

Experimental study of disturbances in the frequency range between 2 and 150 kHz

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Everyday, disturbances in the frequency range 2-150 kHz become more and more important. In order to model these disturbances, many experiments have been done to observe and record results.

This work describes what is called "Measurements methods standards". Three of them are very common; the IEC 61000-4-7 and 4-30, and CISPR 16-2-1. The idea is to understand how those methods work, based on which tools, in order to implement those on platform like Matlab.

Another purpose of this work is to compare the different standards based on experimental signal. Different characteristics of those methods are analyzed in each chapter, to finish by a global comparison between each of them, based on different signals, such as CFL, Water Pump, PV,.... coming from different sources (Panda, Laborelec and our own measurements).

This work indicates that each standard provides result, to give disturbances of signals. But, the voltage and current spectrum depend on the measurement methods parameters and the type of signal analyzed, even if the same basic tools (the FFT) is used by each standard.

Window length/size	Duration of the time window used to compute the FFT
n_{fft}	Length of the DFT
EUT	Equipment under test
CFL	Compact fluorescent lamp
PANDA	equiPment hArmoNic DAtabase
PV	photovoltaic
a_n, b_n	Fourier series coefficients
CISPR	Comité international spécial des perturbations radioélectriques
IEC	International Electrotechnical Commission
PLC	Power Line Carrier
PAT	Pump-as-turbine
VSI	Voltage source inverter
IM	Induction machine
FOC	Field oriented control
$ U_{hx} , I_{hx} $	Amplitude of the harmonic voltage/current at x kHz

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The grid can be impacted by various disturbances (harmonics, voltage dips, unbalance) caused by faults and different components. These disturbances show the importance of standardization to keep the grid working correctly. This work is focused on harmonic disturbances in the frequency range between 2 and 150 kHz, which are also called *supraharmonics*. They are mainly generated by power electronics whose usage has increased significantly the last decades. Consequently, supraharmonics have increased as well.

With the time, supraharmonics have been mostly observed over local areas (within a house or between a couple of houses). Usually, this causes issues on voltage level: communication through grid (PLC), ... Those supraharmonics were observed during couple of experiments, and analysis were done to check their actual impact. A general reminder of what was already done is presented in the [chapter 1](#). There is a lack of standardization between 2 and 150 kHz; while the frequencies below 2 kHz, and above 150 kHz are standardized.

Lot of work still needs to be done about this problematic but in the present work, it has been decided to focus only on the experimental aspect. In fact, a lot of models of different equipments have already been developed in previous work. The idea is to compare the different standards and bring conclusions about their utility in this context. The different methods are implemented on MATLAB. The structure of this master thesis is as follow:

1. The [chapter 1](#) gives the context of study (emission, immunity level standards,...).
2. The main signal processing tools (DFT, STFT) used by each standards are described in [chapter 2](#).
3. The third chapter is about the measurement standards. Three are explained; the IEC 61000-4-7, the IEC 61000-4-30, and the CISPR 16-2-1 standards ([chapter 3](#)). Block schematic and explanations describe the purposes of those methods.
4. Experimental part is covered in the fourth chapter. Since different experiments and signals were studied, the comparison between the three standards is representative of the problem linked to the supraharmonics ([chapter 4](#)).

In order to understand the objective targeted by this work, this chapter presents the context. In fact, before giving this work purposes, it is important to define precisely the problematic. Firstly, elements on the grid are affected by disturbances in the frequency range from 2-150 kHz. Secondly, there is a lack of standardization in this frequency range. Both problems are linked because to fix limits, affected elements need to be known, and from which levels they are victim of those perturbations. To summarize, the problem is that the standardization, supposed to regulate the emission of the disturbances and the immunity of sensitive devices is almost inexistent in this frequency range.

Due to a lot of research done on this subject (from Swedish and German researcher, like Anders Larsson, Sarah Rönnberg, Martin Lundmark). A general overview needs to be done in order to better understand the context in which this work is done. This enables to describe what is already done concerning this topic, as well as the purpose of this work. This chapter is divided in three main categories:

- Particularity of this frequency range; it is important to know why this frequency range is targeted and its utilization;
- Present standardization situation
- Purpose of this work regarding what was already done

1.1 Utilization of the frequency range (2-150 kHz)

Below 2 kHz: the European power grid works at a frequency of 50Hz and it was previously considered that no significant harmonics were produced above the 40th order (i.e. 2 kHz). This is why main restrictions and standardization are done below this frequency.

Above 150 kHz: standards above 150 kHz were introduced to protect telecommunication services and prevent interference produced by the grid itself.

2-150 kHz: as it does not belong to any of the two previous categories, no complete limitation has been done for this frequency range yet. Standards existing currently will be described in [chapter 3](#). Components in signals (currents or voltages) with frequencies exceeding the harmonic frequency range (approximately 2 kHz) but below the upper limit of the low-frequency range (approximately 9 kHz) are due to several phenomena, for example:

- pulse-width modulated control of power supplies at the mains side connection (synchronous or asynchronous to the frequency of the mains), such as used in “power factor correcting systems”;
- emissions, such as mains signalling;
- feed-through of components from the (load side) output to the (supply side) input of power converters;
- oscillations due to commutation notches.

Utilization of the frequency range 2-150 kHz

Intentional and unintentional emissions coexist in the frequency range 2-150 kHz. Since the first one come from the PLC (Power Line Carrier), the other is due to power electronics. The utilization of the frequency range is represented on figure 1.1. The motivation for the development of appropriate standardization framework (compatibility levels, emission limits, immunity requirements and measurement methods) is justified due to the increase of the Electromagnetic interference (EMI) case at higher frequencies (up to 150 kHz). Long waves broadcasts such as flight and sea navigation are limited to the band 148.5-500 kHz.

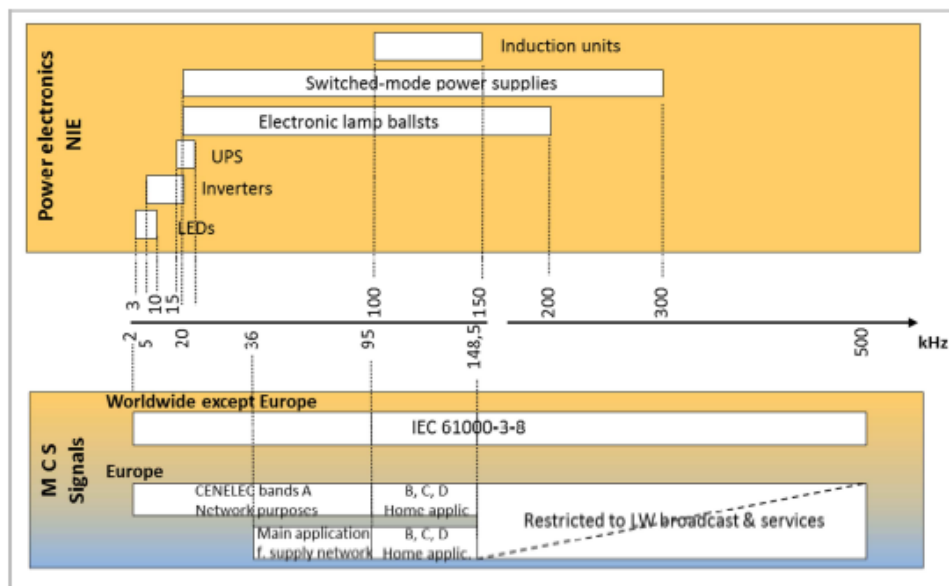


Figure 1.1: Utilization of frequencies in the range 2 - 500 kHz [6]

1.2 Present standardization situation

1.2.1 Compatibility levels

The compatibility levels can be defined as *“the specified electromagnetic disturbance level used as a reference level for co-ordination in the setting of emission and immunity limit. By convention, the compatibility level is chosen so that there is only a small probability that it will be exceeded by the actual disturbance level. However electromagnetic compatibility is achieved only if emission and immunity levels are controlled such that, at each location, the disturbance level resulting from the cumulative emissions is lower than the immunity level for each device, equipment and system situated at this same location.”*[1]

The last version of the standard IEC 61000-2-2 has been accepted by the CENELEC commission. This part of IEC 61000 is concerned with conducted electromagnetic phenomena (disturbances and signals from mains communicating systems: voltage fluctuation, flicker, voltage dips, ...) in the frequency range from 0 to 150 kHz. It gives compatibility levels for public low voltage [12]. The compatibility levels are given in table 1.1.

Frequency range [kHz]	Compatibility levels [dB μ V]
9 to 30	129.5 to 122
30 to 50	122 to 119
50 to 150	113 to 89

Table 1.1: Compatibility levels for voltage distortion in differential mode from 9 kHz to 30 kHz [12] [13]

1.2.2 Emission limits standards

Up to one year ago, emission limits were set only for

- intentional signals from mains communicating equipment (EN 50065-1)
- non-intentional emissions from mains communicating system (EN 50065-1)
- non-intentional emissions from lightning equipment (CISPR 15, EN 55015)
- non-intentional emissions from induction cooking equipment (CISPR 11, EN 55011)

Standard EN 50065-1 Electrical equipment which uses public electricity distribution network to transmit information between 3 and 148.5 kHz is applied by this standard. Its purpose is to limit interference between different equipment. Firstly, frequency band, which allocates different application are defined by this standard. Moreover, spurious emissions and intentional signals limits from equipment are fixed.

Standard EN 61000-3-8 Similar to the standard En 50065-1. But, limit levels of conducted and radiated disturbances are also given as well as measurement methods.

Measurement methods standards Important questions concerning this frequency range appear: voltage or current, with FFT or EMI-receiver / Spectrum analyser, amplitude and/or phase,... In order to solve these questions, sources and grid need to be characterized. However, measurement methods already exist, and are denoted as: IEC 61000-4-7, IEC 61000-4-30 and CISPR 16-2-1. Those are the standards covered in this work. Questions concerning the implementation, and the results given by those measurement methods are detailed in this master thesis, without forgetting comparison between them.

1.2.3 Immunity test level standards

The immunity level is first defined as *"the maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance "* [1]. Two standards are considered for immunity testing in this frequency range: IEC 61000-4-19, and IEC 61000-4-16. Test for immunity to conducted and differential mode disturbances in the frequency range 0-150 kHz are considered by the first one, since the other applies for common mode. Each standard is characterized by its own purpose:

- The IEC 61000-4-19 is used to demonstrate the immunity against differential mode¹ disturbances due to power electronics and PLC
- The IEC 61000-4-16 is used to demonstrate the immunity against common mode² disturbances coming from power line currents and return leakage currents in grounding systems

1.3 Purpose of this work regarding what was already done

Researchers have worked on this topic before me. It is interesting to come back on what they have done.

Anders Larsson Now teacher in Lulea University of Technology in Sweden, he has worked on "high-frequency distortion in Power grid due to Electronic equipment" (more details are given in his licentiate thesis [14]). Based on experimental measurement, he already has done comparison between the measurements standards. All the results were coming from spectrometer and other specific equipments, which respect the standards.

Sarah Rönnberg Now researcher in Lulea University of Technology in Sweden, she has worked on "emission and interaction from domestic installations in the low voltage electricity network" (more details are given in his doctoral thesis [19]). Based on various signals coming from PV, LED lamps,..., she has studied their influences on the grid. The supharmonic impact also PLC, by a loss of communication. Her work was focused on studying influences of harmonic on the grid.

At the end, no implementation (on MATLAB for example) of the measurement standards were developed, before what is done for this master thesis, considered as an important purpose of this work.

1.4 Conclusion

In conclusion, the standardization of the frequency range 2-150 kHz is not yet complete. Different standards already consider the PLC as a source of disturbances. However, it could be a victim, but no standard specifies that.

Concerning the measurement methods standards, the basis of this master thesis, three are considered, characterized by different implementations and parameters. It is important to know in which case each of them are useful, and overall, on what kind of signal is better suited for each method.

Emission levels are now standardized. Immunity test level standards already exist for different disturbances modes, but no immunity level are provided. The biggest problem is that, the victim of the supharmonics are almost identified, but no limit on the emission are fixed. This is a crucial point in this frequency range.

¹Voltage between any two-phase conductors or between any phase conductor and the neutral conductor [12]

²RF voltage between the artificial midpoint of a two-conductor line and reference ground, or in case of a bundle of lines, the effective RF disturbance voltage of the whole bundle (vector sum of the unsymmetrical voltages) against the reference ground measured with a clamp (current transformer) at a defined terminating impedance [22]

In this chapter, necessary theoretical knowledge used during this report are explained. The content consists of two different methods used to observe the signal frequency spectrum. Since this work is based on harmonic of voltages and currents, the essential tool to study the spectrum is the Fourier Transform. However, several methods exist. Two of them are detailed, **the Discrete Fourier Transform (DFT) and the Short Time Fourier Transform (STFT)**. What is important as well regarding this master thesis, is the differences between both methods, and their influence on the different standards which are detailed in [chapter 3](#).

2.1 Discrete-Fourier Transform (DFT)

Two fields can be distinguished: the time and frequency domain. The DFT is calculated to obtain the frequency content of signals. Two parameters are used to compute the spectrum,

- The sampling frequency (f_s) limits the maximum harmonic (between 0 and $f_s/2$), because of the Shannon-Nyquist theorem.
- The DFT time window directly specifies the frequency resolution (the space between two successive spectral lines). Following the fact that the size of the time window is bigger or smaller than the duration of the signal, leakage on the spectrum can appear.

The DFT is applied on the sequence of samples $x_n := x_0, x_1, \dots, x_{N-1}$ into complex numbers written, $X_k := X_1, X_2, \dots, X_{N-1}$, define as in [\[27\]](#).

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi kn}{N}} \quad (2.1)$$

few notes:

- N = number of time samples
- n = current sample (0 .. $N-1$)
- x_n = value of the signal at time n
- k = current frequency (0 Hertz up to $N-1$ Hertz)
- X_k = magnitude at frequency k (amplitude and phase)

When DFT is used, the Fourier series coefficients are defined. In fact, any periodic function $f(t)$ of period T can be written as

$$f(t) = a_0 + a_1 \sin(\omega t) + b_1 \cos(\omega t) + a_2 \sin(2\omega t) + b_2 \cos(2\omega t) + \dots \quad (2.2)$$

The coefficients a_n and b_n , linked to a time function $f(t)$, are computed by the following formulas

$$a_0(f) = \frac{1}{T} \int_0^T f(t) dt, \quad (2.3)$$

$$a_n(f) = \frac{2}{T} \int_0^T f(t) \sin(n\omega t) dt, n \geq 1 \quad (2.4)$$

$$b_n(f) = \frac{2}{T} \int_0^T f(t) \cos(n\omega t) dt, n \geq 1. \quad (2.5)$$

Due to the Shannon-Nyquist theorem, the spectrum is symmetric from 0 to f_s . In our case, 1 MHz/s of sampling rate should be enough (because the maximum frequency under interest is 150 kHz).

Since each standard specifies different parameters for computing the DFT, the results are different. This comes from the fact that if the time window on which the DFT is calculated does not cover an integer multiple of signals periods, the spectrum is spread on the side peaks, which gives worse result. This effect is shown on figure 2.1.

