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# Proposal of a Desynchronized Processing Technique for Assessing High Frequency Distortion in Power Systems

# Proposal of a Desynchronized Processing Technique for Assessing High Frequency Distortion in Power Systems

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*Abstract*—Assessing high frequency (HF) distortion in power systems is a new challenge in the framework of in-situ power quality monitoring. The IEC suggests the use of a high-pass filter in the measurement chain, which can be analog (with a dedicated channel for HF assessment) or integrated in its digital form into the signal processing stage, in order to reduce the measurement uncertainty. This paper proposes a desynchronized processing technique (DPT) as an effective alternative to the other digital filtering techniques presented in literature, which also allows for a potential simplification of the measurement hardware. The DPT performance is analyzed by means of numerical experiments and laboratory measurements performed using two different test beds and both 16 and 24 bit analog to digital converters (ADCs). The test beds are used to evaluate the combined contribution of the ADC and the signal processing stage to the whole measurement chain uncertainty and identify achievable accuracy levels for different frequency ranges and magnitudes of HF distortion. The results highlight the strengths of the DPT compared to other techniques and demonstrates its potential to include HF in a comprehensive waveform distortion assessment in power systems.

*Index Terms*—Filtering, high frequency distortion, IEC standard, power quality, power systems, signal processing, spectral leakage.

## I. INTRODUCTION

IN recent years, there has been a well-documented increase in the interest of high frequency (HF) distortion within the power quality community. This is a consequence of the proliferation of electronic devices with HF switching circuits, which emit distortion above the traditional 2 kHz harmonic frequency range. Accordingly, the previous extension to the analysis range (2 to 9 kHz) has been further extended to 150 kHz, in order to cover HF distortion. Such emissions are already reported to cause certain problems in the power system, e.g. they can introduce errors in revenue meters and control systems and they can also accelerate the ageing of electronic components within household equipment, as well

as network components [1]–[3]. However, there is still much work to be done to better understand all possible consequences that HF distortion may have on the power system.

A crucial step towards this understanding is the ability to obtain accurate and reproducible results of HF distortion. This is vital for in-situ monitoring in ac power supply systems but also for laboratory immunity tests and model development. Although there are several proposals presented in literature, e.g. [4]–[7], and the informative annexes of IEC standards [8], [9], the measurement and analysis framework of HF distortion is incomplete and is an open topic within the community.

In the framework of in-situ monitoring there are currently two (informative) recommendations from the IEC for the measurement chain suitable for HF distortion analysis, which both suggest the use of a high-pass filter to remove the fundamental component and low frequency (LF) harmonics [8], [9]. This reduces the effect of spectral leakage caused by the use of a window width of exactly 200 ms, as suggested by [8], and better utilizes the analog to digital converter (ADC) range for the very small magnitudes of HF components (0.002-5 % of the fundamental [8]), in the case of analog filtering.

An analog filter is considered part of the measurement chain and, although it may reduce the signal to noise ratio, it requires the use of two dedicated recording channels to measure both LF components and HF distortion. Conversely, a digital filter is considered part of the signal processing stage and requires only one dedicated recording channel. However, a digital filter should be used in conjunction with a high resolution ADC, in order to ensure that the uncertainty introduced by the quantization stage is acceptable. The target uncertainty defined by the IEC is up to 10 % for the entire measurement chain [8]. It is expected that the transducer will be the single biggest source of error in the measurement chain so, the higher the accuracy of the acquisition and signal processing stages, the more headroom is available for the other stages of the IEC framework.

The IEC proposals are developed for the purpose of continuous assessment performed over long observation periods (an integer number of weeks). Results are presented using specified statistical representation of the measured data. The time varying behavior of the distortion is observed by introducing smoothing/averaging actions over proper time intervals (3s, 10min and 2hours), constituted by contiguous time windows of about 200 ms length each. Consequently, intra 200ms and/or intra-cycle time varying phenomena (e.g [3], [5], [6], [10]) are

observed only in terms of their averaged effects [11].

Previous research in [12] provided an intial, numerical assessment of the possibility of extending the Desynchronized Processing Technique (DPT), previously introduced by some of the authors in [13] for the analysis of LF harmonics and interharmonics (IH), to the HF distortion range where the distinction between harmonics and interharmonics is not needed [14]. The numerical experiments suggested that the DPT can be used for assessing the HF components present in waveform distortion. This paper formalizes and justifies the proposal of using the DPT to assess HF distortion in experimental conditions. The work in [12] is extended in the following ways: the development and characterisation of a test set-up to verify the previously presented numerical results is presented and implemented in two different test systems; the assessment of four HF distortion analysis techniques using 16 bit and 24 bit ADCs is discussed; a more realistic test signal for comparing signal processing techniques is introduced and analysed; and the operational limitations of HF analysis realised with 16 bit and 24 bit ADCs is proposed.

The rest of the paper is structured as follows: Section II provides a brief overview of HF waveform distortion analysis; Section III introduces the DPT; Section IV presents and characterizes the test systems; Section V presents the case studies with further discussion in Section VI; Conclusions are offered in Section VII.

## II. Assessment of High Frequency Distortion

### A. IEC standards

Informative annexes in IEC Std 61000-4-7 [8] and IEC Std 61000-4-30 [9] present HF assessment recommendations.

