

## Application aspects and measurement methods in the frequency range from 9 kHz to 150 kHz

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### ABSTRACT

The installation of emission sources in the frequency range from 9 kHz to 150 kHz in the power grid is rapidly increasing. Main drivers are decentralized power generation and demand for energy efficiency. Compatibility levels and emission limits are commonly published as quasi-peak detector values for a bandwidth (BW) of 200 Hz measured by CISPR 16 receivers. In 2015 a measurement method was published as informative Annex C of IEC 61000-4-30 Ed. 3. Comparative measurements between different standards have shown substantial deviation for some test signals. The paper will present an overview of different measurement methods and compare them regarding performance requirement for implementation in Power Quality instruments, their accuracy and compatibility with CISPR 16-1-1.

### INTRODUCTION

Emissions in the frequency range from 9 kHz to 150 kHz are source of electromagnetic interference to other electrical equipment in the power grid and therefore the need of measurement of disturbances is increasing. Recently compatibility levels have been published and the standardization work on emission limits has started. Along with the discussion on measurement methods the more general question regarding the characteristics of supraharmonic signal measurements that are required for comparability with compatibility levels and emission limits needs to be addressed. Two different approaches are used in this frequency range:

- Power quality measurement in power systems
- Electromagnetic compatibility test of equipment to determine compliance with emission limits

### EMC measurement basics

Existing EMC standards regarding compatibility levels and emissions limits refer to CISPR 16-1-1 and specify receiver settings for the measurements. CISPR 16-1-1 specifies a type of instrument rather than a method, the measurement method is mostly implied by the instrument specification. The instrument is a measurement receiver, a calibrated AM radio receiver

- with specific selectivity characteristics in the frequency domain and
- with specific impulse response characteristics in the time domain.

The combination of both frequency and time domain constraints is what makes developing a compatible method a non-trivial issue.

### Relevant measurement receiver parameters

Measurement receivers typically support multiple bands, each band using filters for a specific set of frequency selectivity and impulse response characteristics. Measurement receivers also support multiple detectors. A detector is a nonlinear filter placed into the signal path after amplitude demodulation. The detector additionally contributes to the receiver's impulse response. Detector choice influences measurements of non-steady state signals, while for purely sinusoidal signals all detector outputs are equal by definition. EMC standards that specify compatibility levels or emission limits also specify which detector to use in which CISPR band for which type of measurement. Of interest for power quality measurements is band A from 9 kHz to 150 kHz with a measurement bandwidth  $BW_{-6\text{dB}} = 200$  Hz and the Quasi-Peak, Peak and possibly RMS detectors.

### MEASUREMENT METHODS

The measurement method for voltage distortion specified in Annex C of IEC 61000-4-30 Ed. 3 [1] provides a rough assessment of the disturbances in a power system. It is a DFT based method with bins of a nominal bandwidth of 2 kHz, however it makes no effort to suppress spectral leakage from off-center frequencies. This method is not comparable with IEC 61000-2-2 AMD1+2 [2]: 2018, which refers to CISPR 16 with a -6 dB bandwidth of 200 Hz and a Quasi-peak detector. For some test signals substantial deviations on the order of 10 dB between both methods have been published. They are consistent with a theoretically predicted difference of 10 dB for wideband signals significantly exceeding 2 kHz bandwidth.

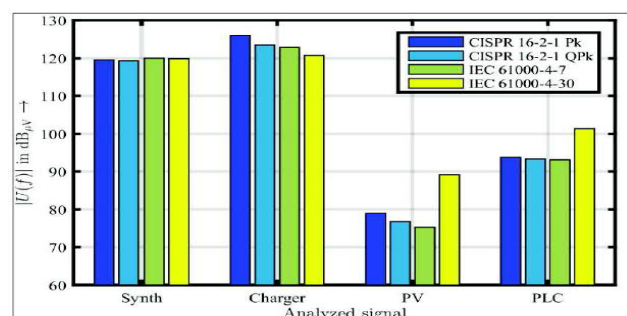


Figure 1: Comparison of measurement methods [3]