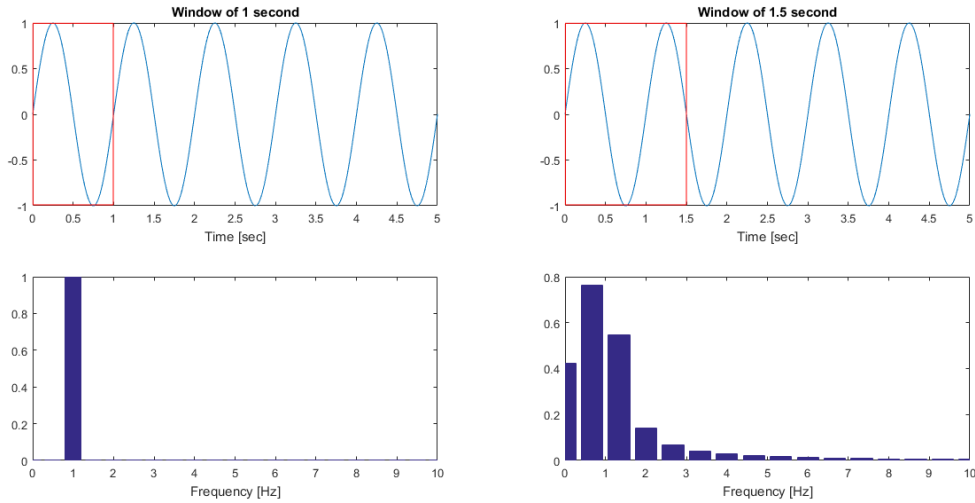


Figure 2.1: Effect of the time window; on the right/left above figures, the sine wave with time window of 1/1.5 second; on the right/left below figures, the DFT of the sine wave with a time window of 1/1.5 second

A sine wave of 1 Hz is taken over 5 seconds. Two DFTs are performed with two different time windows; one of 1 second and the other 1.5 second. Non-idealities can be clearly seen. Instead of having only one peak at 1 Hz (as on the left below figure), side peaks are also obtained (on the right below figure), which do not give the expected spectrum.

2.2 Short-time Fourier transform (STFT)

The STFT can be considered by the CISPR based standard, more particularly with peak and quasi-peak detector. This type of FFT is used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time. Most of the time, the signal is not

stationary. This method is also called a sliding DFT. The idea is to break up the signal in time domain to several signals of shorter duration, then transform each signal to frequency domain. This method enables the study of the signal at different locations, and check if other harmonics occur [5].

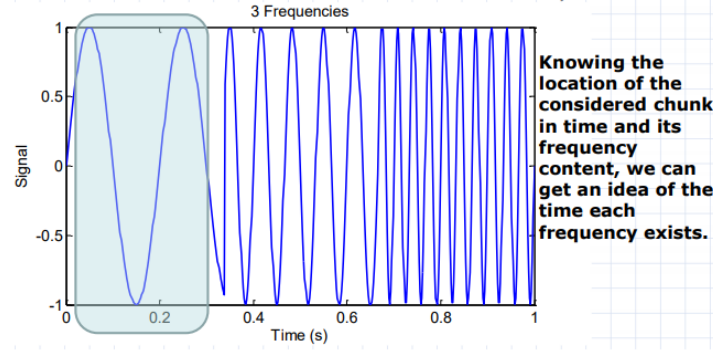


Figure 2.2: Window used for the STFT on a signal composed of 3 different frequencies [5]

When the signal is segmented into narrow time intervals (narrow enough to be considered stationary, figure 2.2), the Fourier transform of each segment is taken. A 3D plot (or spectrogram) is generally used to represent the result of the STFT (figure 2.3).

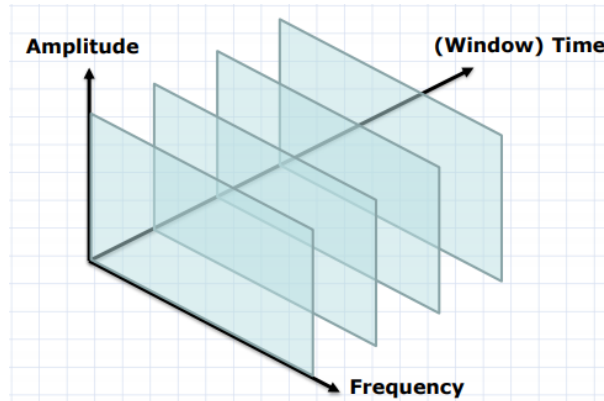


Figure 2.3: 3D representation of the spectrum [5]

The time-frequency resolution of the STFT is usually defined as the product of the time resolution and the frequency resolution. The type of window used affects the time-frequency resolution of the STFT. The Gaussian window has the optimal time-frequency resolution.

The window length also affects the time resolution and the frequency resolution of the STFT. A narrow window results in a fine time resolution but a coarse frequency resolution because narrow windows have a short time duration but a wide bandwidth. A wide window results in a fine frequency resolution but a coarse time resolution because wide windows have a long-time duration but a narrow frequency bandwidth. This phenomenon is called the window effect. You cannot obtain a fine time resolution and a fine frequency resolution simultaneously using the STFT. With a time-invariant window, the STFT has the same time resolution and frequency resolution across the entire time-frequency plane [3]. This type of FFT is used in section 3.3, which speaks about CISPR based methods.

One last thing about the STFT, a parameter is called the **overlap**¹. This factor makes the resulting spectrum slightly bigger than if there was no overlap. This effect is seen in section A.3.

¹To avoid losing data when STFT is computed, the successive window used are overlapped, to "retrieve the data". This factor is generally of 50%

2.3 Effect of the FFT

Depending on the FFT parameters, two effects can be used by the program: truncation or zero padding. More details about those two operations are given in this section.

2.3.1 Truncation

The action of truncation simply means that the signal is multiplied by a rectangular window, which gives only a precise part of the complete signal. An example is given on figure 2.4 [27].

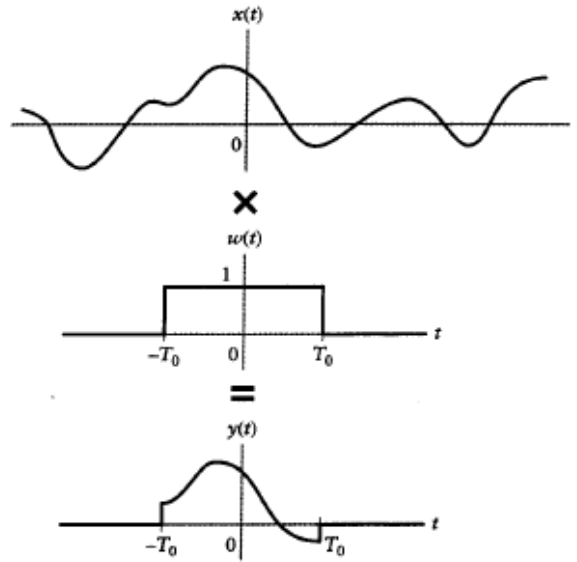


Figure 2.4: Truncation of a signal, product between a signal and the rectangular waveform [27]

2.3.2 Zero-padding

When frequency sampling is performed, sometimes, the position of the harmonic does not match with the resolution frequency (figure 2.5).

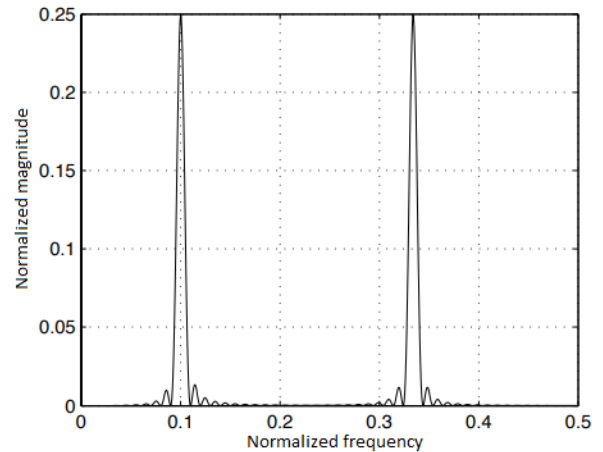
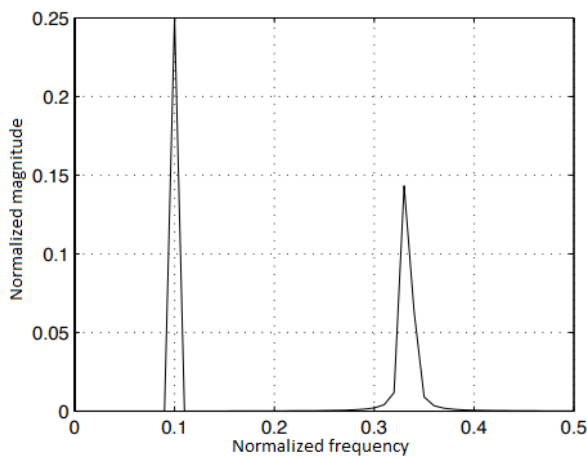


Figure 2.5: Spectrum before zero-padding [18] Figure 2.6: Spectrum after zero-padding [18]

At the end, the peaks are deformed by the frequency sampling. To overcome this default, frequency interpolation is used, by executing zero padding. The way it is performed, is by adding

zeros at the end of the signal in the time domain, which implies a smaller resolution frequency, and so, better harmonic peaks. The result after zero-padding is shown on figure [2.6](#).

However, two things can be underlined about this methods

- Firstly, the central lobes look more precise.
- Secondly, the apparition of side lobes which "disperse the energy", and that can be a major issue in case of too big difference between the DFT window and the signal duration.

In conclusion, the different signal processing tools such as DFT and STFT were described in this chapter. These notions are used in the [chapter 3](#) as said before, without forgetting the influence of the different parameters defined.

This chapter describes the different measurement standards considered in this work. It is divided in three major sections; the IEC 61000-4-7 and IEC 61000-4-30 in [section 3.1](#) and [section 3.2](#), where implementations and important elements are presented. The third part ([section 3.3](#)) of this chapter concerns the STFT (see [section 2.2](#)) based methods, that can be used by different detectors (peak and quasi-peak). The implementations are described, as well as the behavior of the different analog implementations of those methods. The last section (see [section 3.4](#)) speaks about the theoretical comparison of the standards, based on different criteria.

3.1 IEC 61000-4-7

The aim of this section is to detail the standard IEC 61000-4-7. A brief description of the subject is done, followed by the way the method was implemented. Validation tests were made on the code to check if it is correct, with regards to the standard. The results and the different explanations are given in the appendix [A](#).

3.1.1 Description

The complete name of this standard is "*Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*".

This part of IEC 61000 is applicable to instrumentation intended for measuring spectral components in the frequency range up to 9 kHz which are superimposed on the fundamental of the power supply systems at 50 Hz and 60 Hz. For practical considerations, this standard distinguishes between harmonics, interharmonics and other components above the harmonic frequency range, up to 9 kHz.

The part of the standard concerning the frequency range from 2 kHz to 9 kHz is given by the Appendix B (of [\[7\]](#)), which is informative. One goal of this master thesis is to show that this standard can be **extended up to 150 kHz**.

3.1.2 Working principle below 2 kHz

The general structure of the measuring instrument is given on figure [3.1](#).

The different blocks can be explained as follows

1. The first block regroups **the main instrument part**. This block was not implemented in this work, since it is simply data acquisition. Only the sampled data coming from block 1 are analyzed.

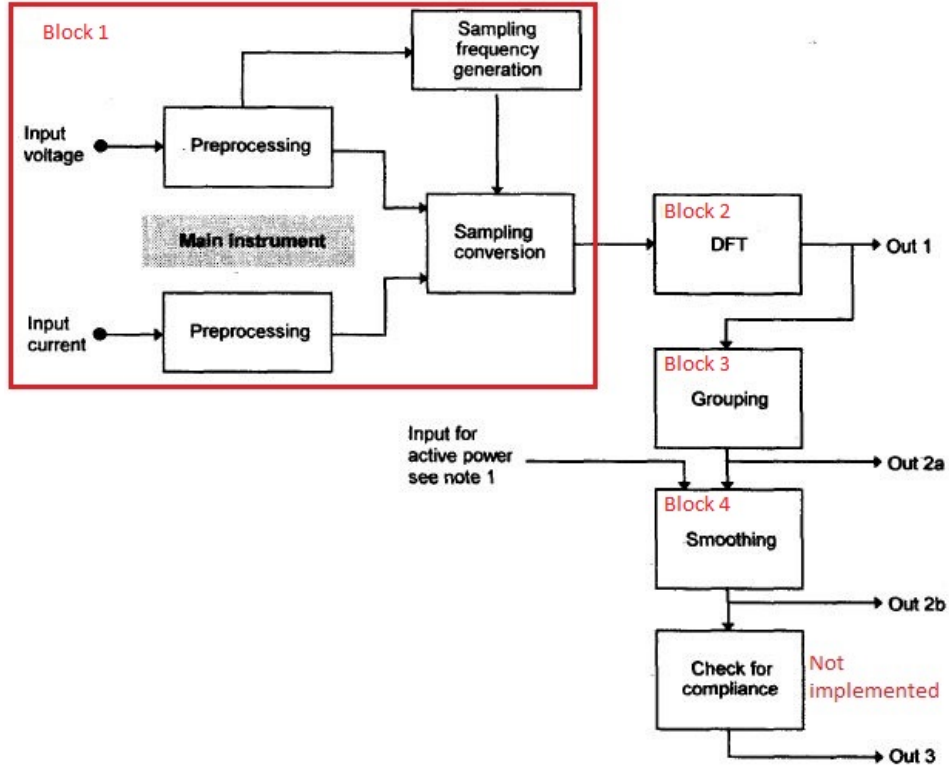


Figure 3.1: General structure of the measuring instrument [7]; with the block 1 representing the data acquisition, block 2 making the DFT, block 3 performing grouping, and the last 2 blocks to smooth the final spectrum

2. The second block is the so-called **DFT**. The signal is assumed stationary on the 200 ms intervals. The first output called 'Out1' gives the individual coefficients a_n and b_n of the DFT (see chapter 2 for more details) for the current and the voltage.
3. The third block represents the **grouping**. (Inter-)harmonics are grouped following different rules. Those rules impose the resolution frequency at 5 Hz, and the harmonics must be grouped by group of 50 Hz. An illustration of that procedure is shown on figure 3.2. To assess harmonics, the output 'Out1' on figure 3.1 of the DFT is first grouped to be the sum of squared intermediate lines between two adjacent harmonics according to equation 3.1, visualized on figure 3.2. The resulting harmonic group of order n (corresponded to the centre line in the hatched area) has the magnitude $G_{g,n}$

$$G_{g,n}^2 = \frac{C_{k-5}^2}{2} + \sum_{i=-4}^4 C_{k+i}^2 + \frac{C_{k+5}^2}{2} \quad (3.1)$$

In the equation 3.1, C_{k+i} is the rms value of the spectral component corresponding to a spectral line of the DFT, and $G_{g,n}$ is the resulting rms value of the harmonic group.

4. The fourth block is for the **smoothing**. The standard recommends performing this filtering over the rms value of the grouped harmonics, using a digital equivalent of a first-order low-pass filter with a time constant of 1.5 seconds, as shown on figure 3.3.

$$H(z) = \frac{z}{\alpha - \beta z} \quad (3.2)$$

Concerning figure 3.3, z^{-1} designates a time window delay; α and β are the filter coefficients,

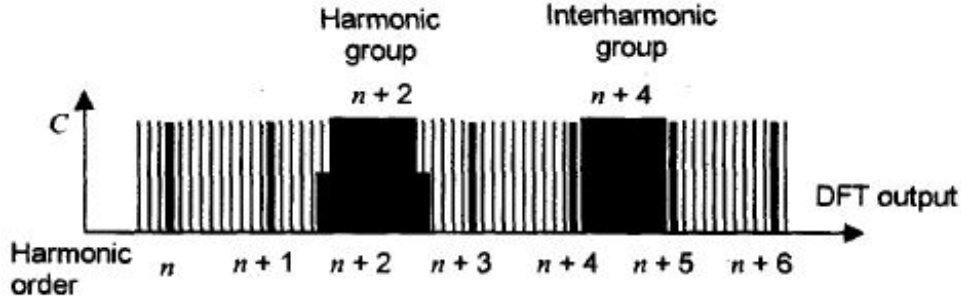


Figure 3.2: Illustration of harmonic and interharmonic grouping [7], below 2 kHz

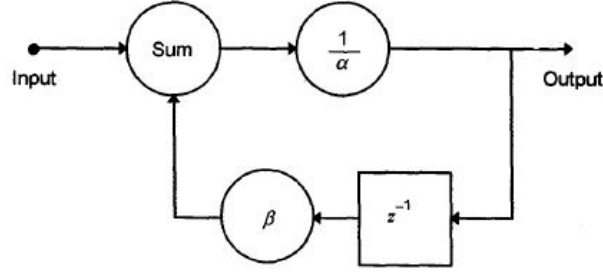


Figure 3.3: Block diagram of the smoothing [7]

which in this case, are 8.012 and 7.012 respectively ¹.