*1) IEC Std 61000-4-7:* In informative Annex B, this standard proposes a methodology for assessing HF distortion in the frequency range 2 to 9 kHz. For the purpose of this paper, this is extended up to 150 kHz, as also suggested in IEC Std 61000-4-30 [9]. In this methodology, a rectangular data acquisition window with a width of exactly 200 ms is used, corresponding to approximately 10 fundamental periods of 50 Hz systems. A Discrete Fourier Transform (DFT) is used to obtain the spectral components $Y_{C,f}$ with a 5 Hz resolution. For the assessment of HF distortion, the spectral components are grouped into bands of 200 Hz, beginning at the first centre band above the LF harmonic range (i.e. above 2 kHz). The centre frequency of the first group is 2.1 kHz for a 50 Hz system. The output $Y_{B,b}$ of each band is the rms value calculated according to (1).

$$Y_{B,b} = \sqrt{\sum_{f=b-95Hz}^{b+100Hz} Y_{C,f}^2} \qquad (1)$$

*2) IEC Std 61000-4-30:* In informative Annex C, this standard also presents methodologies for assessing distortion in the range from 2 to 150 kHz. One method considered is that described in the previous subsection; another is to implement the CISPR 16-1-2 method [15], although this is considered too complex and expensive for power quality monitoring. The third methodology is defined as follows.
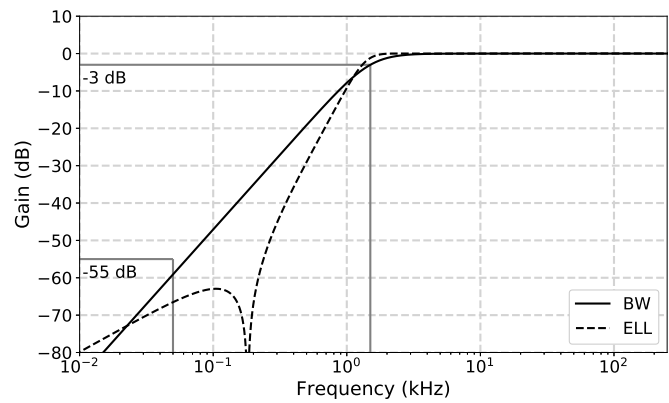


Fig. 1. Amplitude response of the Butterworth (BW) and Elliptic (ELL) filters.

A 10-cycle interval is to be analysed. Therefore, synchronization is assumed and a rectangular window is used. For every 10 cycles, 32 measurement intervals, consisting of 512 samples, are transformed using a Fast Fourier Transform (FFT) algorithm. The first four bands and the last 181 bands of the spectrum are discarded, with the remaining 71 bands starting from 8-10 kHz and finishing at 148–150 kHz. Minimum, maximum and average values are obtained from the 32 intervals and used for reporting.

*3) Comparison of IEC Stds:* The third method proposed in IEC Std 61000-4-30 covers only 8% of the signal at a bandwidth of 2 kHz. Therefore, it may not capture all power quality events, although its reduced data requirements may have benefits for in-situ measuring. In this paper, the gapless method in IEC Std 61000-4-7 is considered for its full signal coverage and also for the narrower bandwidth of 200 Hz. A detailed comparison is available in [16].

### B. Filter techniques

*1) Traditional:* In IEC Std 61000-4-7, a bandpass filter is recommended to attenuate the amplitudes of the fundamental component and components above the HF range. The attenuation of the fundamental frequency should exceed 562 times (55 dB), but no guidance is presented for higher order harmonics. In IEC Std 61000-4-30, cascaded high-pass and low-pass filters are recommended. This standard suggests that the high-pass filter could have 2 poles, with a 3 dB point at 1.5 kHz or higher, while the low-pass filter could have 4 poles, with the 3 dB point at 200 kHz.

The Butterworth filter (BW) is commonly used due to the simplicity of design and overall performance [4]. The amplitude response of the BW designed with respect to IEC Std 61000-4-30 is shown in Fig. 1, which identifies the 55 dB and 3 dB points. Although the required criteria are satisfied, the poor performance of the BW at the 2 kHz cut-off at the lower edge of the HF distortion region is observed. A third order Elliptic filter (ELL) was proposed in [4] to overcome this issue. Also shown in Fig. 1, the ELL has a steeper transition at the cut-off frequency; however, it still introduces a small error in the pass band.

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*2) Wavelet Approach:* The Discrete Wavelet Transform (DWT), used as a filter bank, has received considerable attention in the power system community, e.g. [5], [17]. The Wavelet Packet Transform has also been applied to directly calculate the IEC groups (1) in the LF harmonic range [18] and the HF range [19].

## C. Signal processing

IEC standards explicitly name the DFT and FFT but do not discount other techniques [8], [9]. A number of parametric techniques have been successfully applied to stationary and non-stationary waveforms, e.g. [5], [6]. A comprehensive review is available in [20]. These techniques offer improved accuracy, but they can result in an increase in computational time, although there has been considerable effort in reducing the computational burden, e.g. [6]. However, at the time of writing, the DFT is considered the only suitable method for in-situ measurements in the IEC framework, so parametric techniques are not considered in the comparisons presented in this paper.