Table 1: Comparison of measurement methods

Measurement method	1	2	3	4	5	6
<b>implemented standard</b>	IEC 61000-4-30 Ed. 3 Annex C	IEC 61000-4-30 Ed. 3 Annex C modified	IEC 61000-4-30 Ed. 3 Annex C gapless	IEC 61000-4-30 Ed. 3 Annex C 200 Hz bins	IEC 61000-4-7 Ed. 2.1 [4] Annex B	FFT-based CISPR implementation (presented below)
<b>gapless</b>	<b>No</b>	<b>No</b>	Yes	Yes	Yes	Yes
<b>Sampling rate</b>	1.024 MHz	1.024 MHz	1.024 MHz	409.6 kHz	327.68 kHz (655.36 kHz)	409.6 kHz
<b>Window design</b>	rectangular	rectangular	rectangular	rectangular	rectangular	sin(x)/x with 10 ms main lobe width
<b>FFT length</b>	0.5 ms	0.5 ms	0.5 ms	5 ms	200 ms	20 ms (40 ms)
<b>FFT overlap</b>	-	-	0 %	0 %	0 %	77.5 % (88.75 %)
<b>FFT bin width</b>	2 kHz	2 kHz	2 kHz	200 Hz	5 Hz bins in 200 Hz groups	50 Hz (25 Hz), only 100 Hz multiples used
<b>FFT size</b>	512 pt.	512 pt.	512 pt.	2048 pt.	<b>64K pt. (128K pt.)</b>	8192 pt. (16384 pt.)
<b>FFT rate (per phase)</b>	32 per 200 ms	41 per 200 ms	400 per 200 ms	once per 5 ms	once per 200 ms	once per 4.5 ms
<b>Estimated performance factor</b>	1	1.28	12.5	~ 6.1	~ 7.1 (~ 15.1)	<b>FFT part: ~ 35 (FFT part: ~ 74)</b>
<b>Data amount per phase (10/12 cycles)</b>	71 per detector	71 per detector	71 per detector	710 per detector per interval	710 per detector	1420 per detector (in 100 Hz steps)
<b>Available detectors</b>	RMS, Peak	RMS, Peak	RMS, Peak	RMS, Peak	RMS, Peak	QPK, Peak, RMS
<b>Results comparable to CISPR 16</b>	<b>no</b>	<b>no</b>	<b>no</b>	<b>no</b>	<b>no</b>	yes
<b>Rating</b>	Bandwidth incompatible with CISPR 16 (required BW <sub>-6db</sub> = 200 Hz) Impulse response violates CISPR 16 requirements			Selectivity violates CISPR 16 requirements	Impulse response violates CISPR 16 requirements Extremely large FFT size	Performance requirements necessitate FPGA use (Class A only)

Modifications of the existing Annex C method such as the improvement of test coverage within each 200 ms measurement window or a gapless implementation were proposed and tested, but compatibility with CISPR 16 was found not achievable due to incompatible bandwidth in the frequency domain, incompatible impulse response in the time domain and insufficient frequency selectivity against spectral leakage.

Table 1 provides a comparison of methods and a rating regarding comparability of the respective measurements to CISPR 16 specifications.

### Data streaming and separate processing

A high-bandwidth but computationally simple instrument can acquire voltage and current measurements at a high sampling rate and perform only the minimum required preprocessing internally, streaming samples to separate processing hardware that may be located remotely.

The separation of data processing from signal acquisition and the availability of high performance processing solutions “off the shelf” allow a conservative signal processing approach that is only limited by the cost of computing. The software may even perform synchronous

amplitude demodulation for the required frequencies, implementing a down-mixing and filtering approach that closely mirrors the function of a classic superheterodyne or synchrodyne receiver.

This approach relies on a real-time capable connection with a high data throughput as well as dedicated data processing capability. Multiprocessor PC architecture can be used for scalability when using methods that permit procedure-level parallelism to a reasonably high degree. The suitability of this approach for power quality measurements in the field strongly depends on the available connectivity and the cost of computing.

### Analog band pre-selection and Sub-sampling [5]

The input signal is split into a parallel bank of analog band-pass filters, each with a bandwidth that fits into the ADC bandwidth. A filtered output signal is selected from one filter at a time and sequentially routed into a single ADC. The ADC is intentionally sub-sampling the signal and uses aliasing to down-mix the signal, forcing a wrap-around of the input band into the ADC baseband. A small size FFT (computationally highly efficient) is used to process the baseband data.

While possible in theory, a wide bank of analog filters with flat passband and high selectivity is expensive and physically large. Its temperature stability is limited by the

analog filter components, which are furthermore different for each filter in the bank, making calibration and environmental influence compensation an issue. In addition, ADCs typically used in PQ analyzers are not designed to operate in a sub-sampling mode and may lack the necessary analog bandwidth outside the baseband. All  $\Delta$ - $\Sigma$  ADCs intentionally suppress out-of-band signals, making a large class of ADCs altogether unsuitable.