3.1.3 Extension up to 9 kHz

The way the measurement is done below and above 2 kHz, is the same. However, the grouping method is not the same. In fact, the harmonic grouping is done on 200 Hz of bandwidth, and the result is centered on a specific frequency. More details on the grouping are given below for the (inter-) harmonic grouping.

Harmonic grouping

The figure 3.4 illustrates the grouping above 2 kHz. The output of the raw DFT (Out 1 on figure 3.1) is grouped in bands of 200 Hz (see figure 3.4), beginning at the first center band above the harmonic range, for example 2100 Hz. The value of the variable called G_b of each band is the

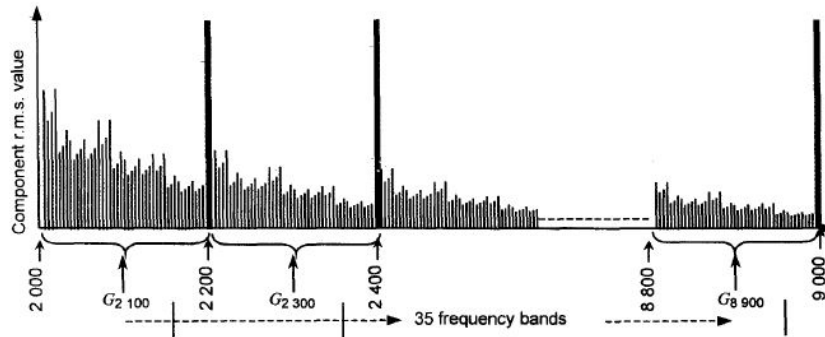


Figure 3.4: Illustration of frequency bands for measurement, in the range 2 kHz to 9 kHz [7]

¹table 2, p16 of [7]

r.m.s value according to

$$G_b = \sqrt{\sum_{f=b-95}^{b+100} C_f^2} \quad (3.3)$$

For signals longer than 200 ms, **an aggregation** is done on the different intervals (10 periods of fundamental). The DFT is computed on each 200 ms intervals, and then, the **quadratic mean** ([17]) of each value, on each interval, for each harmonic is taken. Measurement on longer signal are more interesting, to study the variation of the harmonic content with the time.

Concerning the validation of this method, all the results of the different tests are presented in Appendix A.

3.1.4 Conclusion

In conclusion, the IEC 61000-4-7 determines the harmonic emissions produced by equipment on the grid (those notions about emissions are developed in more details in [section 4.1](#)). Thanks to its resolution frequency, it enables the user to obtain precise spectrum, when signal measured on the grid are studied in repeatable tests.

3.2 IEC 61000-4-30

This section presents the second standard studied in this work, the IEC 61000-4-30. Brief description of this measurement method is given. One of the principle characteristic of this standard is that it does not cover the entire signal. It computes the DFT on several intervals. Furthermore, results depend on the number and on the duration of the intervals. Those parameters are analyzed to point out their influences on the spectrum.

3.2.1 Description

The official title of this standard is *"Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods"* [4]. This part of IEC 61000-4 defines the methods for measurement and interpretation of results for power quality parameters in a.c. power supply systems with a declared fundamental frequency of 50 Hz or 60 Hz. Emissions in the frequency range 2-150 kHz are considered in annex C which is informative [4]. The standard IEC 61000-4-30 proposes method to study the harmonic content of a measured signal, between 2 kHz and 150 kHz. The important specifications (proposed) are given below.

- Signal on 10 periods (50 Hz system) are considered (12 in 60 Hz system).
- **32 intervals of 0.5 ms** (frequency resolution of 2kHz) (represent a **signal coverage of 8%**) are used, but the implemented program enables the user to tune the parameters (by setting the number and duration of the intervals). An example illustrating the coverage is shown on figure 3.5.
- The spectrum is calculated on each intervals, and the minimum, maximum or RMS values at each frequencies are taken.
- In case of longer signal, an aggregation is performed on each 200 ms interval. Minimum, maximum, and average values could be considered during each aggregation interval. The average r.m.s. value could be used, for example, to determine typical emissions. The maximum and r.m.s. value could be used, for example, to determine worst-case emissions. The difference between the minimum and maximum values could be used, for example, to detect the presence of amplitude modulation. The single maximum r.m.s. value could be used, for example, to set worst-case 95 % limits [4].

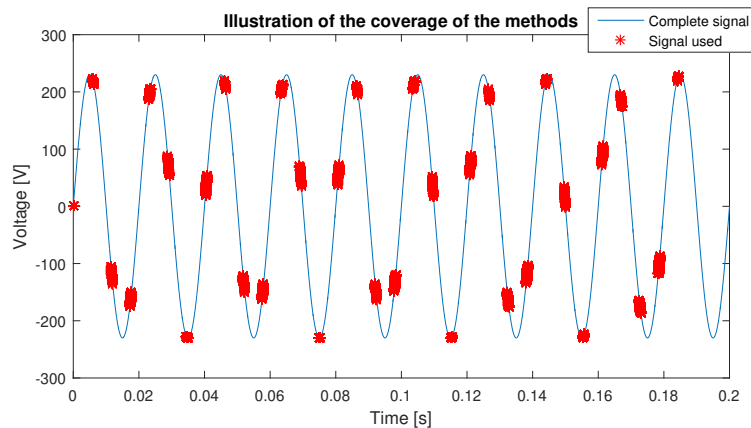


Figure 3.5: Illustration of the method; the 32 intervals are chosen equally spaced, of 0.5 ms, for the IEC 61000-4-30

Depending on the point of view (data processing, reliability of the result), the conclusion about this standard are not the same.

- Based on the signal processing point of view, having a signal coverage of 8 % (and so loss of information due to 92% of the signal not covered) is a major issue. In fact, since the length of the time intervals considered here (0.5 ms), limit the choice of the window to compute the DFT (need to be of the same size, to avoid leakage on the spectra), the obtained resolution frequency in this case is 2 kHz.
- Concerning the reliability of the information, since the resolution frequency is not accurate enough, the obtained spectra only gives a rough idea of the harmonic content. And regarding what was said in section 3.1, there is a trade-off between the resolution frequency and the effectiveness of the computation.

3.2.2 Study of parameter influence (on synthesized signal)

Since, this standard is based on the number and duration of the intervals, and on the frequency resolution, the impact of those parameters is studied on synthesized signal. The same analysis is done on experimental signal, in subsection 4.2.5. A signal of 200 ms was generated, with fundamental (50 Hz), and an harmonic at 40.5 kHz with an amplitude of 0.065 (normalized with respect to the fundamental amplitude).

Influence of the duration/number of intervals

The first two parameters were considered, and the idea was to modify one parameter, while the other is fixed. This is why, two graphs are present on figure 3.6. The first one was obtained by modifying the interval duration, with 32 intervals. The second one was obtained by modifying the number of interval with an unchanged duration (0.5 ms).

The magnitude and position of the harmonic are the most interesting values. However, since the frequency resolution remains unchanged (2 kHz), the position of the peaks in the spectrum stays at 40 kHz. Concerning the magnitude of the harmonic, it can be seen almost constant with the signal coverage. This result is normal, due to the stationarity of the signal.

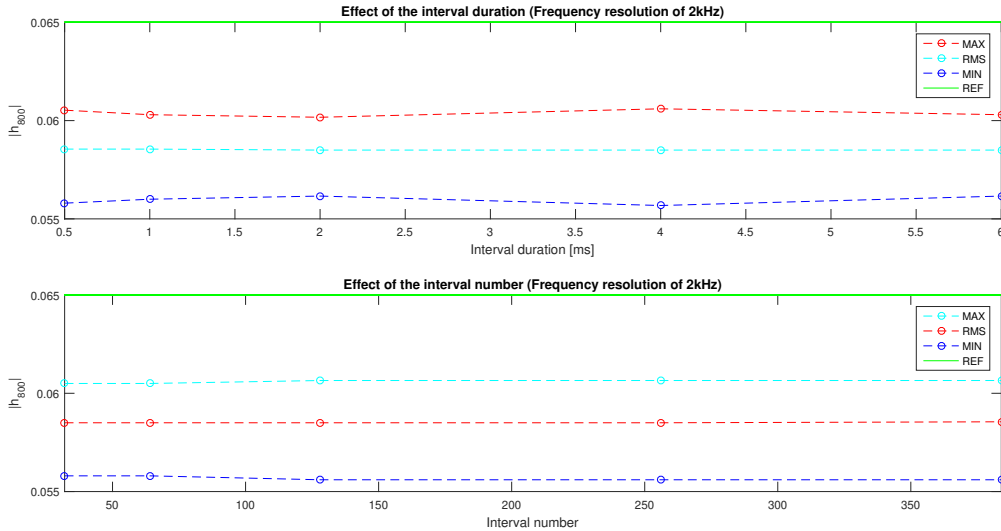


Figure 3.6: Influence of the duration and number of intervals; the magnitude of the harmonic is represented, based on different interval duration and on interval number on the above graph

In conclusion, the precision of the result depends only on the frequency resolution (for stationary signal). However, there is an error between the result and the reference value of 7% for the maximum value, 10% for the RMS value and 14% for the minimum value. These errors

can be explained by the fact that since the targeted harmonic is not a multiple of the frequency resolution, there is a spread of spectrum power on the nearest harmonic from the one we are interested in. An example with an harmonic multiple of 2 kHz is given in [section A.2](#), and the errors are lower.

Influence of the frequency resolution

Secondly, concerning the frequency resolution, it is linked to the size of the time window used in the computation of the DFT. The idea is the same as the previous section. The computation was made on 32 intervals, but the duration of intervals varies. The window length is the same as the intervals duration because

- If the window length is smaller than the interval duration, the signal is truncated.
- If the window length is bigger than the interval duration, zero-padding is performed.

The effect of the window length is shown on figure 3.7, where for different values, the result shows an interesting behavior.

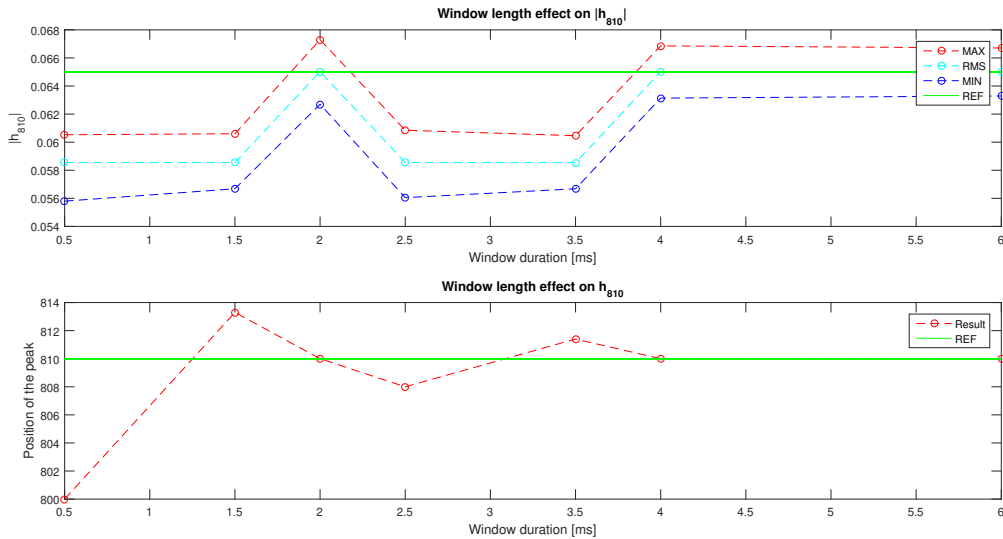


Figure 3.7: Influence of the frequency resolution

On the figure 3.7, the first graph represents the magnitude of the obtained harmonic depending on the window length, and the second gives the position of the maximum peak in function of the window duration.

- Concerning the magnitude, the difference between the maximum, minimum and RMS values remains almost constant. But, the effect that was expected is shown. When the bigger window is used, smaller the frequency resolution becomes, since those 2 quantities are inversely proportional. This tendency gives more precise value, since the targeted harmonic becomes a multiple of the frequency resolution. On the graph, when the window duration is about 2 ms, 4 ms, 6 ms, the correct magnitude is obtained.
- The same explanation can be done concerning the precision of the harmonic position. When the window duration is about 2 ms, 4 ms, 6 ms, the harmonic is at correct frequency position.

3.2.3 Conclusion

In conclusion, based on what was said before, the IEC 61000-4-30 is a solution to obtain rapidly a rough estimation of the signal spectrum. However, the obtained spectrum greatly depends on the position of the intervals, but also on the type of measured signal. If the signal is modulated, like presented in [section 4.3](#), where the signal has always the same shape, or on CFL signal, like in [section 4.2](#), where the signal is not the same all the time, the obtained spectra is not of the same "quality"².

At the end, the purpose of the 4-30 is to give disturbances levels on the grid, in contrary to the 4-7, which only measures disturbances produced by equipments on the grid.

²the word quality denotes the precision of the harmonic (magnitude and position) present in the resulting spectrum

3.3 CISPR 16-2-1

As said at the beginning of this chapter, this last section speaks about STFT based methods, denoted by CISPR. The title of this standard is "*Specification for radio disturbance and immunity measuring apparatus and methods – Part 2-1: Methods of measurement of disturbances and immunity – Conducted disturbance measurements*" [22].

This standard is based on spectrum analyzer composed of filters and detectors. Three different are used: the peak, quasi-peak and average detector. The CISPR standard specifies three bands of frequency. The band A, from 9 kHz to 150 kHz is considered for this work. Depending on the types of disturbance, measurements may be carried out using a measuring receiver with [22]:

1. A quasi-peak detector provided for the weighted measurement of broadband disturbance for the assessment of audio annoyance to a radio listener, but also usable for narrowband disturbance;
2. A peak detector which may be used for either broadband or narrowband disturbance measurement.

3.3.1 Peak detector

The model and the response of the peak detector is given on figures 3.8 and 3.9. To understand how this detector works, its behavior is analyzed based on simulation done with LTSpice.