## III. Desynchronized processing technique

### A. Recalls

The two-stage DPT was originally developed in [13] for LF harmonic (LFH) and IH (LFIH) analysis. In the first stage, a Hanning window of exactly 200 ms is applied to the signal. With a proper sampling frequency, the number of samples is always a power of two, allowing the use of the FFT and removing the need for a Phase Locked Loop (PLL). The LFHs are then estimated using a high accuracy frequency interpolation technique and subtracted from the original signal in the time domain to minimize the effect of spectral leakage caused by the use of a window whose width is in general desynchronised with respect to the fundamental frequency. In the second stage, the filtered signal is re-processed to obtain the LFIH components.

### B. Extension

Here, a third stage is added in the DPT proposed in which the filtered signal used in the second stage is re-processed to obtain the HF distortion components, without further distinction between harmonics and IHs [14]. As an alternative, a new filtered signal, where the assessed main IH in the second stage are also filtered, can be used. It is worth noting that the HF distortion can be assessed as part of the IEC analysis or for any other distortion evaluation study.

### C. Comparison with other techniques

An overview and comparison of the approaches discussed in the previous section and the DPT are shown in Fig. 2. The analog and digital approaches in this figure represent a simplified overview of the measurement chain required to assess HF distortion (HFD), LFH and LFIH assessment, as defined in IEC Std 61000-4-7 [8]. This assumes a signal has been obtained, e.g. by a transducer, and outlines the required high-pass (HP) and low-pass (LP) analog and digital filters (AF, DF) and the signal processing (SP) stages. The subscript *synch* denotes that some form of synchronisation technique, e.g. PLL, has been included in the measurement chain.
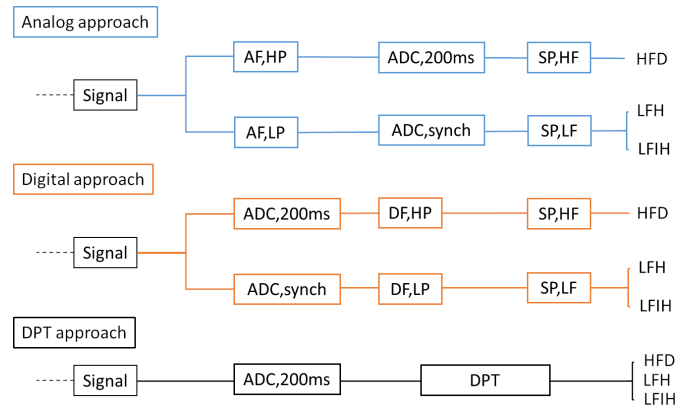


Fig. 2. Comparison of high frequency distortion analysis approaches and the proposed desynchronized processing technique.

## IV. Measurement framework

In this section, the two test beds are introduced and the test bed uncertainty characterization process is described in detail.

### A. Test bed description

As one of the aims of this paper is to evaluate the combined contribution of the ADC and the SP stage to the overall measurement chain accuracy, no external transducers were used in either test system. This allowed for a clearer assessment of the contribution of the considered factors of influence.

An overview of the developed test bed is shown in Fig. 3. In this approach an Arbitrary Waveform Generator (AWG) emulates the desired characteristics of the power system signal measured using an appropriate transducer, which can be either taken from a network or equipment under test (EUT) in a laboratory. Two systems were independently configured at different locations, with some general technical specifications included in Table I. A detailed analysis of the uncertainty of the AWG is reported in the next section.
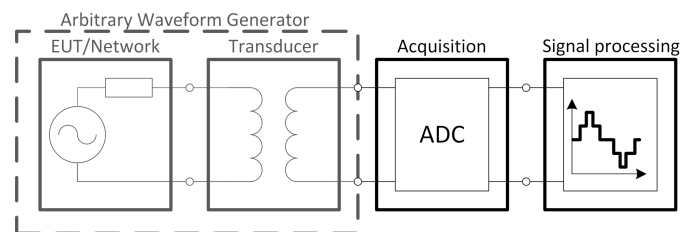


Fig. 3. Measurement system overview.

TABLE I
Test Systems

| Test System | Function | Model | fs (kHz) | Voltage range (V) | bit (N) | Ref |
|---|---|---|---|---|---|---|
| TS1 | AWG | NI PXIe-5433 | 2,000 | ± 10 | 16 | [22] |
|  | ADC | NI 9222 | 500 | ± 10 | 16 | [23] |
| TS2 | AWG | NI PXI-5422 | 2,000 | ± 10 | 16 | [24] |
|  | ADC | NI PXIe-6124 | 500 | ± 5 | 16 | [25] |
|  | ADC | NI PXI-5922 | 500 | ± 5 | 24 | [26] |
| In both test systems, NI PXI Express Chassis PXIe-1078 [21] was used. | | | | | | |

*1) Test system 1:* was implemented at the Brno University of Technology (Czech Republic). The AWG was an NI PXIe-5433 (80 MHz bandwidth, 16 bit, passband flatness $\pm 0.4$ dB@1MHz, AC amplitude accuracy $\pm 1.0\%$ $\pm 1$ mVpk-pk, total harmonic distortion (THD) $< 79$ dBc up to 1 MHz, spurious-free dynamic range (SFDR) $< 62$ dBc up to 1 MHz) while the ADC board was the NI 9222 mounted in a CompactDAQ chassis (4 AI, 16 bit, 500 kHz/ch simultaneous, gain error $\pm 0.02\%$ of reading and offset error $\pm 0.01\%$ of range, noise 0.75 least significant bit root-mean-square (LSBrms), THD -85 dB). The accuracy of the generated signals have also been checked using the ZES Zimmer LMG 500 Precision Power Analyzer [27].

