The Impact of Harmonics Calculation Methods on Power Quality Assessment in Wind Farms

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Abstract—Different methods of calculating harmonics in measurements obtained from offshore wind farms are shown in this paper. Appropriate data processing methods are suggested for harmonics with different origin and nature. Enhancements of discrete Fourier transform application in order to reduce measurement data processing errors are proposed and compared with classical methods. Comparison of signal processing methods for harmonic studies is presented and application dependent on harmonics origin and nature recommended. Certain aspects related to magnitude and phase calculation in stationary measurement data are analysed and described. Qualitative indices of measurement data harmonic analysis in order to assess the calculation accuracy are suggested and used.

Index Terms—harmonic assessment, harmonic calculation, offshore wind farms, stationary signal processing.

I. INTRODUCTION

The number of wind turbines (WTs) with converters used in large offshore wind farms (OWFs) as in Figure 1 is increasing. They are mainly connected through a widespread MV subsea cable network and long HV cables to the transmission system [1]. This represents new challenges to the industry in relation to understanding the nature, propagation, effects and appropriate assessment of harmonics [2].

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.

A. Nowadays wind farms

Nowadays, variable-speed WTs are grid friendly machines in most power quality respects. The power electronic devices with advanced semiconductor technology and advanced control methods that are used in WTs for transferring power from the generator to the grid can meet the most demanding grid requirements seen today [3]. However, there are issues with regard to the power quality, voltage stability, transmission losses, and reliability that need to be addressed and improved [4], [5] in order to exploit the potential and advantages that large OWFs have as important elements in the efforts to reach renewable energy targets while maintaining a stable and robust power system [6].

B. Power quality aspects

The interest in the power quality of wind farms (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 [7].

Figure 1 Large offshore wind farm with many wind turbines equipped with power converters.

It is of major importance to assess the possible impact that WFs have on the power quality of a specific grid. The relevance of an accurate assessment resides in the expensive mitigation measures. Furthermore, from the distribution system operator (DSO) and the transmission system operator (TSO) perspective is important in order to supply adequate power quality to consumers. Therefore, WFs should fulfil power quality requirements. For the wind farm developer an optimal assessment means a cost-effective design fulfilling the requirements [8].

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II. HARMONIC ANALYSIS

A. Stationary and non-stationary signals

Measured electrical signals such as voltage and current waveforms can be classified into two cases: stationary and non-stationary signals. The signal processing methods introduced in this paper for harmonic studies are for stationary signals and performed on measurements from steady-state operation of WTs. A signal is stationary when the statistics of the signal are independent of time (or is statistical time invariant). However, strictly stationary signals as well as steady-state operation do not exist in real-life WTs and power systems. Both small and large statistical changes occur in the signal parameters. The presence of small and relatively slow statistical changes which can be neglected is addressed through so-called block-based methods. The signal is assumed to be stationary over a short duration of time (or window), a block of data; the signal features (or characteristics or attributes) are estimated over this window. Afterwards the window is shifted in analysed time-series, and the calculations are repeated for a new block of data. The resulting estimated features, such as mean value, variation, frequency, RMS value or harmonic magnitude and phase, become a function of time depending on the location of the window. This is a commonly applied technique in harmonic analysis [9].

It can be difficult in some cases to assess whether a signal is stationary or non-stationary. To mathematically prove the stationarity, the knowledge of the probability density function (PDF) of the signal is required and is therefore not a straightforward task. Stationarity or a more broad type, wide-sense stationarity (WSS), where a signal is statistically invariant to the time difference of the signal, is however a property that is implicitly assumed with all the signal-processing tools for harmonic studies discussed in this paper. Under this assumption the statistical properties of a signal are the same over any window.

Non-model-based methods (or nonparametric methods) to decompose the signal into components and transform into a different domain where the signal characteristics can be easily extracted will be considered in this paper. One of the main disadvantages of these methods is a relatively low frequency resolution, which is dependent on the length of the signal being processed which is directly related to the sampling rate. For harmonic purposes it has been assumed that signals with 51200 kS/s/ch and 10-cycle window will be used. This allows extracting high-order harmonics generated by switching power electronic equipment and decomposing signal with sufficient accuracy.