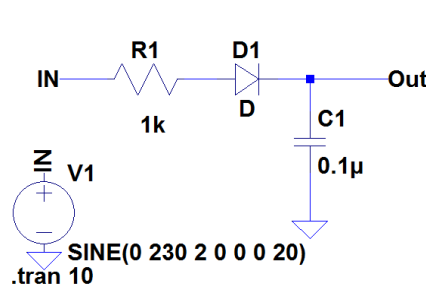


Figure 3.8: Analog circuit of the peak detector, composed of resistor, diode and capacitor

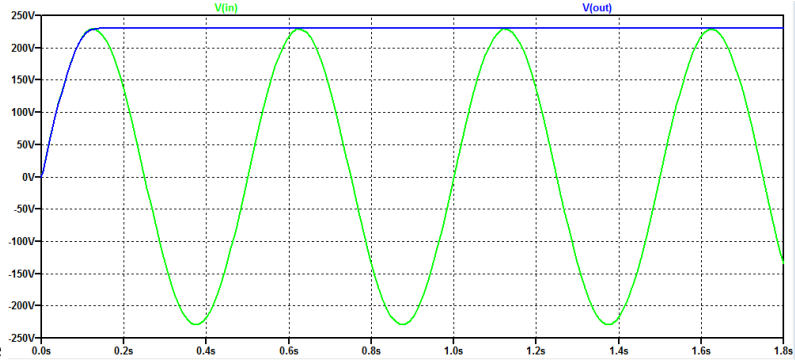


Figure 3.9: Time response of analog circuit; voltage [V], in function of the time [s]

The circuit is composed of an RC and diode. In this case, a circuit without any non-idealities is considered. This LTSpice implementation was done, only to give a practical view of the peak detector. However, this last is not the final implementation chosen. In fact, the analog implementation could have been done on Simulink, but due to its low computational efficiency, the measurement standard was implemented in MATLAB code, in another way.

The idea is to use signal, which lasts T seconds to provide the time evolution of the signal spectrum. This is why, the STFT is used. The resolution frequency chosen in the code is 40 ms³. In fact, if the STFT is too much precise, the program never stops (due to the limit of available memory for the result computation). So, the parameter of STFT computation need to be wisely chosen. The validation of this method is given in appendix section A.3.

³The reason why this value was chosen is based on the technical possibilities of the computer. The standard normally specifies 0.5 ms. But, since the peak detector implementation used in this work, is different from the one given by the standard, a choice in the parameters values had to be done, to be able to obtain results.

3.3.2 Quasi-peak detector

A first implementation of the quasi-peak detector is possible, based on different articles ([26], [11], [10]), but the approach is too complicated. This is why, it was decided to use the quasi-peak detector analog circuit. The schematic is shown on figure 3.10. It was implemented using Simulink, to study the time dependence of the signal frequency content.

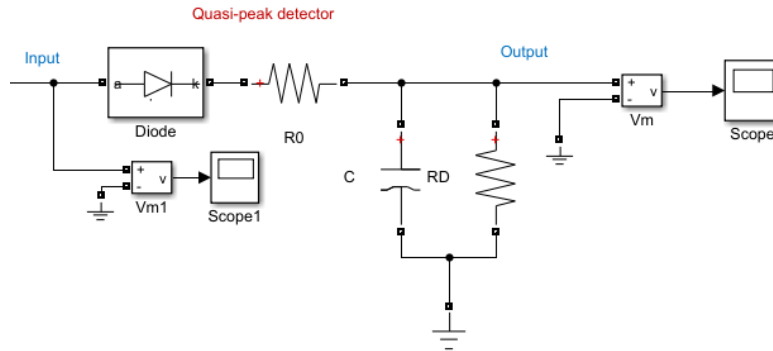


Figure 3.10: Quasi-peak detector model; composed of resistors, capacitor and diode

The model is composed of one capacitor and two resistors (for the charge and discharge). CISPR standard specifies, for the band A, τ_c (charging time) and τ_d (discharging time) of 45 ms and 500 ms respectively.

The values are respectively of $25 \mu F$ for the capacitance, with $1 k\Omega$ for R_0 , and $20 k\Omega$ for the R_D (on the model). An example was done on LTSpice, to see if the sizing is correct, and the time response on a small frequency signal. This sizing of component comes from [25], page 45.

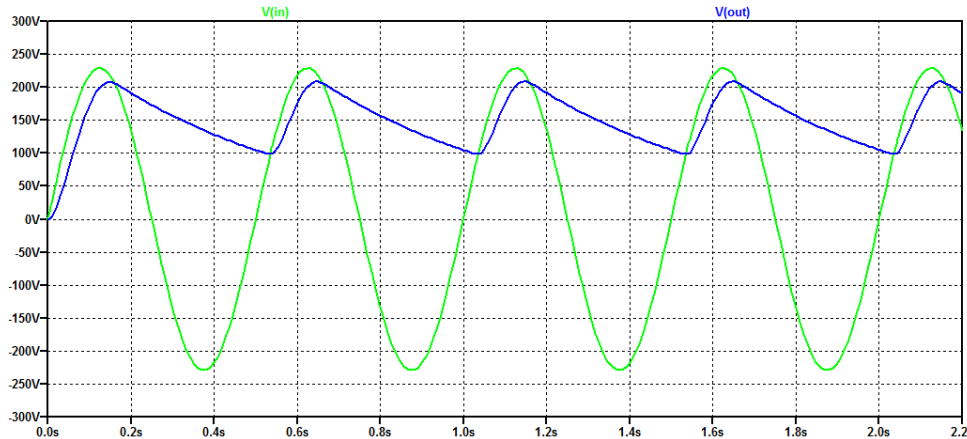


Figure 3.11: Result with sine wave of 2 Hz as input, the voltage [V] in function of the time [s]

One difference between both detectors (peak and quasi-peak) is that weights are applied on the signal by the quasi-peak [26]. Those weights depend on the repetition rate/frequency of the spectral component making up the signal. When peak and quasi peak detector response are compared on figure 3.9 and 3.11, both output signals are different, due to the weighting performed by the second detector.

3.4 Comparison of the standards (based on parameters, synthesized signal and amount of computation)

This section presents a first comparison between the standards. Firstly, based on synthetic signal used in [Appendix A](#), the four different standards are compared. Secondly, the question about the differences between DFT-STFT based methods is detailed, as well as the differences between the IEC 61000-4-7 and IEC 61000-4-30.

3.4.1 Comparison between standards based on parameters and synthesized signal

It can be useful to remind the general parameters description of the different standards (see [table 3.1](#)).

Standard	IEC 61000-4-7	IEC 61000-4-30	CISPR 16-2-1
Purpose	Emissions levels from equipment, in the grid	Levels in grid	Levels in grid and emission from equipment
Method	Discrete Fourier transform (DFT). 200-ms-interval aggregation into 200-Hz bands per 200 ms	DFT, 0.5-ms-intervals, aggregation into avg and max spectra per 10/12 cycles	Spectrum analyzer with tunable filter and detector(peak and quasi peak)
Frequency range in kHz	2-9	9-150	9-30000
Application	Emission levels in the grid, emission levels of equipment	Emission levels in the grid	
Bandwidth	200 Hz	2 kHz	200 Hz $\pm$ 100 Hz
Status	Informative annex	Informative annex	Normative

Table 3.1: Comparison of standards; IEC 61000-4-7 (Annex B), IEC 61000-4-30 (Annex C) and CISPR 16-2-1; regarding the frequency range from 2 kHz to 150 kHz [\[6\]](#)

Parametrical comparison of the standards can be done, based on [table 3.1](#).

- Each standards fill different purposes and applications.
- The frequency range is not the same for each of them. the CISPR is the one with the wider range, because it is considered for EMI emissions at high-frequency.
- As described in the different sections of this chapter, each one is implemented in different way.

What can be interesting now is to compare the different result, given by each standard, used on the same synthesized signal, written below:

$$v(t) = 0.65 * \sin(2\pi 50e3t) \quad (3.4)$$

The idea is to take each harmonic given by each standard, and put them together on a graph, to check if differences appear. Normally, all the values should be close (normally equal) from each other. The bar plot is shown on [figure 3.12](#). Some observations can be done on the results.

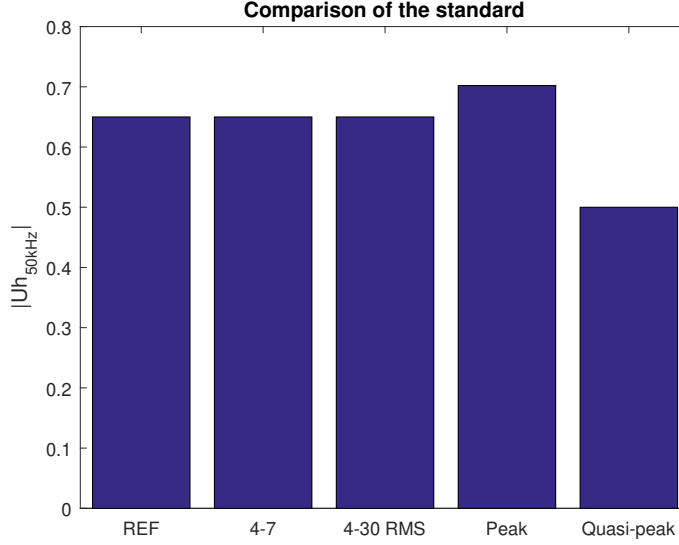


Figure 3.12: Theoretical comparison between the four standards, based on a signal at 50 kHz, with 0.65 of amplitude; the different bars correspond to the reference (0.65), the IEC 61000-4-7 (extended up to 50 kHz), the IEC 61000-4-30, peak and quasi-peak detector values

- First, the IEC 61000-4-7 and IEC 61000-4-30 give the same result, which is totally logical. In fact, the signal is constant, with no distortion, and the resolution frequency is sufficiently low.
- Second, the peak detector gives a bigger value. In fact, as said at the end of [section 2.2](#), one parameter used in the STFT is the overlap factor. This last induces slight differences in the values given by the peak detector.
- Third, the quasi-peak detector gives smaller value than other methods. This is due to its time response (weighting effect), as shown on figure [3.11](#).

3.4.2 Comparison FFT-STFT based methods

As said previously, notable differences exist between the two main ways of measuring. According to IEC 61000-4-7 (2002), measurements in the range up to 9 kHz means taking a snapshot of the current or the voltage waveform and apply mathematical tools to obtain the spectrum. Each spectral component is then merged in specified frequency band (grouping). Besides, according to CISPR 16, measurements above 9 kHz, use a frequency domain approach in which a receiver sweeps through the whole frequency range, taking one band at a time [\[14\]](#). Both methods are referred to here as “IEC method” and “CISPR method”.[\[14\]](#)

The difference between the two methods is shown schematically on figure [3.13](#). A time window of the waveform is used by the IEC method for each frequency band over this window. Only one band at a time is taken by the CISPR method. The same result is achieved if the signal is stationary (i.e., its properties does not change with time)[\[14\]](#). However, that type of signal is rare. Most of the time, signals are either discontinuous or modulated in some way, and this leads to different results for both methods. In defence of the CISPR method it should be mentioned that this method was developed for measuring the emission of equipment. When the equipment is in fixed operational state, the emission can be expected to be stationary, although this is not guaranteed [\[14\]](#).

The CISPR method can cover a very wide bandwidth and has a large dynamic range. It uses basically the same technology as radio receivers, which has been well developed and been

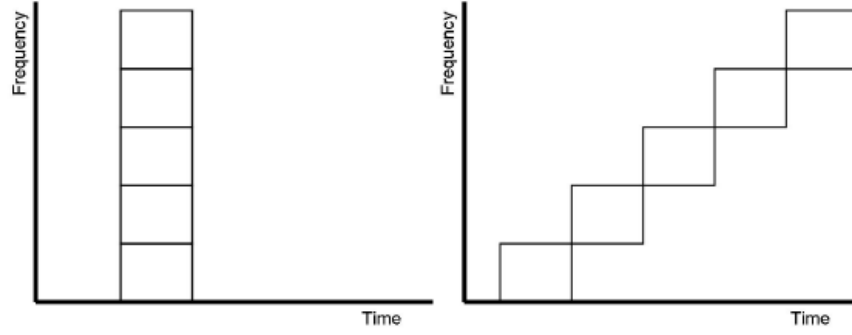


Figure 3.13: Coverage of time and frequency domain for IEC method (left) and CISPR method (right)[14].

widely available for many years. Fast sampling technology and high computing power have only recently become widely available. Actually, digital technology has become so much cheaper that the IEC method may by now be easier and cheaper than the CISPR method up to frequencies well beyond 9 kHz [14].

3.4.3 Comparison between the IEC 61000-4-7 and the IEC 61000-4-30

The parameters used in IEC 61000-4-7 and IEC 61000-4-30 are different. A summary of those is given in table 3.2.

	IEC 61000-4-7	IEC 61000-4-30
Frequency range	2 kHz - 9 kHz	9 kHz - 150 kHz
Frequency resolution	200 Hz	2 kHz
Measurement interval	200 ms	32x0.5 ms in 10/12 cycles
Signal coverage	100%	8%

Table 3.2: Summary of the parameters for the IEC methods

Amount of computation

The number of operations impact the computation speed of the DFT. This is why, a comparison of the amount of computation is done, to check if the IEC 61000-4-30 is really faster than the IEC 61000-4-7. The reasoning is proposed in table 3.3. According to [23], the DFT requires $2N^2$ of multiplication and addition, which gives a complexity in $O(N \log_2(N))$. For this comparison, the sampling frequency chosen is the same for both standards, as well as the duration of the signal. Concerning the IEC 61000-4-30, the signal coverage must be taken into account, in order to obtain the total samples per interval.

	IEC 61000-4-7	IEC 61000-4-30
Sampling frequency [MSample/s]	1	1
Signal duration [ms]	200	200
Total of samples	200.000	16000
Total of samples/interval	200.000	500
Number of operations	8e10	5e5

Table 3.3: Comparison of the number of operations between the IEC 61000-4-7 and IEC 61000-4-30

The total number of operations, given in table 3.3, implies that the IEC 61000-4-30 is faster than the IEC 61000-4-7 based on the spectrum computation point of view.

3.5 Conclusion about measurement standards

Concerning the FFT based methods (IEC 61000-4-7 and IEC 61000-4-30), one is used to determine the harmonic emissions produced by equipments on the grid. While, the other gives disturbances level of equipments on the grid. Moreover, regarding the way both methods are implemented, the utilization case of those methods is also important. In fact, the type of signal measured (from CFL, water pump,...) influences the resulting spectrum. Mostly in the IEC 61000-4-30, the result can be different depending on the place the intervals are taken. However, the non-stationarity of signal can be studied on spectrogram given by CISPR methods, thanks to the STFT. At the end, all depend on the context the measurement standards are used.

This chapter deals with the second major part of this master thesis, the experimental chapter. The purpose is to make comparison between the different standards, presented in [chapter 3](#), based on different type of signals. Before beginning the main part, a small reminder on the different kinds of disturbances ([section 4.1](#)) is done, since those notions are used in further section. Then, the signals (voltage and current) coming from CFLs ([section 4.2](#)), of different power are studied. This equipment was used because it is commonly found on the grid and is easy to measure. Secondly, in the context of the SmartWater project, water pump signals ([section 4.3](#)) were obtained, to analyze signals coming from inverter, which have interesting shapes. One section is dedicated to signals coming from an online platform called PANDA ([section 4.4](#)), to analyze other types of signals, coming from equipments such as camera charger, or PV. The last part gives a general conclusion about this chapter.

4.1 Primary and secondary emissions

When the level of disturbance is measured at the output of one device, you have to distinguish the primary and the secondary emission. The measured level of disturbance is the sum of both terms as illustrated in [figure 4.1](#). The difference between primary and secondary emissions is explained hereafter.

4.1.1 Primary emissions

This first is defined as the emission originating from the equipment under test (EUT). The level of primary emission in the field is mainly affected by [\[20\]](#)

- the topology of the EUT
- the impedance at the connection point and
- the resonances

4.1.2 Secondary emissions

This is defined as the emissions that is generated elsewhere and propagates to the equipment due to the low impedance level at the terminal of the component. For equipment connected to the low voltage network, like it is in our case, the secondary emission is affected by [\[20\]](#)

- the emission from neighbour equipment

- the impedance at the terminal of the EUT in relation to impedance of the grid and of the installations

An illustration of those concepts is given on figure 4.1. Each equipment is modelled by its Norton equivalent (the grid is considered as a simple resistance, and only the capacitor of the filter is considered). The current flowing between the device 1 (on the left) and the grid is composed of two components:

- The primary emission, the current driven by the internal emission of the device itself [21].
- The secondary emission, the current driven by the internal emission from the other device [21].