*2) Test system 2:* was implemented at the SUN-EMC Laboratory of the University of Campania "Luigi Vanvitelli" (Italy). The AWG was an NI PXIe-5422 (200 MHz bandwidth, 16 bit, AC amplitude accuracy $\pm 1.0\%$ of desired amplitude $\pm 1$ mV, THD $< 85$ dBc up to 1 MHz, SFDR $< 66$ dB up to 1 MHz). Two ADC boards were used: the NI PXIe 6124 (2 MHz bandwidth, 16 bit, gain error $< \pm 0.0215\%$ of reading and $\pm 0.0040\%$ of range, offset error lower than 1.9 LSBrms, SFDR 100 dBc up to 1 MHz, THD lower than -93 dB, antialiasing filter) and the NI PXI 5922 (0.5 MHz bandwidth, 24-Bit, AC amplitude accuracy $\pm 0.06\%$ percent of reading, noise $< -117$ dBFS, THD $< -90$ dBc, SFDR $< 92$ dBc up to 1 MHz, antialiasing filter).

### B. Evaluation of the generation system uncertainty

In order to characterize the accuracy of the generation system, specific tests were designed to evaluate the measurement uncertainty for magnitude and phase of the recorded tones. Phase angle results are not shown for the sake of brevity. For characterisation purposes, a single HF tone was superimposed on the fundamental tone of 100% magnitude, zero phase angle and 50 Hz frequency under synchronized conditions:

$$s\left(t\right) = A_1 sin\left(2\pi f_1 t + \theta_1\right) + A_{HF} sin\left(2\pi f_{HF} t + \theta_{HF}\right) \quad (2)$$

where: $A_{1/HF}$, $f_{1/HF}$ and $\theta_{1/HF}$ are the magnitude, frequency and phase of the fundamental and HF tone.

The ranges of all other parameters were designed to be as representative of those encountered by ADCs utilised in practical situations as possible. A sample frequency of 500 kHz, i.e. the maximum achievable sampling frequency of the 24 bit ADC, was selected.

The following conditions have been considered (Table II):

- The fundamental tone magnitude was set to 3 different utilizations of the ADC range: 10, 50, 90 %;
- The superimposed HF tone magnitude was set to 3 different values: 0.002 % (min), 0.1 % (mid) and 5 % (max) of the fundamental, based on [8]
- The superimposed HF tone frequency covered the 2 − 150 kHz band according to the set of 10 discrete values: {2, 2.5, 5, 10, 25, 50, 75, 100, 120, 150} kHz

In total, 90 experimental test points were performed (3 range utilizations x 3 HF tone magnitudes x 10 HF tone frequencies) for each fundamental frequency value selected.

TABLE II
PARAMETERS CONSIDERED FOR HF ANALYSIS

| Parameter | Quantity | Value(s) | Unit |
|---|---|---|---|
| ADC | Utilisation | {10, 50, 90} | % |
| Signal Fundamental Tone | Magnitude | 100 | % |
| | Phase | 0 | Degree |
| | Frequency | {49.5 : 50.5 : 0.01} | Hz |
| Signal HF Tone | Magnitude | {0.002, 0.1, 5.0} | % |
| | Phase | 30 | Degree |
| | Frequency | {2, 2.5, 5, 10, 25, 50, 75, 100, 120, 150} | kHz |
| where: $\{start : step : stop\}$ is a range from $start$ to $stop$ with step size $step$ and {val1, ... , valN} is a set of N values. | | | |

To assess the uncertainty during the characterisation stage, each test point have been repeated 5 times, each time recording waveforms of 10 s length; successively, 10 portions of each waveform of 1 s length were processed by DFT. In total, for each test point, 50 results (10 portions times 5 repetitions) were obtained, allowing for analysis by statistical means.

Fig. 4 presents exemplar results, using the superposition for the HF tone with mid (0.1 %) magnitude and a utilisation of 90 % for 16 bit and 24 bit ADCs. Boxplots of the HF tone magnitude in pu of the expected value are shown versus the HF tone frequency. The boxplots show the 25$^{th}$, 50$^{th}$, 75$^{th}$ percentiles and the most extreme data points ($\pm 2.7\sigma$ coverage if the data are normally distributed) not considered outliers.