B. Origin and nature of harmonics

Wind turbine generators (WTG) with a power electronic interface significantly contribute to overall harmonic emission in nowadays large OWFs. The harmonic contribution at the point of common coupling (PCC) of a wind farm consisting of multiple WTGs results from the harmonic generation of all individual WTs [10]. Harmonics can be distinguished between characteristic harmonics and non-characteristic harmonics, where the phase angle is randomly distributed among different WTs.

If the loads and transmission and distribution systems are balanced, only characteristic harmonics exist. These are of zero sequence for orders $n = 3m$, $(m = 1,2,3 \ldots)$, of positive sequence for the $n = 3m - 2$ orders, and of negative sequence for the $n = 3m - 1$ orders. However, asymmetries always exist, causing non-characteristic harmonics in the system [11].

The harmonic emission of WTs with an integrated power electronic interface can be categorized in characteristic and non-characteristic harmonics. The characteristic harmonic emissions are determined by the converter topology and the switching pattern applied during ideal power system operation: balanced AC voltages, symmetric three phase network, and constant power system frequency [12]. For instance, a typical configuration found in nowadays WTGs is a two-level, three-phase voltage-source converter (VSC) with sinusoidal pulse-width modulation (PWM). The frequency modulation factor $m_f$ is defined as the switching frequency $f_s$ divided by the fundamental $f_1$ [13],

$$m_f = \frac{f_s}{f_1}$$

When $m_f$ is sufficiently large and properly selected (odd and multiple of 3), the characteristic sideband harmonics for this configuration will occur at orders $m_f \pm 2$, and next at orders $2m_f \pm 1, 3m_f \pm 2, 4m_f \pm 1, \text{etc.} [14],[15]$. In a wind power plant, these harmonics show a certain degree of correlation among the different WTs because are determined by a common control system.

Non-characteristic harmonics are not related to the converter topology, but are determined by the operating point of the individual converter and vary if power system conditions change as well. Therefore, these are weakly correlated or even completely uncorrelated between different WTGs [16] especially in large OWFs.

C. Measurement campaigns

Anti-aliasing is needed to prevent frequency components above the Nyquist frequency (half the sampling frequency) that might be sampled by analog-digital converters (ADCs) from showing up at low-frequency components. This is a standard part of any digital measurement device.

The first step with any harmonic measurement is to remove unwanted frequency components. When an analog signal is sampled with a sample frequency $f_s$, the highest frequency component that is present in the digital signal is equal to half the sample frequency

$$f_n = \frac{1}{2} f_s$$

If the analog signal contains frequency components higher
than the Nyquist frequency, these will appear as lower frequency components in the digital signal due to aliasing phenomena. In other words, it is the undesirable effect of the digitiser modulating out-of-band components into the Nyquist bandwidth. The greatest danger of aliasing is that it cannot be determined whether aliasing occurred by looking at the ADC output. If an input signal contains several frequency components or harmonics, some of those components might be represented correctly while others contain aliased artefacts. To prevent high-frequency components from affecting the measured spectrum, an anti-aliasing filter is used. The anti-aliasing filter is an analog low-pass filter that is placed before the analog–digital (A/D) conversion, as shown in Figure 2.

One of the results of using a high-order filter is the introduction of time delay and phase errors. A decreasing phase angle is not a problem in itself. What matters is the difference in time delay for different frequencies that plays a crucial role in a proper harmonic assessment. During measurements carried out in our WFs dynamic signal acquisition (DSA), cards with two-pole lowpass Butterworth filter are used. This solution minimises phase errors as well as delays and improves data acquisition performance. Butterworth filter has a smooth response over all frequencies and a monotonic decrease from the specified cut-off frequency [17].

Each ADC in the DSA device uses a conversion method known as delta-sigma modulation. Within sampling rate of interest which is 44100 kS/s/ch, each ADC actually samples its input signal with 128 times higher sampling rate, simultaneously improving anti-aliasing filtering. Close to maximum data acquisition (DAQ) board sampling rate 64f_s oversampling is applied, due to this fact lower sampling rate is used in order to improve data acquisition performance.