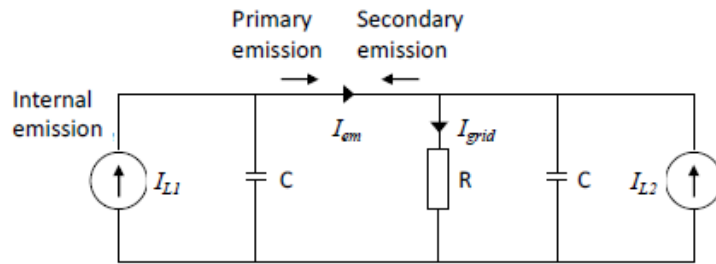


Figure 4.1: Simplified model for two devices connected to the grid [21], which gives an illustration of primary/secondary emission; the grid is represented by a simple resistance, and all the element are modelled by their Norton equivalent

The kind of emissions are important for the rest of the work. In fact, in section 4.2, it is a question of experimental measures done on the grid. This is why, it is crucial to distinguish the grid harmonics, from the one belonging to the CFL.

4.2 Measurement results on compact fluorescent lamps (CFL)

As said in the introduction of this chapter, this section speaks about one of the most common component on the grid, the **CFL**. In order to understand its behavior, a theoretical description of its working principle is done. After that, frequency treatment of the different signals measured is presented, as well as the comparison between the spectra given by each measurement standard.

4.2.1 Theoretical aspect

The first studied component is CFL. This lamp was used because it is commonly found on the grid, and its emission are very interesting to analyze. But, a first theoretical review is done

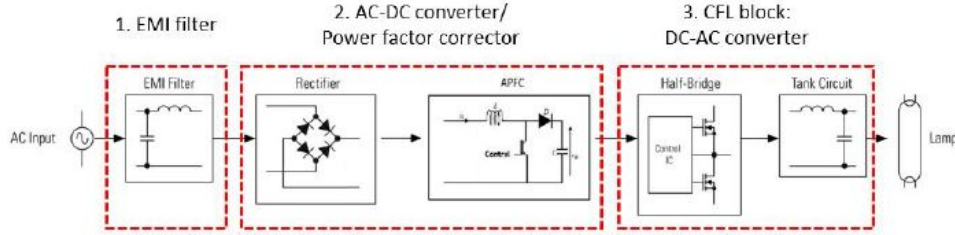


Figure 4.2: Block schematic of CFL [16]; (1) EMI filter, (2) AC-DC converter, (3) CFL block: DC-AC converter

EMI filter Passive filter used in order to reduce harmonics higher than 150 kHz. Standards exist to specify the necessary attenuation for these harmonics to guarantee the proper working of telecommunications services [16].

AC-DC converter/APFC Since the CFL needs to be fed by high-frequency signal, it is better to convert first the signal coming from the grid into a DC voltage, and then reconvert it into a high-frequency signal. The AC-DC converter is composed of 4 diodes, followed by a boost converter. This last is also there to get a power factor as close as possible to unity, leading to a reduction of the low-frequency harmonics [16]. This part of the model certainly produces high-frequency components in the signal.

CFL block (DC-AC converter) Based on the signal coming from the boost, it converts it into high-frequency sinusoidal voltage to feed the lamp represented by a resistive load [16].

4.2.2 Experimental set-up

Since the measures were done by myself, it is important to present the measurement set-up used to acquire the signals, as well as the experimental conditions.

Materials

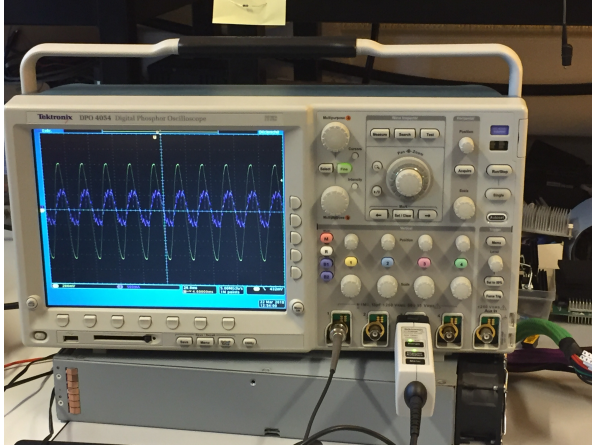


Figure 4.3: Tektronix DPO 4054

Oscilloscope The first major instrument used is the oscilloscope shown on figure 4.3. It was used to capture the voltage and current data measured by the probe. Here are its specifications

- Bandwidth: 500 Mhz
- Resolution: 11 bits
- Sampling frequency: 5 MSample/sec

Since we want to study harmonic up to 150 kHz, the bandwidth and sampling frequency were very important.



Figure 4.4: Tektronix TCP0030

Current probe The specific probe used to measure the current is shown on figure 4.4. Since the level of current is very weak (0.5 A), we needed a very precise probe. Here is its specification

- Bandwidth: 120 Mhz
- Accuracy: 1.5%



Figure 4.5: Tektronix P5200

Voltage probe The last important element used was the voltage probe. It is represented on figure 4.5. This is a differential probe, used to measure high-voltage. Here is its specification.

- Bandwidth: 25 Mhz
- Accuracy: 3%

Characterization of the source (the grid)

Since all the measurements present in this section are done on the grid, a first try was done on an incandescent lamp ¹, in order to know its frequency response. Moreover, it is a practical example about secondary emissions define in [section 4.1](#). In fact, the impedance of the grid at those frequencies is sufficient to measure harmonics. And based on the definitions given in [section 4.1](#), the four zones present on both current and voltage can be called secondary emissions (coming from the grid itself). This explanation is used in [subsection 4.2.4](#).

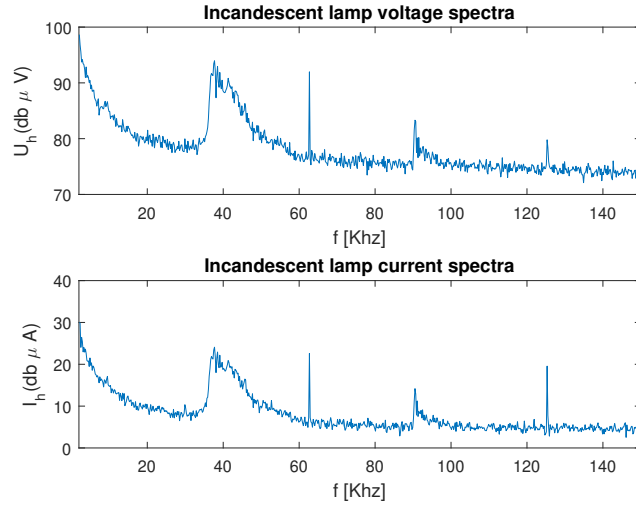


Figure 4.6: Incandescent lamp spectrum; obtained with the IEC 61000-4-7, extended up to 150 kHz

From the spectrum of the incandescent lamp, voltage coming from the grid can be seen showing parasitic harmonics. This observation is important for the next section, to distinguish primary from the secondary emissions.

¹ This component was chosen due to its resistive behavior. This implies similarity between the voltage and current spectrum (shown on figure 4.6)

4.2.3 Signal observation

Measurements were done on three CFLs of different rated power; 18, 11 and 8 W. The time signals can be observed on figure 4.7. The acquisition was done on 200 ms, which corresponds to 10 periods of fundamental (as the IEC 61000-4-7, IEC 61000-4-30 standards specified). Observations can be made on the voltage and current signals.

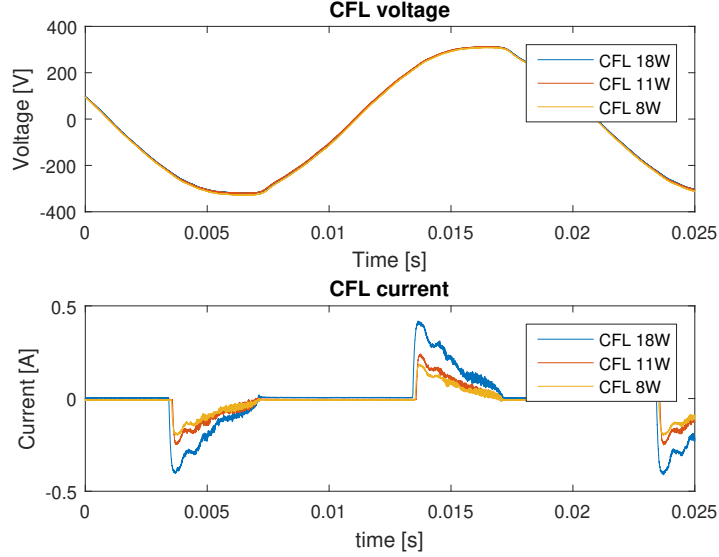
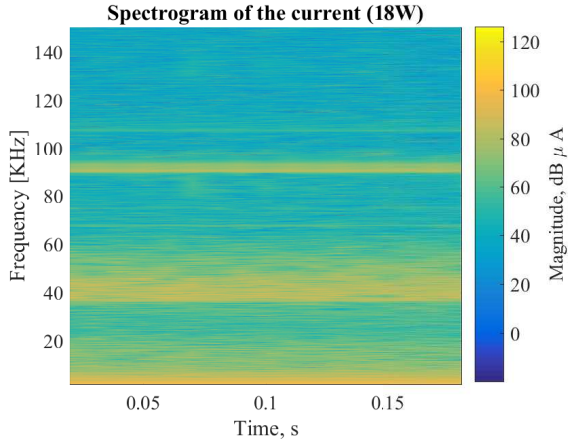


Figure 4.7: Voltage and current of the CFLs, measured on 200 ms interval, for three different CFLs of 8, 11 and 18 W

One remark can be done regarding the presence of low and high frequency components on the voltage (less visible due to the scale) and the current.



A first rough idea of the spectrum can be given by the spectrogram of the current coming from the CFL of 18 W (figure 4.8). Four zones can be distinguished: one at low frequency, the second around 40 kHz, and another around 90 kHz which belong to the grid. The last lighter zone around 110 kHz belongs to the CFL. The reasons are given in the next section.

Figure 4.8: Spectrogram of the current for the 18W CFL, obtained by using STFT, presented in [section 2.2](#)

4.2.4 Spectrum of the CFL signals

In this section, the standard IEC 61000-4-7 was chosen since it is the most precised, compared to the others. However, a comparison of the different standards is done afterwards. Based on the measurement methods presented in the previous section, the figure 4.9 shows the spectrum of all the CFLs measured.

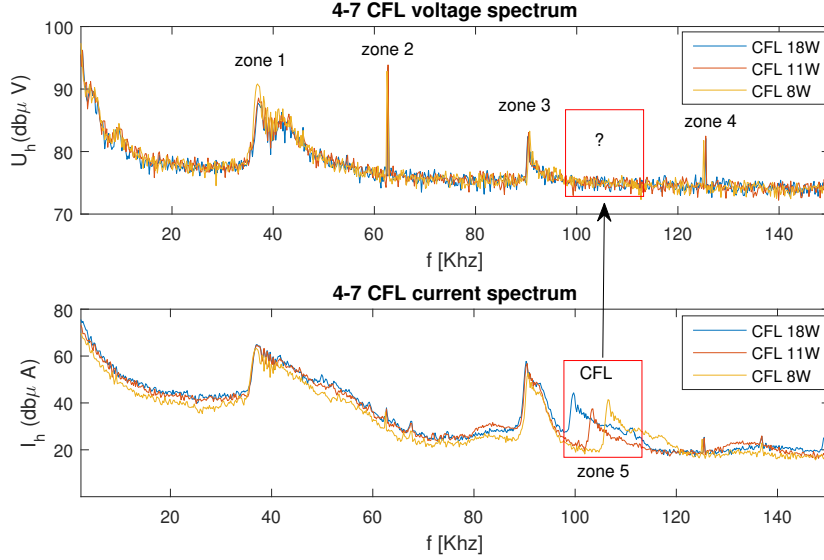


Figure 4.9: CFLs spectrum; obtained by the IEC 61000-4-7, extend up to 150 kHz

Different emissions can be observed on figure 4.9.

1. Based on what is shown on figure 4.6 (and explained in the part describing the grid behavior, in subsection 4.2.2), **secondary emissions** are present on the voltage and the current. Four main "harmonic zones" can be distinguished, one around 40 kHz, the second near 60 kHz, and the last two around 90 kHz and 120 kHz.
2. A fifth zone can be seen, framed in red on figure 4.9, which is present on the current spectrum, but not on the voltage. Based on the definitions given in section 4.1, the power dependence of the harmonic position (at ≈ 100 , 103 and 106 kHz for 18, 11 and 8 W respectively), those peaks could be considered as **primary emissions**. The fact that the fifth zone does not appear on the voltage could be due to a too small impedance of the grid at that frequency (≈ 100 kHz).

One interesting thing is to make the same parameter study of the IEC 61000-4-30, done in section 3.2, but on the signals (current and voltage) of the 18 W CFL.

4.2.5 Parameter study of the IEC 61000-4-30 on CFL measurement

This subsection uses the same approach as subsection 3.2.2, to investigate the influence of various parameters characterizing the IEC 61000-4-30.

Influence of the duration/number of intervals

In this section, we are interested in the influence of the duration/number of intervals. The test signals used come from 18 W CFL. More details are given in subsection 4.2.1.

On figure 4.10, the first and second graph represent the current amplitude of the most significant harmonic (at ≈ 38 kHz) in function of the duration of the intervals and the number

of intervals respectively. Since precise emissions levels of the CFL are not available of the CFL, it is not possible to compare the value given by the IEC 61000-4-30 with reference value. The signal coverage does not make the result vary that much. The values stay almost stationary.

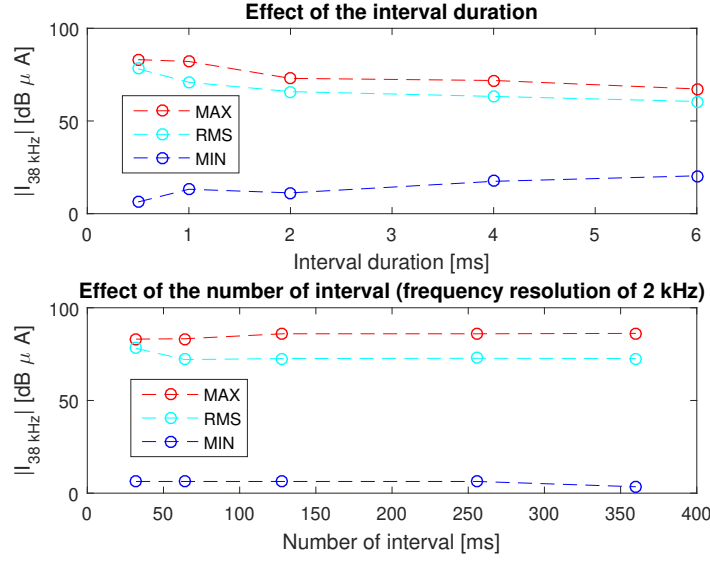


Figure 4.10: Influence of the duration and number of intervals, for an harmonic frequency of 38 kHz

Influence of the frequency resolution

Secondly, concerning the frequency resolution, as previously, the size of the time window is going to be modified, in order to compare the result of the IEC 61000-4-30 and the one given by the IEC 61000-4-7. The effect of this parameter is shown on figure 4.11.