This method makes a very unbalanced tradeoff between computational power and analog filter complexity, which is especially unfortunate given that the cost of computing continues to decline in accordance with Moore's law while precision analog components tend to become more expensive over time due to their boutique nature and decreasing availability of suppliers in a world that is heavily focused on digitalization.

### A NEW DIGITAL CISPR COMPATIBLE MEASUREMENT METHOD FOR POWER QUALITY INSTRUMENTS

Digital implementations of CISPR 16 receivers for EMC testing have been available from RF test equipment manufacturers such as Rohde & Schwarz for several years.

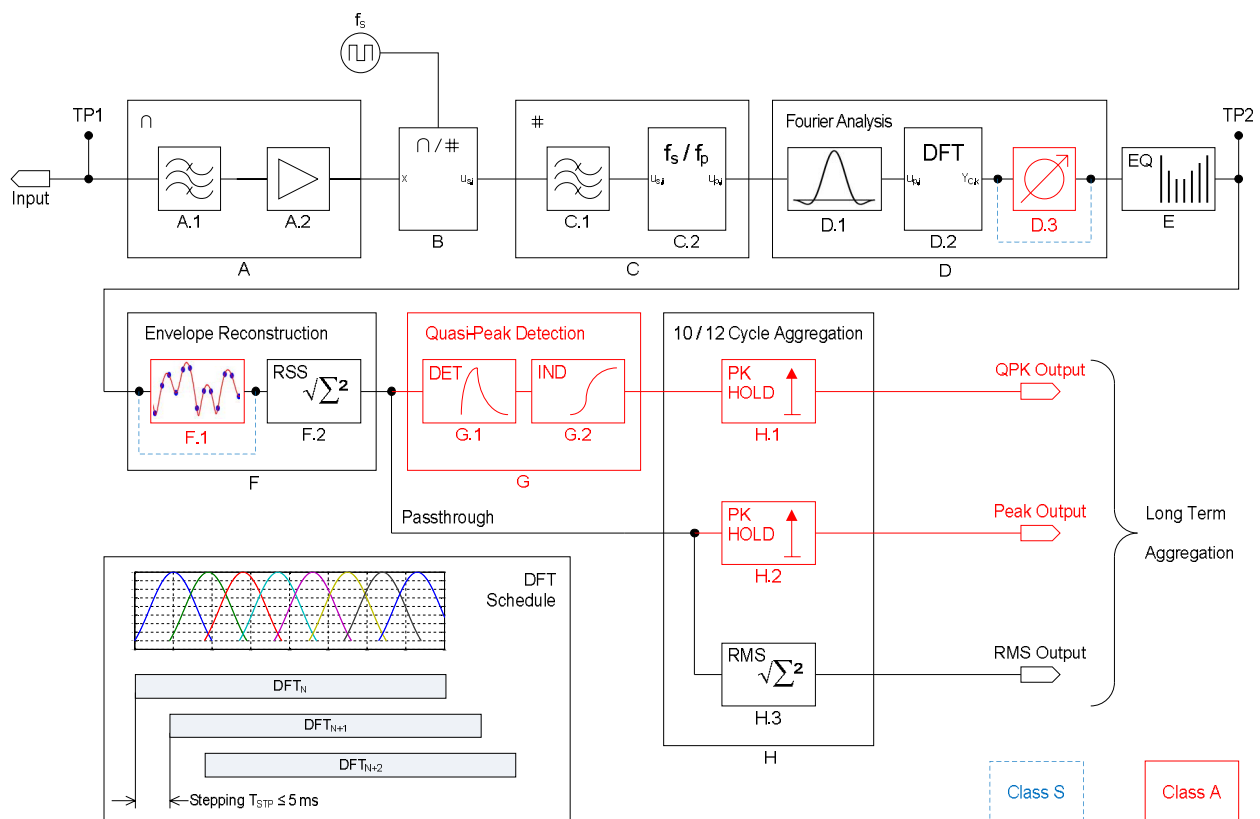


Figure 2: DFT-based instrument for measuring 9 kHz to 150 kHz disturbances in power supply networks (red: Class A only, blue: pass-through paths for Class S only)

While such instruments are now well established in their own field, they have not been designed for power quality measurements. Under laboratory conditions the emission levels are controlled and considered to be steady-state, therefore performing measurements sequentially, having historically been necessary, is still considered acceptable. An approach as in Class A of IEC 61000-4-30, where simultaneous measurements of all relevant quantities are performed at all times and a gapless temporal coverage is a basic requirement for compliance, was not considered a requirement by the EMC testing community.