Lowpass filtering to eliminate components above, the Nyquist frequency can guarantee, either before or during the digitisation process, that digitised data set is free of aliased components. DSA devices employ both digital and analog lowpass filters to achieve this protection. The delta-sigma ADCs on DSA devices include an oversampled architecture and sharp digital filters which cut-off frequencies that track the sampling rate. Even if the digital filter eliminates almost all out-of-band frequencies, it is still susceptible to alias from certain narrow frequency bands which are related to multiplied sampling rates due to oversampling dependent on assumed sampling rate.

This can be improved by applying lowpass analog filter which removes high-frequency components in the analog signal path before they reach the ADC. This filtering addresses the possibility of high-frequency aliasing from the narrow bands that are not covered by the digital filter. Described above anti-aliasing filtering approach can be seen in Figure 2.

Some of the power quality disturbances of interest such as harmonics and transients require the measurement of significantly higher frequencies than commonly applied for measurement purposes of electrical quantities close to the grid frequency. For those frequencies the accuracy of the instrument transformers can no longer be taken for granted. For some measurements special equipment such as differential voltage sensors, Hall-effect based current sensors and Rogowski coils are being used.

D. Measurement and processing uncertainties

Precision and accuracy are terms used to describe systems and methods that estimate, measure, or predict (Figure 3). The method provides a measured value which is wanted to be as close to the true value as possible. Precision and accuracy are ways of describing the error that can exist between these two values [18], [19].

![Image](image-url)

Figure 3 Accuracy indicates proximity of measurement results to the true value, precision to the repeatability or reproducibility of the measurement.

Poor precision results from random errors while poor accuracy results from systematic errors and is usually dependent on how the measurement equipment is calibrated. While random errors occur instantaneously in the course of the measurements, the actual values of systematic errors are predetermined before the measurements get started. Therefore it is of great importance to be certain about possible systematic errors before the measurement process is started in order to compensate errors and improve accuracy. Random errors can be attributed to small fluctuations of estimated values which affect the measuring process and prove to be uncontrollable. According to experience, the random errors of stationary experimental set-ups may be considered, at least in reasonable approximation, to follow a normal probability distribution. Due to fact that it is not a straightforward task to understand these phenomena in detail, some guidance in the central limit theorem of statistics [20] can be found. According to this, loosely stated, the superposition of sufficiently many similar random perturbations tends to a normal distribution [21].

A random variable is said to be normally distributed with parameters μ and σ^2, and can be written X~N(μ, σ^2), if its probability density function is [22]

\[
f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(x-\mu)^2/2\sigma^2}, -\infty < x < \infty
\]

Precision of the measurement, and is expressed by quoting the standard deviation, the signal-to-noise ratio (SNR).

The standard deviation can be described as the root mean square (RMS) deviation of the measurements x_1, x_2, ..., x_N. It proves to be a useful way to characterise the reliability of the
measurements.

\[ \sigma_x = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2} \]

where \( \bar{x} \) is the mean value as the best estimator following expressed

\[ \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \]

Signal-to-noise ratio is defined as the power ratio between a signal and the background noise

\[ SNR = \frac{P_{signal}}{P_{noise}} \]

Before signal as meaningful information is logged, it is also recommended to measure input noise level on order to assess the measurement precision[23].

E. Harmonic analysis in standards

The IEC standard for harmonics [24] uses the following notation for the Fourier series

\[ f(t) = c_0 + \sum_{m=1}^{m \rightarrow \infty} c_m \sin \left( \frac{m}{N_p} \omega_1 t + \varphi_m \right) \]

where \( \omega_1 = 2\pi f_1 \) is the angular frequency of the fundamental, \( c_m \) is the amplitude of the component with frequency \( f_m = \frac{m}{N_p} f_1 \), \( N_p \) is the number of fundamental periods within the window width, \( c_0 \) id the DC component, \( m \) is the order of the spectral line.

According to the IEC 61000-4-7 [24] and IEC 61000-4-30 [25] standards, the Fourier series shall be obtained over a rectangular window with a length equal to 10 cycles in a 50-Hz system. The length of this basic window is about 200 ms. The window length is not exactly 200 ms as the frequency always differs somewhat from the nominal frequency. Therefore, a more correct term used in the IEC documents is 10-cycle window.

