earlier in this document, to avoid any aggregation errors during the calculation of the Thévenin equivalent harmonic voltage sources, it is recommended to apply harmonics directly from the Fourier decomposition (i.e. from the 10-cycle window). Later the obtained results (i.e. Thévenin equivalent harmonic sources) could be aggregated according to the methods recommended earlier.

The requirements for needed measurements to develop a model can be adapted from standards such as IEC 61400-21 where at least nine 10min time-series of measurements for each power bin are recommended. Based on experience, it can be said that one month of measurements should be absolutely enough.

VI. SUMMARY AND CONCLUSIONS

Harmonic analysis of wind turbines is a complex process, nevertheless important for both wind turbine manufacturers as well as wind power plant developers. Therefore, there is a strong need to put as much effort as possible to obtain the most sophisticated results.

Currently, the approach presented in applicable standards is insufficient to perform appropriate harmonic analysis of wind turbines and wind power plants including measurements, data processing, data analysis, and modelling. Thus, there is a need to continue the cooperation between the academia and wind power industry in order to improve analysis methods.

In the paper it was shown that each of harmonic analysis stages is equally important and should be carefully taken into consideration. That is why there is a need to have a comprehensive and coherent standard that will cover all the above aspects. This would promote a shared understanding of harmonic aspects for all parties (i.e. transmission system operators, universities, wind turbine manufacturers, wind power plant developers, consultants) involved in the wind power industry.

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BIOGRAPHIES

Łukasz Kocewiak was born in Grójec, Poland, in 1983. He holds BSc and MSc degrees in electrical engineering from Warsaw University of Technology as well as a PhD degree from Aalborg University. Currently, Lukasz is employed with DONG Energy Wind Power in the Grid Analysis department on the development of large offshore wind power plants.

He is a member of IEC TC88 MT21 (maintenance of IEC 61400-21) standardization group, he is actively participating in the DC grids for integration of large-scale wind Power (OffshoreDC) research project, he is an IEEE member. The main direction of his research is related to harmonics and nonlinear dynamics in power electronics and power systems especially focused on wind power generation units.

Nikolaus Goldenbaum received his Master degree in Electrical Engineering from the Technical University of Denmark in 2008. He has been with Siemens Wind Power in Denmark since he finished his Master degree. At Siemens Mr. Goldenbaum has worked with different aspects of wind turbine modelling (including harmonic emission models), development of control features related to grid connection and measurement and testing of full scale wind turbine systems.

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