In addition, laboratory test equipment is operated under controlled conditions where line transients are limited by LISNs and uncontrolled transient overvoltages on the measurement signal inputs are not normally expected. Field test equipment for power quality measurements however is subject to transient overvoltages of various origins, both switching and atmospheric, and must work in a harsh power network and industrial environment.

### Design choice rationale

It was therefore desirable for the new method to be based on established analog hardware known from Annex C of IEC 61000-4-30 Ed. 3 and to maintain the use of the DFT as the main signal processing component while extending the digital signal processing methods where necessary to achieve CISPR 16-1-1 compatibility for reasonably steady signals that can be expected in power networks.

While the performance requirements for the new method necessitate a technology change at least for Class A from a CPU or DSP only solution to a CPU-FPGA pair, this can be considered a common approach due to the already prevalent use of FPGAs in existing frequency domain measurement instruments including low-cost spectrum analyzers with measurement receiver functionality.

### Method description

An overview schema of the proposed method is presented in Figure 2.

For the purposes of this method the measurement bandwidth is the frequency range from 9 kHz to 150 kHz. It is divided into overlapping equidistant and equal-width segments where each segment position is given by its center frequency  $f_c$ . Measured values are identified by the centre frequency  $f_c$  of the segment from which they were obtained.

The samples for 9 kHz to 150 kHz measurements are acquired continuously at a minimum sample rate of 409.6 kHz at the output of the analog (A.1) and digital (C.1) preselection filters and grouped into overlapping blocks of  $T_{FFT}$  duration taken continuously at stepping time intervals  $T_{STP}$  of 4.5 ms or less (a maximum stepping of 5 ms under ideal conditions can be derived from the Nyquist sampling criterion).

To each block the Lanczos window function  $W_{Lanc}$  is applied (D.1). The block duration  $T_{FFT}$  is selected in accordance with the chosen number of side-lobe pairs  $N_{SLP}$  of the Lanczos window function, so that its main

lobe (from zero-crossing to zero-crossing) is exactly 10 ms long. The entire block  $T_{FFT}$  will then be at least 20 ms long and an integer 10 ms multiple, resulting in segments with a fixed bandwidth  $BW_{-6db} = 200$  Hz and a frequency selectivity within CISPR 16-1-1:2015 band A limits.

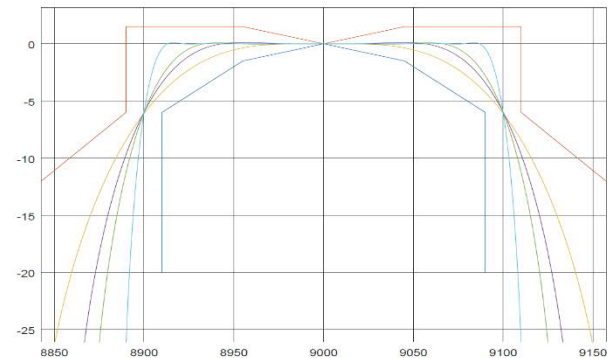


Figure 3: Zoom plots for different FFTs with Lanczos windows for a 200 Hz resolution bandwidth (Window and FFT lengths shown – yellow: 20 ms, violet: 30 ms, green: 40 ms, blue: 100 ms)

After windowing, the blocks are processed with a Discrete Fourier Transform (D.2) or equivalent having a size as required for blocks of  $T_{FFT}$  duration, yielding bins at centre frequencies  $f_c$  spaced no wider than by 100 Hz, any bins spaced closer than 50 Hz being discarded. A block duration  $T_{FFT}$  of 20 ms necessitates an 8K point DFT, with a block duration  $T_{FFT}$  of 40 ms the required DFT length is doubled to 16K points.

The DFT bins below 8 kHz and above 150 kHz can be discarded. The remaining bins contain the in-phase and quadrature values of emissions from 8 kHz to 150 kHz, spaced no further than 100 Hz and typically no closer than 50 Hz apart. These emissions are processed by an equalization algorithm (E) that embodies the inverse of the transfer function of the preselection filters (A.1, C.1), so that the overall flatness of the passband after equalization (as measured from TP1 to TP2) is  $\pm 0.2$  dB or better within the measurement bandwidth.