The use of a rectangular window requires that the measurement window is synchronized with the actual power system frequency, hence the use of a 10-cycle window instead of a window of exactly 200 ms. The IEC standard requires that 10 cycles correspond with an integer number of samples within 0.03%. To ensure synchronism between the measurement window and the power system frequency, most harmonic analysers use a phase-locked loop (PLL) generating a sampling frequency that is an integer multiple of the actual power system frequency. A synchronization error leads to cross-talk between the different harmonic frequencies. The 50 Hz component is by far the dominating component in most cases so that the main concern is the cross-talk from the 50 Hz component to higher order components.

The result of applying the discrete Fourier transform (DFT) to the basic window is a spectrum with 5-Hz spacing between frequency components. The spectrum thus contains both harmonics and interharmonics.

Another IEC 61400-21 standard [26] concerning measurements and power quality assessment in wind turbines predicts measurements of 10-minute harmonic current generated by a wind turbine for frequencies up to 50 times the fundamental frequency of the grid [27], [28].

III. MEASUREMENT DATA PROCESSING FOR HARMONIC STUDIES

Analysing the sampled voltage or current waveforms offers quantitative descriptions of power quality. For harmonic studies it can be the dominant harmonic components and their associated magnitudes and phases as well as qualitative indices related mainly with stationary aspects and application of appropriate transforms for harmonic studies.

If the measurement data (or block of the data) is stationary, frequency-domain decomposition of the data is often desirable. A standard and commonly preferred method is the DFT or its fast algorithm, the fast Fourier transform (FFT).

A. Resampling data

Maintaining the frequency close to its nominal value is a natural consequence of maintaining the balance between generation and consumption. Due to this fact, the variations in the frequency of the voltage are the first power quality disturbance which violate stationary assumption and has influence on characteristic harmonics behaviour and nature.

One can potentially transform a non-stationary time series into a stationary time series by removing any trend or slow variation from the time series. There could also be benefits by slicing the time series into approximate stationary sections and separately analyse each section, as recommended in previous standards.

Resampling consists an important issue, since it cannot be said that measurement data is stationary in nature. Changing the sampling rate of the signal improves accuracy as well as precision of calculated harmonics linked with the power grid frequency. This process helps minimise spectral leakage of frequencies which are an exact multiplication of an integer number and the main frequency even if it varies.

During resampling, one of the most important parts is signal single tone detection. This can be performed from the Hanning weighted spectrum. Of course, everything can be performed with stationary assumptions. This is why small blocks of data are used during signal processing. The changes of the power frequency during 10 cycles which consists the block can be neglected which is checked by applying stationarity test if a time series is mean and variance stationary with 95% of confidence interval.
Another issue is that the disturbances in their higher frequency range are typically not linked to the power system frequency but are due to active controllers that operate at a certain switching frequency which tends to produce characteristic harmonics only under ideal operation. This limits a need to resample measured signals according to the main period. Furthermore, resampling can even give wrong results and lead to misinterpretation of calculated data and as a consequence develop inappropriate models for high-frequency components in a WF.

When using a rectangular window, it is important to synchronize the measurement window accurately with the power system frequency. For example, when the power system frequency is 50.2 Hz, whereas the window size is 20 ms, the spectral lines of the DFT no longer correspond exactly to the zero crossings of the continuous frequency response for the power signal frequency component. The DFT spectrum of a single power system frequency signal becomes an interharmonic with spectral leakage as a consequence. This creates a need to resample 10-cycle data blocks and therefore the frequency variation of harmonics simultaneously strengthening stationarity assumption. As it can be seen in Figure 4, resampling high precision definitely improves signal quality. The discrepancy as a difference between two measured values in Figure 4(b) is acceptably small, and the standard deviation is $\sigma_x = 4.3548 \cdot 10^{-6}$.

### B. Stationary test

One fast method appropriate for real-time measurements is the estimation of stationarity or more broad WSS of an input univariate time series by examining the mean and variance values of the subsequences. Stationarity estimation on an univariate time series can be performed by testing the inversion number [29].

Firstly, a time series $X_t$ is divided into $l$ subsequences. The mean value of each subsequence forms a time series $\mu_1, \mu_2, \ldots, \mu_l$. The standard deviation value of each subsequence forms a time series $\sigma_1, \sigma_2, \ldots, \sigma_l$. Secondly, the sum $S_{\mu}$ ($S_{\sigma}$) of inversion number for the time series $\mu_1, \mu_2, \ldots, \mu_l$ ($\sigma_1, \sigma_2, \ldots, \sigma_l$) is calculated.