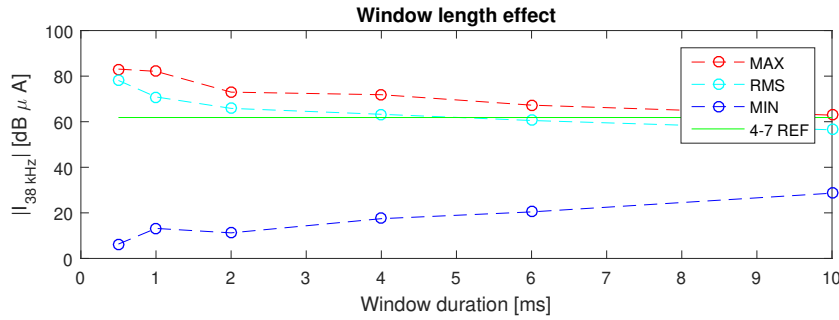


Figure 4.11: Influence of the frequency resolution

The green line represents the value given by the IEC 61000-4-7 (taken as reference in this case). It can be seen that the longest the window duration is, the closest the max, min and RMS values are to the reference. It is normal, because the frequency resolution is reduced, to values closer to the one defined in the IEC 61000-4-7 (5 Hz/200 ms).

4.2.6 Comparison between the standards

Current comparison analysis

The first signal being compared is the current, and the comparison is shown on figure 4.12.

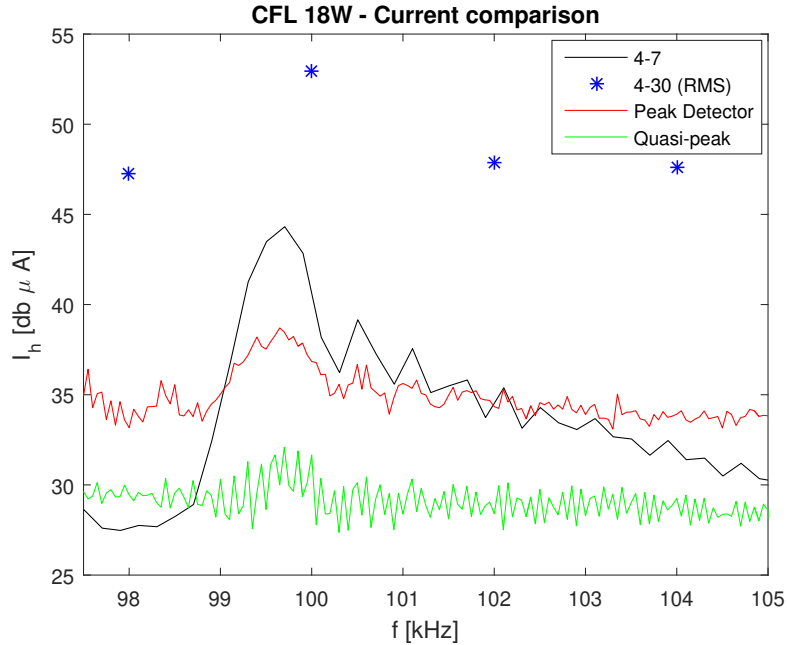


Figure 4.12: Zoom of the current spectrum, between 97 kHz and 105 kHz, given by each standards for the 18W CFLs; the frequency axis is different for each standard; the IEC 61000-4-7 (extended up to 150 kHz), IEC 61000-4-30 (RMS), the peak detector and the quasi-peak detector

Since, all the three different CFLs were analyzed in the previous section, the analysis is focused on the 18 W CFL.

1. Firstly, IEC 61000-4-7 values are close from those of the peak detector. Its frequency resolution (5 Hz), and grouping provide clear idea of the current spectrum. The harmonic magnitude at around 100 kHz is ≈ 45 dB μ A.
2. IEC 61000-4-30 is the one giving the highest value out of the three methods, simply because the frequency resolution (1/time window, 2 kHz) is not small enough to guarantee enough precision. The parameters used to obtain that result are given below.

Signal coverage	8%
Number of intervals	32
Duration of the intervals	0.5 ms
Duration of the signal	200 ms

The size of the time window is of the same duration as the 32 time intervals in order to avoid leakage on the spectrum. The harmonic magnitude at around 100 kHz is ≈ 55 dB μ A.

3. The third one is the peak detector. This one gives values lower than the IEC 61000-4-30, due to a better frequency resolution. In fact, the duration of the time window used to compute the STFT is 40 ms² (25 Hz). The harmonic magnitude at around 100 kHz is ≈ 40 dB μ A.

² This value is chosen in order to obtain the result as fast as possible. If a more precise STFT is required, my computer can not finish the program.

4. The last one is the quasi-peak detector. It gives at around 100 kHz, $\approx 33 \text{ dB}\mu\text{A}$. Based on the time response presented on figure 3.11, the value given by this method is always smaller than the peak detector, which is the case (around 15% of difference between both). The computation of the spectrum was limited to the region of interest (around 100 kHz). In fact, due to the excessive execution time of the Simulink simulation (18 hour for 8 kHz of spectrum), it was decided to limit the computation to only obtain the spectrum around the region of interest ($\approx 100 \text{ kHz}$).

At the end, a difference of maximum $\approx 20 \text{ dB } \mu\text{A}$ is observed in this first comparison.

Voltage comparison analysis

The comparison of the standards for the voltage of the 18 W CFL is shown on figure 4.13. The principle difference, regarding the obtained result for the current, is the difference of magnitude between the three methods. For the harmonic around 40 kHz, a difference of $\approx 10 \text{ dB dB}\mu\text{V}$ is observed between the IEC 61000-4-7 and the peak detector, and of $\approx 30 \text{ dB}\mu\text{V}$ with the IEC 61000-4-30.

This is due to small harmonic level at higher frequencies ($\leq 150 \text{ kHz}$). The magnitudes are of hundreds $\text{dB}\mu\text{V}$, due to the fundamental (50 Hz) of 300V, which let imagine that compared to 50 Hz, the rest of the spectrum is negligible. This is why, those big differences are observed between the three methods. The voltage looks pretty clean compared to the current on figure 4.7.

Quasi-peak detector result are not computed due to the fact that there are no CFL harmonic on its spectrum. It was chosen to focus the quasi-peak only on the current.

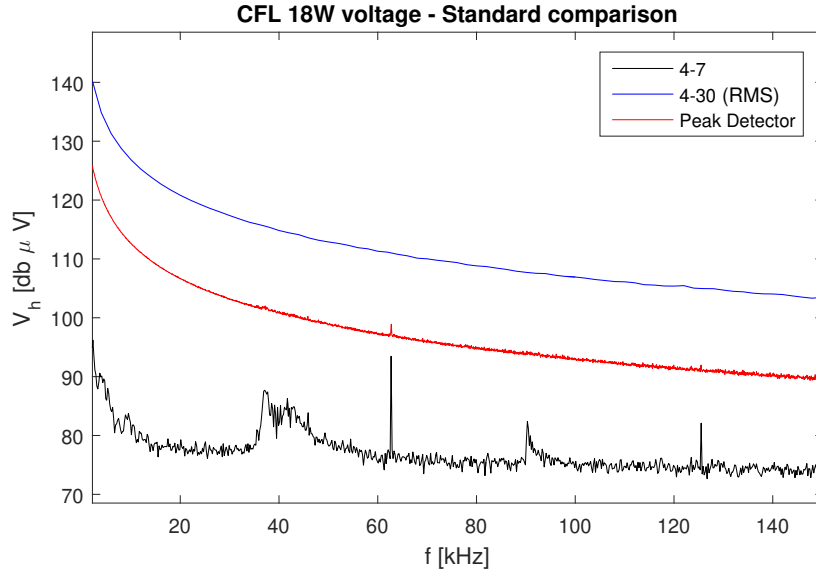


Figure 4.13: Voltage spectrum given by each standards for the 18W CFLs; the frequency axis is different for each standard; the IEC 61000-4-7 (extended up to 150 kHz), IEC 61000-4-30 (RMS) and the peak detector. Frequency axis begin at 2 kHz

In conclusion, if the harmonics levels are too low, compared to the fundamental, the IEC 61000-4-30 gives result very different from the other methods. The same remark can be applied to the peak and the quasi-peak detector, even if they are closer from the IEC 61000-4-7.

4.3 Water pump measurement (Laborelec)

Laborelec has sent signals coming from measurements done on a water pump of 16.43 kW [24], as part of the Smartwater Project. In this chapter, different signals (measure at different locations) are analyzed with different standards. A reminder about theoretical aspect is given as well.

4.3.1 Theoretical aspect

This section gives technical description, in order to understand what is present in the spectrum of the signal. To understand well the working principle, a block diagram is given on figure 4.14.

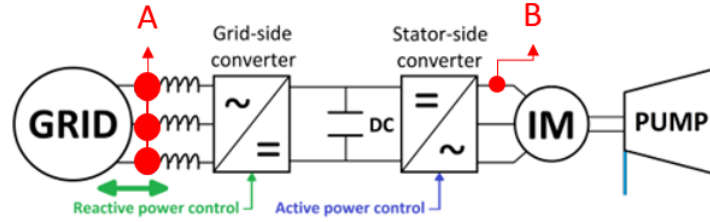


Figure 4.14: Electromechanical configuration of the studied power plant [24]; composed of pump, connected to an induction machine, linked to the grid via two voltage sources inverters. Measures were done at two different places (three-phase on A and one-phase on B)

The PAT (Pump-as-turbines) drives a three-phase IM (Induction machine) connected to the grid through an industrial reversible back-to-back power converter composed of two voltage sources inverters (VSIs). Based on the well-known field oriented control (FOC), the stator-side VSI magnetizes the electrical machine and controls the active power developed by the PAT. On the other side, the grid-side VSI keeps the DC-link voltage to its nominal value, thereby injecting active power to the grid, while varying injections of reactive power in order to support the grid voltage [24]. The inverter could give harmonics multiple of each other.

4.3.2 Measurement results

Two measures were done at different places. The first on A (see figure 4.14), to measure the three-phase voltage and current on the grid (see figure 4.15).

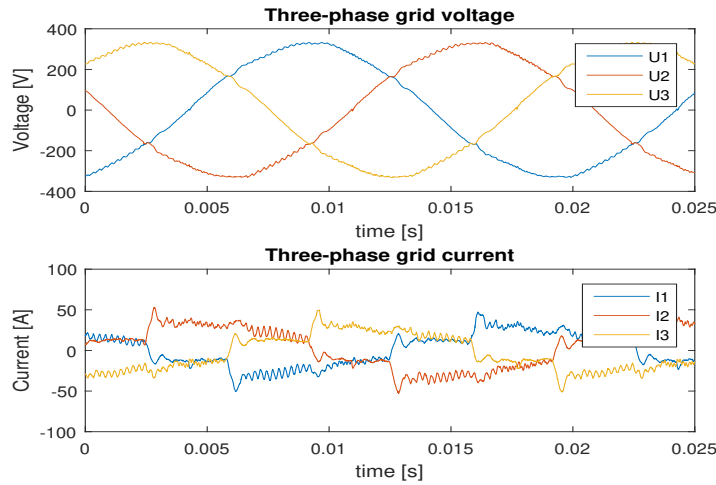


Figure 4.15: Three-phase current and voltage measured on the grid, located on A, on figure 4.14

The other measure is done on B, at the output of the induction machine (see figure 4.16).

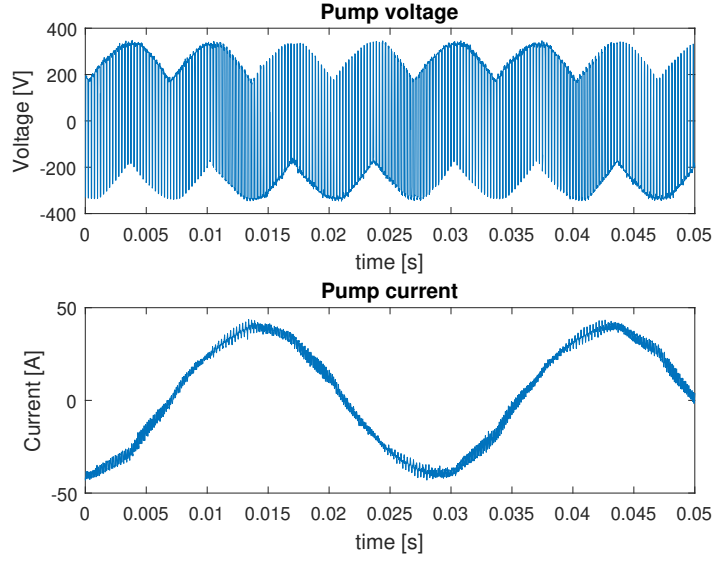


Figure 4.16: Measured voltage and current at the output of the induction machine, located on B, on figure 4.14

Low and high-frequency components are present on the voltage and the current on both measurements.

4.3.3 Spectrum of the water pump signals

The IEC 61000-4-7 is used to obtain spectrum of the four signals, three measured on A and the other on B. The result is shown on figure 4.17.

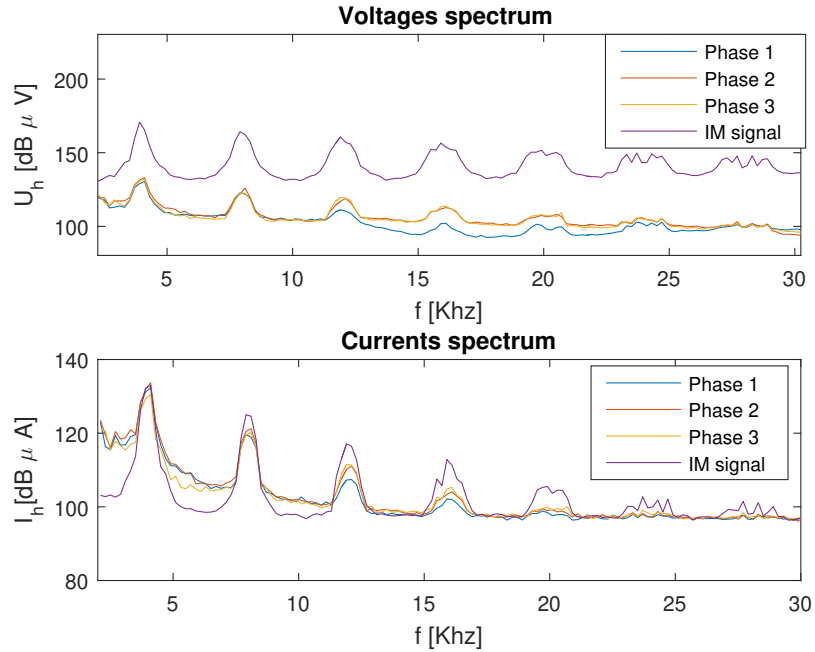


Figure 4.17: Spectra of the measurements done at two different locations; given by the IEC 61000-4-7, extended up to 30 kHz

Repetitive peaks can be seen on the spectrum, at each multiple of 4 kHz, which is the

switching frequency of the inverter. Harmonics voltage and current are at the same position in frequency, with almost the same magnitude. The same observation is done concerning the three-phase signals. But, the voltage harmonics coming from the induction machine are bigger than those from the grid.

4.3.4 Comparison between the standards

Current comparison analysis

One of the main point of this section is to compare the different standards results between each other. Firstly, the comparison (on figure 4.18) is done for the current.