For each  $T_{STP}$  spaced time interval, the emissions thus obtained for each centre frequency are phase-corrected (D.3), re-establishing a coherent phase reference between frequency components calculated from time domain datasets delayed by consecutive multiples of  $T_{STP}$ .

The phase-corrected complex emissions for each centre frequency  $f_c$  thus obtained every  $T_{STP}$  are then up-sampled using a reconstruction filter (F.1) to a higher data rate given by the reconstructed stepping duration  $T_{REC} \leq 0.5$  ms, which results in a minimum re-sampling frequency of 2 kHz. For the impulse response of the reconstruction filter a Lanczos window  $W_{Lanc}$  with  $N_{SLP} = 5$  can be considered enough if the DFT stepping  $T_{STP}$  is 4.5 ms or less.

The reconstruction and up-sampling is performed on in-phase and quadrature values (the real and imaginary parts



of the DFT output) individually. The absolute magnitude values at each  $T_{REC}$  step and for each centre frequency  $f_C$  are calculated from the complex emissions after the re-sampling (F.2) and the phase information is discarded afterwards. For a Class S instrument, where peak-based detectors are not included, the up-sampling can be omitted entirely as any additional data points provided by the interpolation provide no advantage to the R.M.S. detector accuracy. In addition, the stepping time  $T_{STP}$  can then be increased to 5 ms exactly as a bandwidth reserve is not necessary when reconstruction is not performed.

The re-sampled absolute magnitudes of the emissions obtained each  $T_{REC}$  for each centre frequency  $f_C$  are processed by a digital quasi-peak detector emulation (G), a peak hold function and an R.M.S. calculation.

The R.M.S. aggregated values are calculated (H.3) from the emissions at  $T_{REC}$  intervals located within the aggregation interval of 200 ms.

The peak (H.2) and the quasi-peak (H.1) aggregation is performed by taking the maximum values of the corresponding detector outputs at  $T_{REC}$  intervals from all the measurement intervals located within the same aggregation interval.

In a Class S instrument, the maximum-value-based Peak and Quasi-Peak detectors are omitted and only the R.M.S. values are calculated.

For 9 kHz to 150 kHz, at each 200 ms interval the R.M.S. and, if applicable, the Peak and Quasi-Peak aggregated values of each of the centre frequencies  $f_C$  processed are reported.

## DATA EVALUATION

There are two different applications for measurement of emissions in the frequency range from 9 kHz to 150 kHz:

- Long term evaluation: the need from the utility community to measure voltage levels and assess compliance with compatibility levels as defined in IEC 61000-2-2.
- Troubleshooting and root cause identification: the need to assess variations of voltage levels on site in real time.

These applications require different ways to present the measurement data to the user. A user friendly and easy to assess visualization for long term records are heatmaps (Figure 4). The basic information – observation period (x), frequency (y) and measured voltage levels (z) are shown with a colour scheme which indicates significant emissions clearly, even when the amount of data is large.

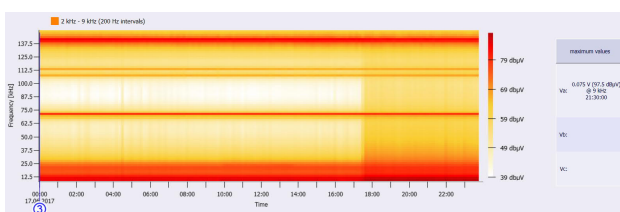


Figure 4: Heatmap visualization of long term emissions

For real-time visualization of emissions a spectrum view is more suitable, especially when combined with a waterfall display, also updated in real time.

## CONCLUSION

The paper presents the market need to develop a CISPR 16 compatible method in next edition of IEC61000-4-30 for implementation in Power Quality Instruments. Different published approaches are compared and a new DFT based CISPR 16 compatible measurement method is presented. In order to accommodate different capabilities and price points of survey and compliance measurement instruments the new method is designed to be modular. This permits the implementation of classes A and S for the different types of applications based on the same physical measurement principles while at the same time allowing a significant differentiation in the hardware performance required to implement each class.

While the presented method intends to address the compatibility with CISPR 16 frequency and time domain requirements, there are other aspects that warrant further consideration. In particular, the accurate measurement of weighted integral emissions over the entire relevant spectrum may require different measurement methods and therefore remains a topic to be addressed.

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