If $X_t$ is stationary, the statistical value $\varepsilon_\mu \varepsilon_\sigma$ satisfies the normal distribution with a mean value of 0 and a standard deviation value of 1.

\[
\varepsilon_\mu = \frac{S_{\mu} + 0.5 - \mu_A}{\sigma_A}
\]

and

\[
\varepsilon_\sigma = \frac{S_{\sigma} + 0.5 - \mu_A}{\sigma_A}
\]

where $\mu_A$ is a theoretical mean value of $S_\mu$ or $S_\sigma$ which equals

\[
\mu_A = \frac{l(l-1)}{4}
\]

and $\sigma_A$ is a theoretical standard deviation value of $S_\mu$ or $S_\sigma$, which equals the following equation

\[
\sigma_A = \frac{\sqrt{l(2l^2 + 3l - 5)}}{72}
\]

Based on given confidence interval $\alpha$ it can be assessed if $\varepsilon_\mu < N_{a/2}(0,1)$, the time series $X_t$ is mean stationary and if $\varepsilon_\sigma < N_{a/2}(0,1)$, the time series $X_t$ is variance stationary.

### C. Phase lock

For harmonic phase measurements and calculations phase lock becomes an important issue. It processes data in a way that an output signal has phase related to the phase of the input reference signal. In this case it is the first harmonic of the first phase voltage in a three phase system.

Applying nonparametric signal processing methods always provides an outcome but sometimes without any physical meaning. Due to this fact, there is a need to apply for all harmonic angels obtained from discrete Fourier transform in all three phases. This allows understanding the results and building appropriate harmonic models of active components in WFs such as WTWs equipped with power electronic devices.

### IV. MEASUREMENT DATA ANALYSIS

It has been decided to choose one minute of 44100 ks/s/ch sampled measurement data. The criterion of choosing was to observe significant frequency variation during one minute of measurements. As it can be seen in Figure 4, at the beginning of measurements the frequency is higher than expected and equals $f_1 = 50.0814$ Hz and afterwards goes through 50 Hz value to finally being lower than expected value with value $f_1 = 49.9372$ Hz.

Measurements are obtained using National Instruments 4472 DSA with oversampling-based anti-aliasing filtering described previously. Processed signals are resampled to 51200 ks/s that gives 1024 samples per analysed cycle. Every certain analysed block constitutes 10 cycles calculated according sampling rate.
At the beginning, the 5\textsuperscript{th} voltage harmonic has been taken into account during signal processing. In Figure 5 it is illustrated that the processing precision of resampled data is much higher. The standard deviations for measured and resampled signal are $\sigma_x = 0.0935$ and $\sigma_x = 0.0294$ respectively. Results are comparable only when measured signal main frequency component is close to the theoretical value. Otherwise, if the frequency variation increases, the precision decreases.

Current calculation also exhibits errors in harmonic assessment due to power grid frequency variation. In Figure 7 the highest errors can be seen at the beginning of the processes one-minute current waveform where the grid frequency is around $50.08 \text{ Hz}$. This is mainly due to spectral leakage available during Fourier transform.

It must be emphasized that depending on the grid codes, different frequency variation is allowable. As an example the Polish grid code entitled the Transmission Grid Traffic and Maintenance Instruction\cite{30} states that the minimum acceptable frequency is higher than $47.5 \text{ Hz}$ and maximum is $51.5 \text{ Hz}$ what indicates that frequency variation can be even higher than analysed in the paper and can produce less accurate results without resampling.

Due to this fact, characteristic harmonics generated by power electronic equipment are no any longer harmonics because the power frequency varies to balance production and loading. While frequency components are generated by internal power converters, control systems are with constant frequency in most cases not adapted to the power grid frequency. According to IEC standard\cite{24}, the harmonic frequency is an integer multiple of the power supply (fundamental) frequency

$$f_n = n f_1$$

and in this case is considered an interharmonic. There are some methods to synchronize the carrier signal frequency of pulse-width modulated (PWM) converters in power systems\cite{31}. Therefore, distinguishing high-frequency components that correspond to the carrier wave frequencies and sideband frequencies around carrier frequencies between harmonics and interharmonics does not make any sense. Note that naturally sampled PWM does not contain low-frequency components, except the desired fundamental which is synchronised with the power system frequency by PLL\cite{32}.