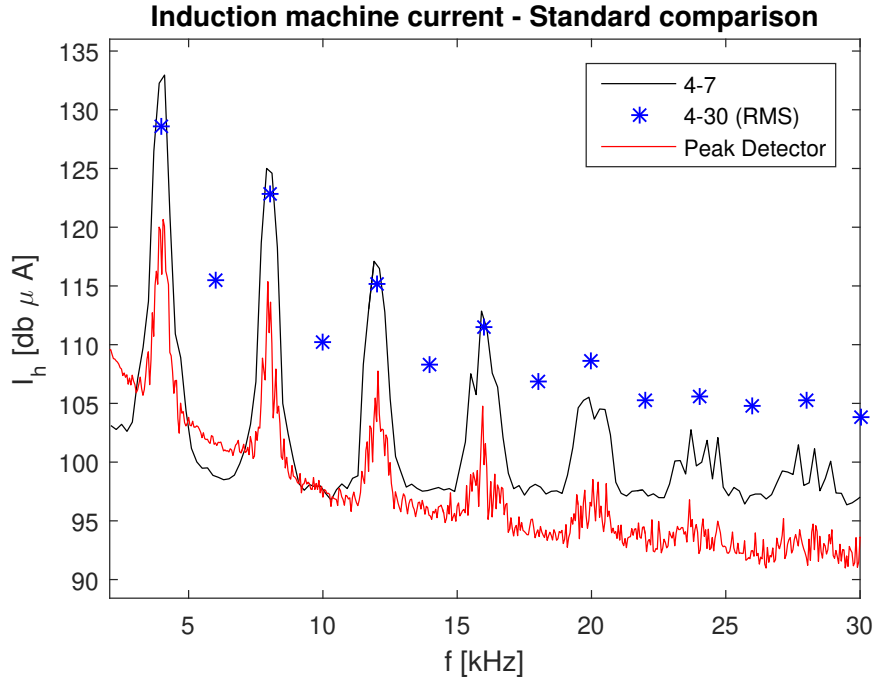


Figure 4.18: Comparison of the result given by each standards based on the current spectrum; the IEC 61000-4-7 (extended up to 30 kHz), IEC 61000-4-30 (RMS) and peak detector

On figure 4.18, the standards give different values for the same harmonics, as already observed in the previous subsection 4.2.1.

- Firstly, the IEC 61000-4-7 gives the highest value. This is due to the grouping. In fact, the harmonic value on the graph is the combination of other harmonics (quadrature mean as said in section 3.1), with non negligible magnitude. Each peaks, multiple of 4 kHz are at the same place as the one of the other two methods. The magnitude at 4 kHz is almost 135 dB μ A. This high value is normal if the power of pump (around 16 kW) is taken into account.
- Secondly, concerning the IEC 61000-4-30, the value at each multiple of 4 khz are near the values of the IEC 61000-4-7. However, the "inter" peaks are higher than the other two methods. Which means that, a lot of leakage appear when the IEC 61000-4-30 results are computed. This is the same phenomena as in the previous subsection 4.2.1. The highest value at 4 kHz is around 130 dB μ A.
- Finally, the peak detector. This last gives the smallest value out of the three, since no grouping is performed, and less leakage occurs. The highest value at 4 kHz is around 120 dB μ A.

In conclusion for the current, all the standards give almost the same result, with ≈ 10 dB μ A of difference.

Voltage comparison analysis

Observations can be also done on the different voltage spectrum results, given on figure 4.19.

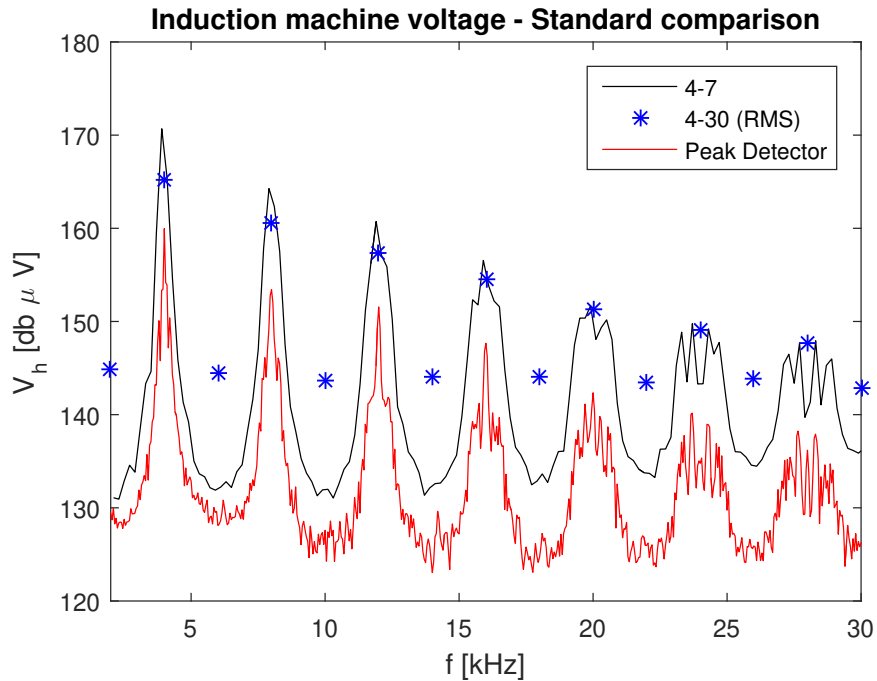


Figure 4.19: Comparison of the result given by each standards based on the voltage spectrum; the IEC 61000-4-7 (extended up to 30 kHz), IEC 61000-4-30 (RMS) and peak detector

The observations are the same for the voltage then those done for the current. In fact, the peaks are multiple of 4 kHz. The difference comes from the magnitudes (170 dB μ V for the IEC 61000-4-7, 165 dB μ V for the IEC 61000-4-30 and 160 dB μ V for the peak detector at 4 kHz). At the end, 5 dB μ V of difference between the results can be noticed. This difference is small compared to the previous section value where the difference was of 30 dB μ V for the voltage. This can be explained by the fact that the signal is more stationary, with a constant 4 kHz time modulation, which is not the case for the CFLs.

4.4 Panda signal

Since this master thesis uses experimental signals, it was interesting to use signals coming from an other database. This is why, Panda is used. In this section, different type of signals are detailed, and comparison between the measurement methods are done based on those data.

4.4.1 What is Panda ?



Figure 4.20: Panda site illustration [2]

This site is a global web-based platform for exchanging harmonic emission measurements from all types of household equipment's (single-phase equipment) between different laboratories around the world [2]. It is managed by the TECHNISCHE UNIVERSITÄT DRESDEN.

4.4.2 Type of signal presentation

In order to make the comparison of the standards, different kind of signals were selected to be studied. Those equipments are

- Photovoltaic device
- The charger of a camera

Photovoltaic signal

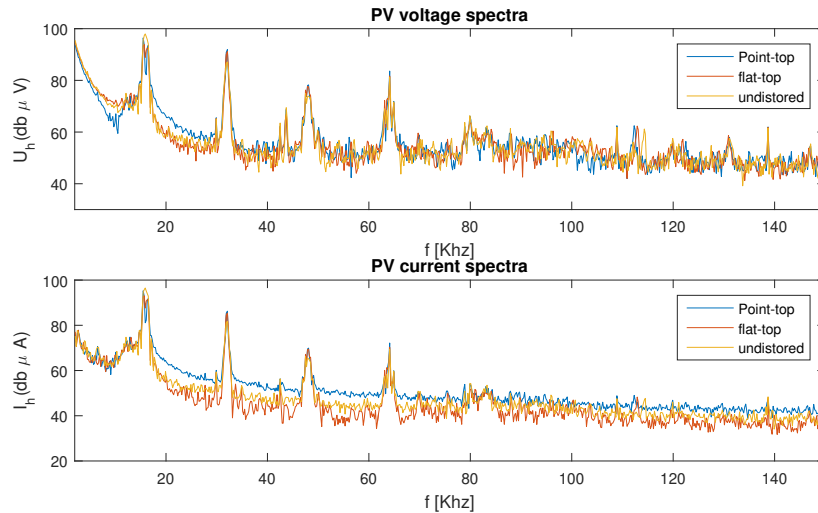


Figure 4.21: Spectrum of all the signals coming from PV, given by the IEC 61000-4-7 (extended up to 150 kHz). Three different signals are considered, the only difference remains in the sampling techniques used to obtain the signals

The spectrum given by the IEC 61000-4-7 is shown on figure 4.21. The shape of the spectrum is typical of photovoltaic panels. Since, this last generates DC, an inverter is necessary, before the connection to the grid. The converter generates the harmonics present on the spectrum of

figure 4.21, which are at multiple of 16 kHz. The scheme of PV with inverter connection to the grid is given on figure 4.22.

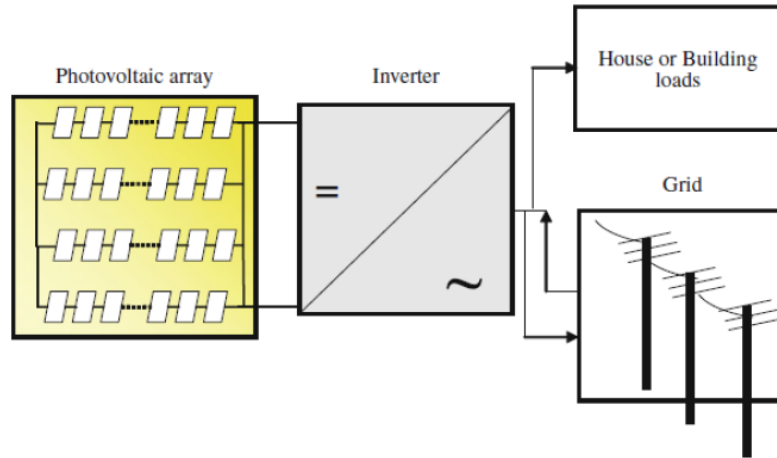


Figure 4.22: PV connection to the grid [9]

Camera charging

The second signal chosen is coming from a charger of camera. One interesting thing specific to Panda is the fact that measures can be found, with different sort of power supply source.

Grid voltage		1
Programmable generator	Sinusoidal voltage waveform	2
	Distorted voltage waveform	only LF Harmonics
		only HF Harmonics
		LF and HF Harmonics
		5

Figure 4.23: Supply sources order based on specifications given by Panda [8]

They are characterized by numbers. Those categories are given on figure 4.23. In this case, category 2 and 3 are used. Concerning the spectrum, it is shown on figure 4.24.

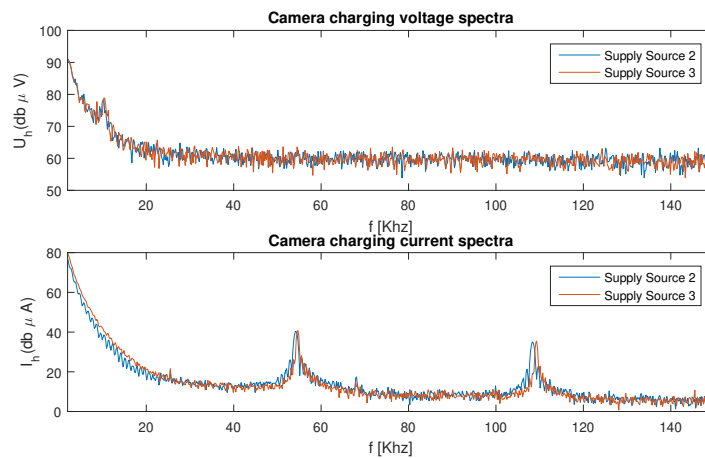


Figure 4.24: Camera charger spectrum, given by the IEC 61000-4-7 (extended up to 150 kHz)

According to figure 4.23, the supply source 2 and 3 correspond to a sinusoidal voltage waveform, and distorted voltage waveform respectively. No harmonic appears on the voltage.

In fact, the impedance of the charger is too small at those frequencies to measure harmonics. However, this is not the case for the current. In fact, two peaks are present, one at 54 kHz, and the second at 108 kHz. Standard comparison based on all the signals presented are given in the next section 4.5.

4.5 Comparison of the signals based on measurement methods

In this section, general comparison based on signals coming from the different equipments studied in this chapter is given on figure 4.25.

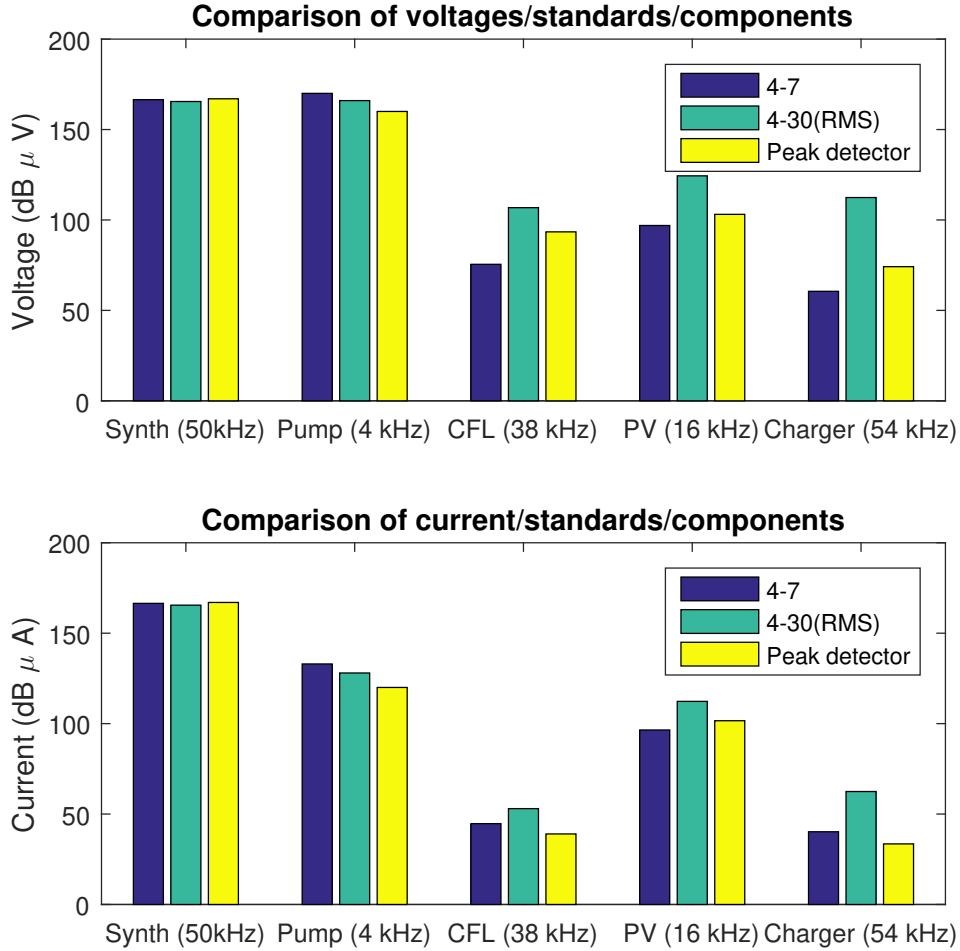


Figure 4.25: Comparison of the standards; the IEC 61000-4-7 (extended up to 150 kHz), the IEC 61000-4-30 and the peak detector; on five types of signals are given: A synthesized signal at 50 kHz, the 16 kW water pump harmonic at 4 kHz, the 18W CFL at 38 kHz, the PV at 16 kHz and the camera charger at 54 kHz from Panda

To make the analysis, results of the different methods are given based on several signals: a synthesized signal at 50 kHz, the 18W CFL at 38 kHz (see section 4.2), the pump harmonic at 4 kHz (see section 4.3), the PV at 16 kHz and the camera charger at 54 kHz (see section 4.4).

Concerning the synthesized signal, all the methods give the same results. It is a stationary signal, of constant amplitude and frequency. However, small and big differences appear between

the methods results for other type of signals.