A systematic error with median values ranging from 0 to 0.003 pu (0 to 0.003 pu) for the 16 bit (24 bit) ADC is present and the largest deviation from the median (i.e. the whisker size) goes from a maximum values of less than 0.001 pu at 2.5 kHz (0.001 pu at 2 kHz) to a minimum value of 0.0005 pu at 120 kHz (0.0002 pu at 100 kHz). The similarity between the mean values of the two ADCs suggest that the systematic error is mainly related to the AWG. The mean values obtained during this process are used as reference values $A_{ref}$ to compensate for this systematic error in subsequent analysis.
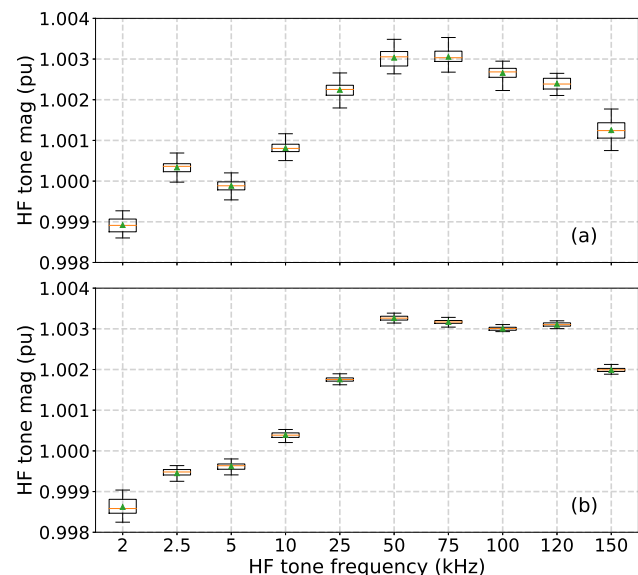


Fig. 4. Boxplots of the HF tone magnitude in pu of the mean measured value versus the HF tone frequency: (a) 16 bit ADC (b) 24 bit ADC.

The maximum value of expanded uncertainty $Uc$ (coverage factor 3) observed over the frequency range, as a percentage of the tone magnitude, of the 16 bit and 24 bit ADCs with 90% range utilization for the three HF tone magnitudes is shown in Table. III, along with the maximum theoretical quantization error $Qe$ [28] of a 16 bit and 24 bit ADC. It is possible to observe that at each tone magnitude $Uc$ values of both ADCs are very close to each other, and that, in particular, they are lower (about 5 times for min tone) than the corresponding $Qe$ in the case of 16 bit ADC, and much higher (40 times for min tone) for 24 bit ADC. This demonstrates that single measurements of very small tones with a 16 bit ADC can lead to very high inaccuracies (over the 10% threshold), while mean values obtained by repetitive measurements do not suffer the problem due to the well known $Qe$ randomness.

TABLE III
MAX EXPANDED UNCERTAINTY UC VALUE (COVERAGE FACTOR 3, 90% ADC UTILISATION) AND MAX THEORETICAL QUANTIZATION ERROR QE

| Tone | 16 bit ADC | | 24 bit ADC | |
|------|------|------|------|------|
| | Uc | Qe | Uc | Qe |
| | (% of the tone magnitude) | | | |
| min | 3.4 | 22 | 3.6 | 87E-3 |
| mid | 85E-3 | 440E-3 | 67E-3 | 1.7E-3 |
| max | 2.6E-3 | 8.8E-3 | 2.6E-3 | 0.03E-03 |

## V. EXPERIMENTAL CASE STUDIES FOR SYNCHRONIZED AND DESYNCHRONIZED CONDITIONS

This section presents experimental results assessed using the DPT presented in Section III, and compares the performance against the ELL presented in [4] (realised as a digital filter) and the DWT (used as a high-pass filter with the Discrete Meyer wavelet, as recommended in [5]). The BW was designed in previous research with respect to the requirements of IEC Std 61000-4-30 [9]. The filter characteristics are presented in Fig. 1 and filter parameters are available in [12].

### A. Single Tone

In this section, a signal $s(t)$ consisting of a fundamental plus one HF tone is considered (2).

The parameters used to characterise the test system (discussed in the previous section and outlined in Table II) are again used for this study. A sample frequency of 500 kHz, i.e. the maximum achievable sampling frequency of the 24 bit ADC, was again selected and the same sample frequency was set for the 16 bit ADC. The fundamental component was stepped from 49.5 to 50.5 Hz in 0.1 Hz steps. Also for this analysis, 450 tests were evaluated for each discrete fundamental frequency value selected (90 test points points repeated 5 times each). The performance was evaluated by the magnitude error $err_{mag}$:

$$err_{mag} = \left| \frac{A_{n,measured} - A_{n,ref}}{A_{n,ref}} \right| \quad (3)$$

where: $A_{n,measured/ref}$ are the measured and reference magnitude (obtained in Section IV) of harmonic order $n$.

A summary of the errors recorded for each individual test, performed at discrete fundamental frequency values of 49.5, 49.9 and 50 Hz, is reported in Fig. 5. These results demonstrate
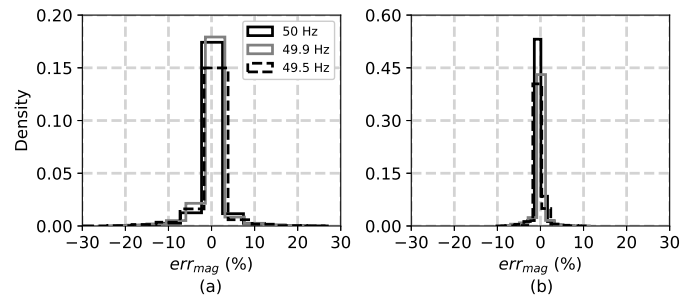


Fig. 5. Combined error statistics of all test points at three discrete fundamental supply frequency values for the DPT: (a) 16 bit ADC (b) 24 bit ADC.

that the performance of the DPT is consistent, regardless of the fundamental supply frequency. Overall, the error introduced by the 24 bit ADC system is lower than the 16 bit system. However, with both systems the likelihood of coming close to the 10 % maximum error value is extremely low.