Another step of the analysis is to compare harmonic current calculation results. It has been observed that it is better to detect voltage frequency for both voltage and current from the same phase. This is mainly due to fact that in general voltage waveform has a smaller total harmonic distortion (THD) level than a current waveform. This can be clearly seen when certain current harmonic level changes rapidly, for instance due to changes in WT power production. During such kind of changes, frequency detection algorithm calculates less accurately which implies additional processing errors. In Figure 6 it is illustrated how current frequency detection during 5\textsuperscript{th} current harmonic level changes affects measurement data processing results.
As mentioned previously, not always in WT grid converters carrier signal frequency is adjusted according to the power system frequency variation. This shows that resampling can contribute to processing errors due to the spectral leakage which is significant for high-frequency components. It emphasizes a need to choose appropriate calculation technique dependent on frequency components’ origin in measured waveforms. Figure 8 shows significant errors if the grid frequency variation is high. It can be seen if the measured frequency goes close to the nominal, the errors can be neglected and obviously both calculation methods give comparable results.

The question is how to check if certain frequency components are actually harmonics. In order to check, it might be possible to find sufficiently long time series characterised at least by WSS and with high sampling rate. Sometimes it could be difficult to satisfy such conditions and long-term measurements are needed to observe signal tendencies and statistical properties.

If a certain frequency component is not an integer multiple of the power system frequency, shapes similar to presented using scatterplot in Figure 9 can be observed. It can be seen that some regularities are exhibited due to spectral leakage. The scatterplot, showing side band frequency of the carrier signal used in pulse-width modulated grid converters in nowadays wind turbines, consists data from more than three-day measurements. This indicates that off-line resampling or adjustment of sampling rate during measurement process can provide inappropriate results for frequencies not synchronised with the power frequency and finally can blurry harmonic assessment.

If the scatterplot shows random dependence between a harmonic and the power system frequency, it can be assumed that there was no deterministic influence in the calculation algorithm during measurement data processing. Fairly normally distributed observations in Figure 10 give an overview of the measurement and processing precision.

From DFT except magnitude information also phase information can be obtained. This can be used in order to analyse harmonic origin, nature and propagation in WFs. It also helps distinguishing between characteristic and non-characteristic harmonics as well as finding harmonic sources in the power system.

Previously observed conclusions regarding 5\textsuperscript{th} voltage harmonic magnitude calculation methods can be seen also for the harmonic phase presented in Figure 11 where the 5\textsuperscript{th} harmonic phase angle calculated form resampled data has smaller standard deviation ($\sigma_\phi = 0.6656$) then calculated directly from measured data ($\sigma_\phi = 1.9264$). The phase angles are phase locked to the first harmonic of the first-phase voltage waveform in order to find non-parametric methods.
physical meaning. To compare Figure 12 data obtained directly from DFT is presented.

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 that are not synchronised with the grid frequency which show higher variation after resampling. Normally, voltage and current waveforms comprise more integer multiple frequencies of the nominal one and resampling should improve analysed data series. Stationarity test results are compared in Table 1. It can be seen that frequency variation after resampling exists only for sideband frequencies of the carrier signal and is smaller than low-frequency content before resampling, but on a certain level. Therefore, the number of passed test is smaller for resampled data series within 99% confidence interval.

The proposed harmonic calculation method also extends already applied due to different origin and nature of existing frequency components in WF. Calculation results have also showed that a direct application of one of techniques in power quality assessment measurement devices unfortunately will produce errors in harmonic assessment. Data processing in the suggested method can be only carried out off-line and because of that used for specific applications such as harmonic models validation.

Of course described signal processing approach can be used for other purposes than only within area of harmonic analysis. Broadly, it can be used for power quality indices estimation from WF steady-state operation measurements.

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VII. BIBLIOGRAPHY


![Figure 12 Phase angle information obtained from analysis in the frequency domain.](image)
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