More detailed results of the different processing techniques are shown in Fig. 6 overleaf for a fundamental frequency value of 49.9 Hz. This figure is composed of three columns and four rows, where the columns (from left to right) show results for the min, then mid then max high frequency tone magnitude and the rows (from top to bottom) show the results obtained using the DPT, the BW, the ELL and then the DWT. The presented results were obtained using the two test systems; the numerical results reported in [12] are also included. The experimental values displayed are the mean value of all three ADC utilisations for each HF tone frequency.

The following observations can be made:

- Generally, the errors in experimental results are higher than the numerical results but they follow the same trend;
- The DPT and ELL present approximately constant responses across the entire HF range;
- For min and mid magnitude tones, the 16 bit ADC constrains the results, whereas, for the 24 bit ADC, the limiting factor is the accuracy of the SP stage, i.e. it is above the theoretical maximum error of the ADC board. For example, for the BW, in the pass band region, it is evident that the signal processing is constraining; in the flat region the influence of the ADC board is observed, which is also visible in the DPT results;
- The ELL follows the 24 bit ADC, which indicates that the error of the SP stage is greater than the error introduced by the ADC board;
- The results of 16 bit ADC from test system (TS) 1 and 16 bit ADC TS2 confirm the reliability of the approach. This is important as it shows the general applicability of the proposed DPT;
- Assuming a 10% allowable uncertainty threshold of the measurement chain, as defined in [8], it is evident that utilising a 24 bit ADC allows more headroom for the other components in the measurement chain;
- With the exception of the DWT for the min magnitude tone, the magnitude error of all techniques is below the 10% threshold. However, the BW error is extremely close to this value around the 2 kHz frequency.
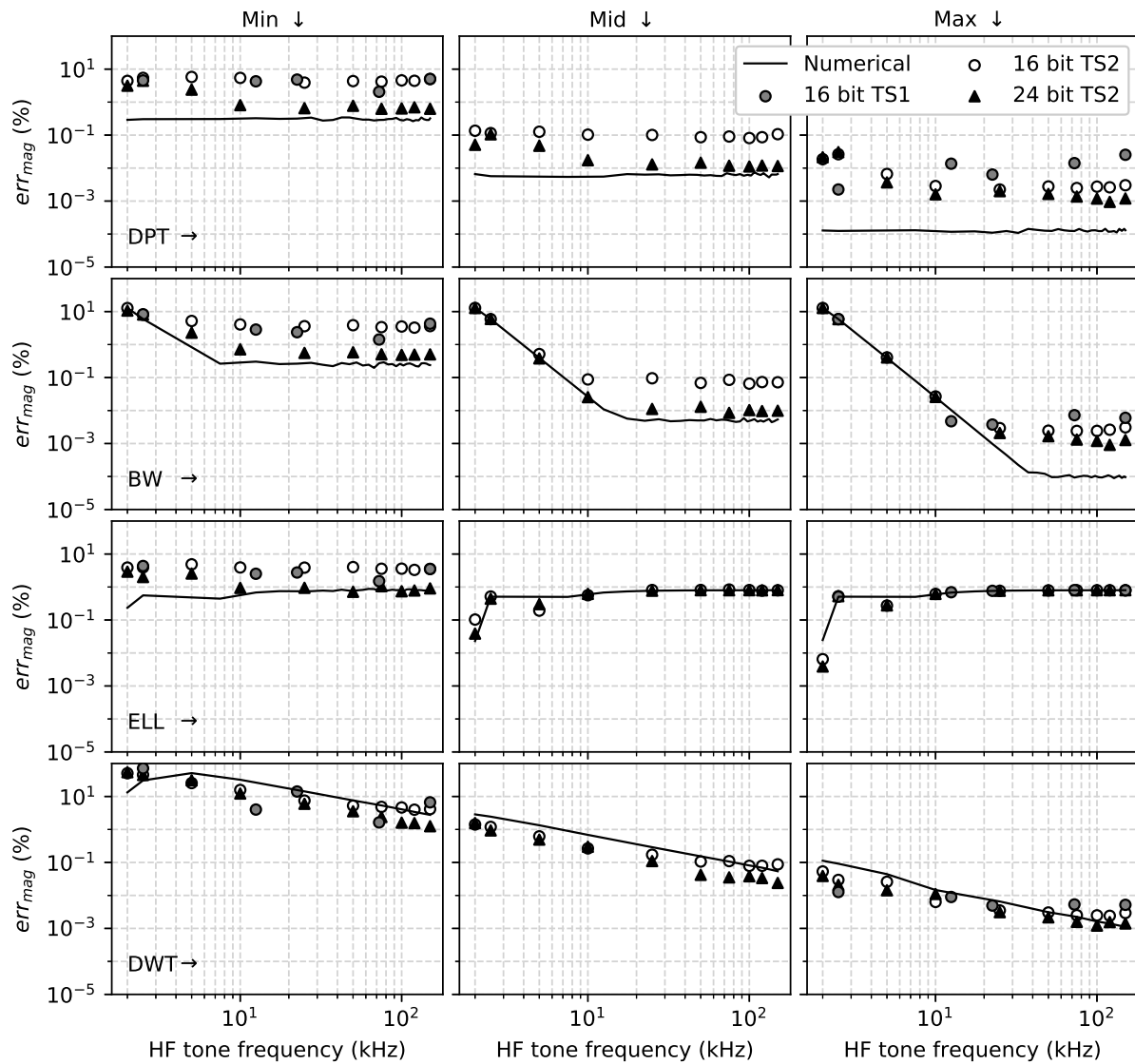
Fig. 6. Comparison of the magnitude error of the considered signal processing techniques for a single tone signal of different frequencies with fundamental of 49.9 Hz. The columns (from left to right) show results for the min, then mid then max HF tone magnitude and the rows (from top to bottom) show the results obtained using the DPT, the BW, the ELL and then the DWT. The acronym TS refers to the Test System from which the measurement was obtained.

## B. Multi-tone signal

In this section, a multi-tone signal generated using TS2 is analysed. A synthetic signal, based on a three-phase pulse width modulation (PWM) signal, was selected for this purpose, as this is a common example of a HF, multi-tone signal present in modern power systems. The PWM signal is characterised by a repeating spectrum, with energy present at the side bands around integer multiples of the switching frequency [29].

The frequency modulation index $m_f$ was selected as 200, corresponding to a switching frequency of 10 kHz in a 50 Hz system. The first three integer multiples of this value were considered. Four sets of magnitudes were considered, based on the previously defined HF tone magnitudes: i- all tone magnitudes set to the max value; ii- all tone magnitudes set to the mid value; iii- all tone magnitudes set to the min value; and iv- tone magnitude reducing with each integer multiple. The results of the most interesting case (iv) are reported due to the space limitation of the paper. The PWM spectrum utilised in the tests is presented in Fig. 7.
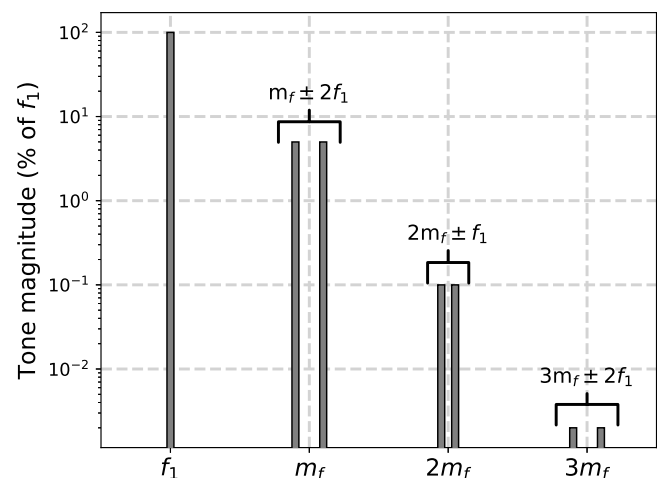


Fig. 7. Synthetic three-phase PWM harmonic spectrum.

The methodology defined in IEC Std 61000-4-7 (Section II.A.1) was applied for this analysis. To obtain reference values, the approach presented in Section IV.B was followed. The recording of the 10 s waveform was repeated 5 times; returning 50 waveforms for characterisation. The analysis was performed at 50 % ADC utilisation under synchronized $f_1$=50Hz and desynchronized $f_1$=49.9Hz conditions.
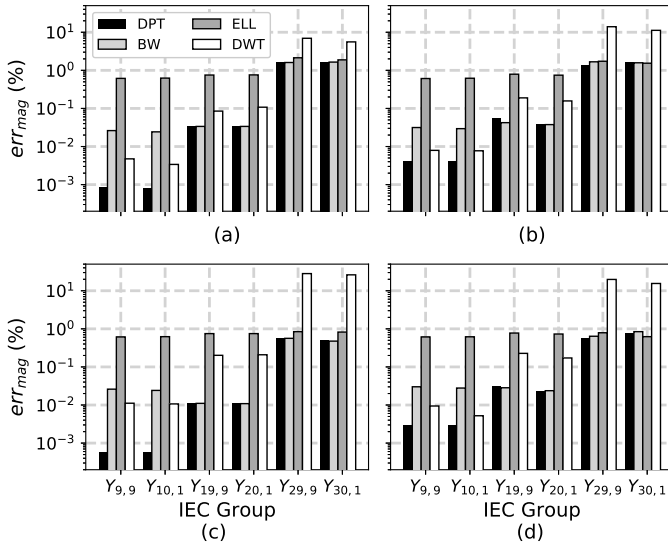


Fig. 8. Comparison of the magnitude errors of the IEC group values calculated with the four techniques: (a) 16 bit ADC, $f_1$ = 50 Hz (b) 16 bit ADC, $f_1$ = 49.9 Hz (c) 24 bit ADC, $f_1$ = 50 Hz (d) 24 bit ADC, $f_1$ = 49.9 Hz.

A comparison of the errors of the harmonic group magnitudes defined by (1) of the multi-tone signal is presented in Fig. 8. There is a slight increase in the errorsf obtained using the DPT technique under desynchronized conditions which is not present in the other techniques, as expected. However, in all cases, the performance of the DPT is better than or equal to the others. Similar errors are observed using the 16 bit and the 24 bit ADC. Comparing the errors between the single tone signal (Fig. 6) and the multi-tone signal it is evident that the order of magnitude is consistent, confirming the accuracy of the generation system and the DPT. The errors of the homogenous tone magnitude cases i, ii, iii are of the same order of magnitude as those of the single tone case.

## VI. DISCUSSION

Fig. 9 shows the comparison of the achievable accuracy for the DPT and ELL operating with 16 and 24 bit ADCs for signals with a single HF tone. Additional measurement points for the single tone signal with HF tone magnitudes of 0.004, 0.01 and 0.02%, i.e. two, five and ten times the min tone magnitude, have been included to provide a clearer representation of the performance of the system around this challenging magnitude range. The DPT and ELL techniques have been selected due to their almost constant response in the frequency range considered.

This is an important figure as it can be used to establish the maximum HF tone magnitude that can be measured for a given allowable error, providing guidance on the selection of an appropriate combination of ADC and SP technique.
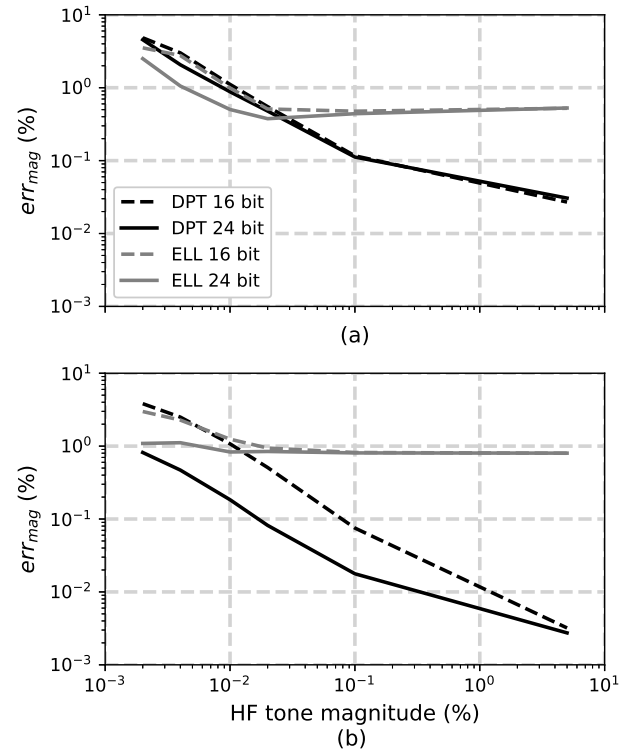


Fig. 9. Comparison of the achievable accuracy of the DPT and ELL operating with 16 and 24 bit ADCs: Frequency range (a) 2-9 kHz (b) 9-150 kHz.

In the frequency range 2-9 kHz, Fig. 9 a):
- The DPT performs better than ELL using either 16 bit or 24 bit ADC for HF tone magnitudes above 0.02 %;
- It is possible to measure HF tones of magnitudes starting from 0.002% with both ADCs and both techniques for a target allowable error of 5.0%;
- It is possible to measure HF components from 0.01% tone amplitude using 16 bit ADC and either the DPT or ELL filter with an error lower than 1.0%;
- As expected, the overall performance of the 24 bit ADC is always better than the 16 bit ADC, although the difference in this operating region is small.

In the frequency range 9-150 kHz, Fig. 9 b):
- The performance of the 24 bit ADC is always better than the 16 bit ADC, with a more pronounced difference observed in this operating region for the DPT;
- Using a 16 bit ADC, the DPT errors for HF tone magnitudes greater than 0.1% are lower than ELL, and can be measured with less than 0.1% error;
- For an allowed 1.0% error it is possible to measure HF tone magnitudes greater than 0.01% with either technique and ADC combination;
- Using a 24 bit ADC, the DPT error drops down almost linearly (in the log-log scale) with a rate of change of one decade per one decade of HF tone magnitude increase, i.e. an error of 0.2% is observed at tone magnitude 0.02% and an error of 0.02% at a tone magnitude of 0.1%;
- ELL can measure HF tones of all magnitudes with a 1% maximum error using a 24 bit ADC; using a 16 bit ADC this error is obtained for HF tone magnitudes greater than 0.02%, confirming the suitability of the ELL in [4],

## VII. CONCLUSION

Assessing high frequency (HF) distortion in power systems is a new challenge in the framework of in-situ power quality monitoring. This paper has proposed a desynchronized processing technique (DPT) as an effective tool for this purpose.

The DPT performance was assessed using numerical experiments and laboratory measurements using two different test beds and both 16 and 24 bit analog to digital converters (ADCs). By carefully evaluating the combined contribution of the ADC and the signal processing stage to the whole measurement chain uncertainty, achievable accuracy levels for different frequency ranges and magnitudes of HF distortion have been proposed.

This is an important result as it clearly defines operating thresholds for a given accuracy for different combinations of signal processing techniques and ADC technologies. The results show that the DPT, which is fully compliant with the IEC framework, performs better than or as well as other methods proposed in the literature in terms of magnitude response for the case studies shown.

This performance suggests that the DPT can be applied as a single-channel, all-purpose approach for analysing waveform distortion from 0 to 150 kHz without the need of additional signal processing steps, due to its capability of also accurately assessing low order harmonics and interharmonics.

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