The smallest difference concerns the pump signals. In fact, as explained in [section 4.3](#), it is a time modulated signal at 4 kHz, almost stationary. The biggest differences are between the IEC 61000-4-30 and the other methods values for the three other signals types. This is due to the fact that the harmonic levels on the voltage are too small regarding the signal coverage (8%) and the resolution frequency (2 khz) of the IEC 61000-4-30. However, all the values are very close for the currents, since the harmonic levels, with respect to the fundamental are bigger.

At the end, this is not possible for the IEC 61000-4-30 to identify signal harmonics with too low magnitude (compared to the fundamental) due to the 2 kHz of resolution frequency. The two other methods give very close results.

The purposes of this master thesis can be recalled as follows

- Understanding the problematic of conducted disturbances in the frequency range 2-150 kHz
- Implementing the measurement methods standards
- Studying various experimental signals to show their influences on the different standards
- Comparing the different standards, based on different criteria and signals

In [chapter 1](#), the presented study context shows the lack of standardization of this range of frequency (except for the emissions levels). This master thesis uses what was already done and compared the measurement standard based on different criteria. There are three main standards that deal with measurement: IEC 61000-4-7, IEC 61000-4-30 and CISPR 16-2-1.

Concerning the IEC 61000-4-7, from what was said in [section 3.1](#) and [chapter 4](#), this method is adapted for laboratory study of signals. It provides precise spectrum, in term of resolution frequency. The type of signal does not influence the result since the signal coverage is 100%. At the end, it determines the harmonic emissions produced by equipment on the grid.

The IEC 61000-4-30 is more useful on the field, when problems occur, to have quick informations about disturbances present on the grid. This could enable to find the origin of the interference and to solve the problems accordingly. Furthermore, the signal coverage of 8% and the easy implementation of this method enable the user to obtain results in no time, and the data storage is also reduced.

Finally, to have the time evolution of signal spectrum, CISPR based methods are the solutions. The spectrogram enables the user to have graphical representation in 3D of the signal, and its harmonic content evolution with the time. As explained in [section 3.3](#), different detectors exist (peak, quasi-peak and average), and each of them provide different results.

One important aspect underlined in [section 3.4](#) is the type of signal being analyzed. Depending on its origin (PV, CFL signal), and its magnitude, the IEC 61000-4-30 could not give representative spectrum of the voltage and current, based on the location of the intervals.

At the end, since all the standards are based on the same tool (the FFT), their respective results should be close to the reality, but all depend on the different parameters value used to compute the spectrum, and the type of signal being analyzed.

This work has tried to understand correctly the different informations given by the standards, and the problematic links to the supraharmonics (which is quite complicated). One limit is the modified implementation of the different detector compared to the one specified by the CISPR 16-2-1. But, the idea behind this work was to provide tools to help the supraharmonics research, even by choosing another implementation of the different detectors given by the CISPR 16-2-1.

This work could be extended by finding a way to implement the spectrogram specified by the CISPR standard, since simplify methods were implemented. Tests with advanced signals on each measurement methods could be used to study how each of them react with non-stationary signal. This could provide as well wider comparison between each result. Concerning the experimental part, tests with different types of sources, not only the grid could be performed, to study the influence of the supply on the results.

In this chapter, different validation tests are presented, in order to check that the code works correctly. First, the different steps present in the IEC 61000-4-7 are checked, as well as the resulting spectrum (section A.1). The same test method is applied on the IEC 61000-4-30 in section A.2. The last part is dedicated to the STFT based methods, in order to check if everything works correctly (section A.3).

A.1 IEC 61000-4-7

The idea of this section is to check each step of the method (DFT, grouping, aggregation,...). First, the DFT result with the parameters specified by the standard has to be correct. Second, the grouping needs to be calculated with the formula given in section 3.1.

A.1.1 DFT-Grouping test

The first test is done to check that the DFT and the grouping are well done. Here is the signal used to make this test:

$$v(t) = 0.65 * \sin(2\pi 50e3t) \quad (\text{A.1})$$

The result is shown on figure A.1. A bar graph was chosen due to its clear presentation.

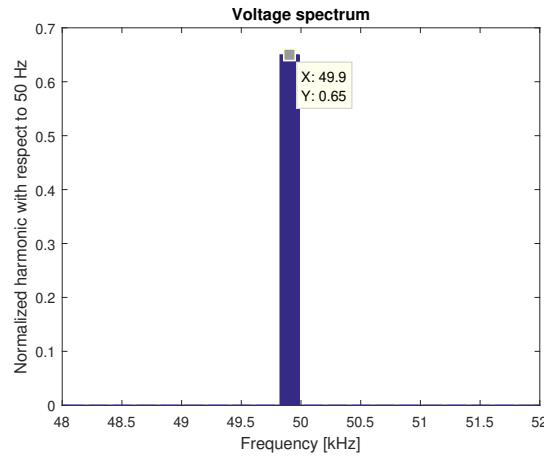


Figure A.1: Test 1 result; harmonic at 50 kHz, with 0.65 of amplitude, obtained with the IEC 61000-4-7, extended up to 150 kHz

Concerning the amplitude of the harmonic, it is of 0.65, as expected. But, concerning its place on the spectrum, the program gives 49.9 kHz, instead of 50 kHz. This is due to the grouping. In fact, based on figure 3.4, it can be deduced that the harmonics after the grouping are placed at multiple of 100 Hz.

A.1.2 Multiple intervals - Aggregation test

The second test checks that the program works correctly on signals longer than 200 ms (in case of multiple 200 ms interval, it performs aggregation). To do that, a signal of 400 ms was synthesized, composed of different harmonic on each 200 ms intervals. But as said at the end of the section 3.1, a quadratic mean is done to perform the aggregation. The signal is detailed below:

$$v(t) = 0.65 * \sin(2\pi 50 \text{e}3 t(0 - 200 \text{ ms})) + 0.5 * \sin(2\pi 60 \text{e}3 t(200 \text{ ms} - 400 \text{ ms})) \quad (\text{A.2})$$

The result is shown on figure A.2. As said before, a quadratic mean is done when the signal is longer than 200 ms. In this case, two harmonics of 0.65 and 0.5 of amplitude are dispatched on 400 ms. Thanks to the small calculations given below; it is possible to deduce the resulting magnitude.

$$|Uh_{50\text{kHz}}| = \sqrt{\frac{0.65^2 + 0}{2}} \approx 0.46 \quad (\text{A.3})$$

$$|Uh_{60\text{kHz}}| = \sqrt{\frac{0 + 0.5^2}{2}} \approx 0.35 \quad (\text{A.4})$$

The two amplitude calculated above are the same as the one presented on figure A.2. Concerning the frequency position of the harmonic, both are correct (if the grouping is taken into account). At the end, on synthesized signal, the different steps in the program work correctly.

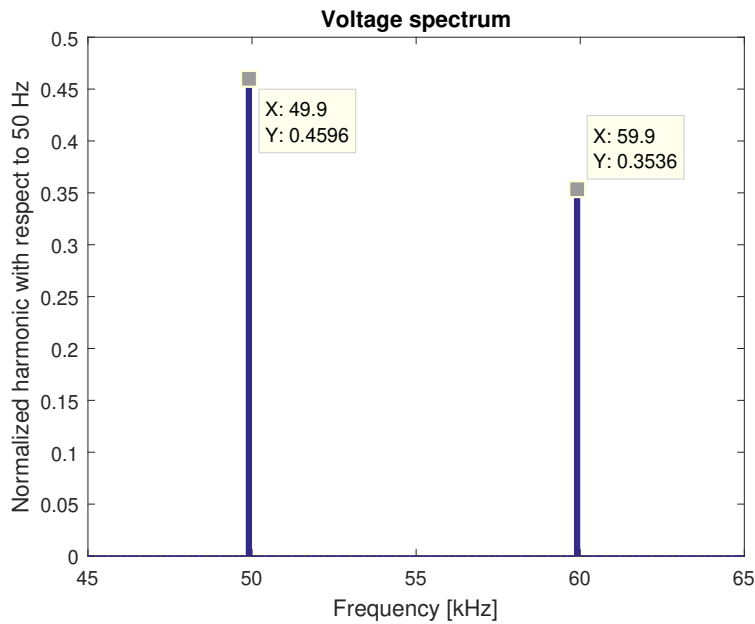


Figure A.2: Test 2 result; 2 harmonics at 49.9 kHz and 59.9 kHz, with 0.46 and 0.35 of amplitude, obtained with the IEC 61000-4-7 extended up 150 kHz

A.2 IEC 61000-4-30

To validate the script developed to study the harmonic content, some tests were done to show that it is correctly implemented. The idea was to check each program parts:

- The DFT calculation depending on the number and duration of the intervals, as well as the frequency resolution (window size), with one or more harmonic.
- The aggregation on signal longer than 200 ms.

The result of the tests are presented, compared to what was expected. The tests are done with 32 intervals, of 0.5 ms (in other word, 8 % of signal coverage), with 2 kHz of frequency resolution.

A.2.1 Check of the spectrum result

The voltage¹ test signal can be written as follow

$$v(t) = \mathbf{0.65} * \sin(2\pi\mathbf{40e3}t) \quad (\text{A.5})$$

The figure A.3 shows the maximum, minimum and RMS voltages spectrum, and a zoom on the peak at 40 kHz. In this case, the frequency 40 kHz is a multiple of 2 kHz, this gives 0.65 of magnitude for the rms value, with no leakage. Besides, for harmonic not multiple of the resolution frequency, the obtained values could not be precise, due to spectrum leakage.

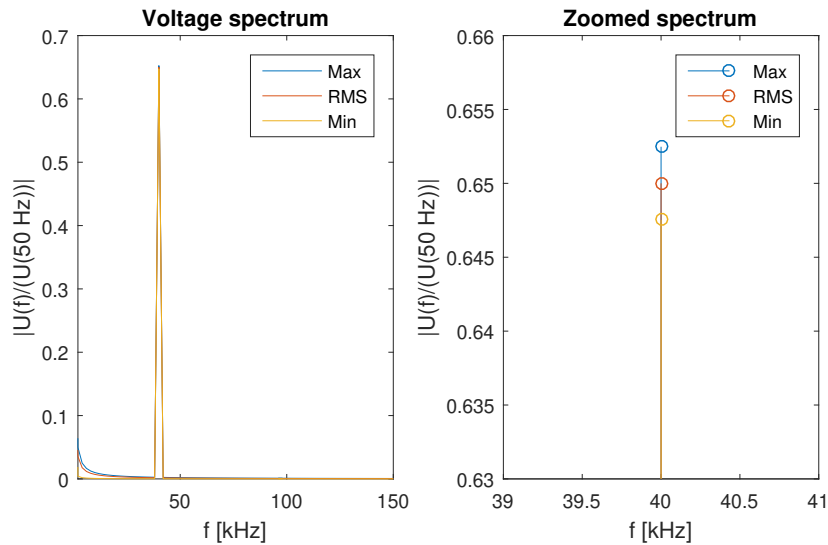


Figure A.3: Test 1 result; on the left figure: the spectrum between 2 and 150 kHz, and on the right figure, a zoom on the peaks at 40 kHz, with 0.65 (RMS) of amplitude; obtained with the IEC 61000-4-30, obtained with 8% of signal coverage

A.2.2 Multiple intervals - Aggregation test

The second test is done to check if the aggregation and the treatment of voltage signal on more than one 200 ms interval is correct (here 400 ms). The test signal used is given below

¹As said in the previous section, since the code is the same for the current and the voltage, explanation are given only for the voltage

$$v(t) = \mathbf{0.65} * \sin(2\pi\mathbf{50e3}t(0 - 200 \text{ ms})) + \mathbf{0.58} * \sin(2\pi\mathbf{60e3}t(200 \text{ ms} - 400 \text{ ms})) \quad (\text{A.6})$$

As in the previous section, the same aggregation (quadratic mean) is done on signal longer than 200 ms. The resulting values can be calculated as follow

$$|Uh_{50kHz}| = \sqrt{\frac{0.65^2 + 0}{2}} \approx \mathbf{0.46} \quad (\text{A.7})$$

$$|Uh_{60kHz}| = \sqrt{\frac{0 + 0.58^2}{2}} \approx \mathbf{0.41} \quad (\text{A.8})$$

Those amplitudes can be compared with the one returned by the program, which are shown on figure A.4. In conclusion, the coverage problem explained in the [section 3.2](#), does not influence the result in this case, because of the synthesized signals.

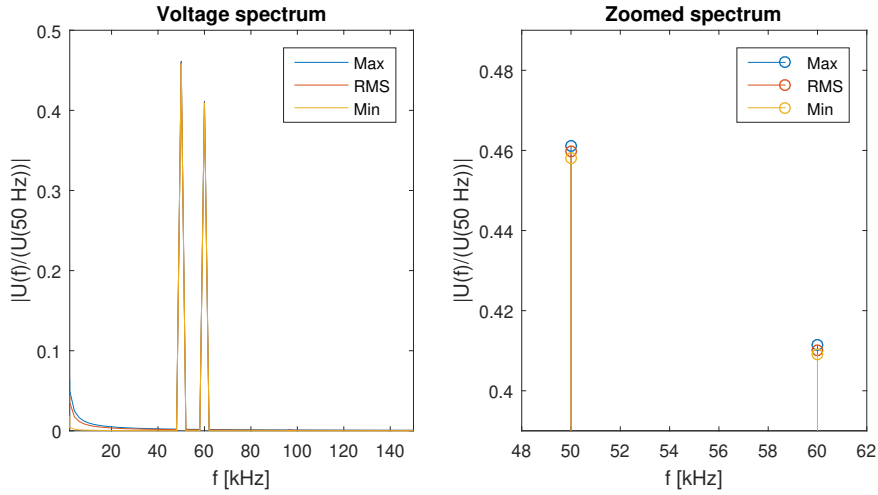


Figure A.4: Test 2 result; two harmonics at 50 and 60 kHz, with 0.46 and 0.41 of amplitude, obtained with the IEC 61000-4-30, with 8% of signal coverage

A.3 CISPR 16-2-1

In this section, validation tests are done on the peak and quasi-peak detector presented in [section 3.3](#). The purpose is to check if the program gives correct results.

A.3.1 Peak detector - Validation

For the peak detector, the test is done on synthesized signal. The test signal chosen is given below

$$v(t) = 0.7 * \sin(2\pi 50e3t) + 0.8 * \sin(2\pi 75e3t) + 0.1 * \sin(2\pi 100e3t) + 0.3 * \sin(2\pi 125e3t) \quad (\text{A.9})$$

The representation in time of the test signal is presented on figure [A.5](#). Since the signal is built with different harmonic over different period of time, and it looks pretty distorted.

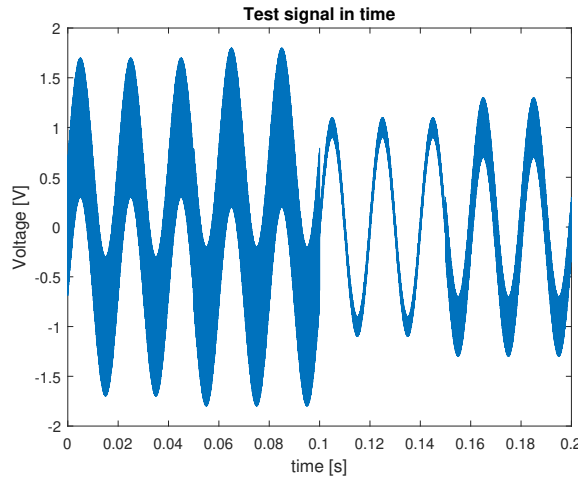


Figure A.5: Time representation of the test signal

Based on what was said in [section 2.2](#) and [section 3.3](#), two graphs were obtained, and are presented on figure [A.6](#).

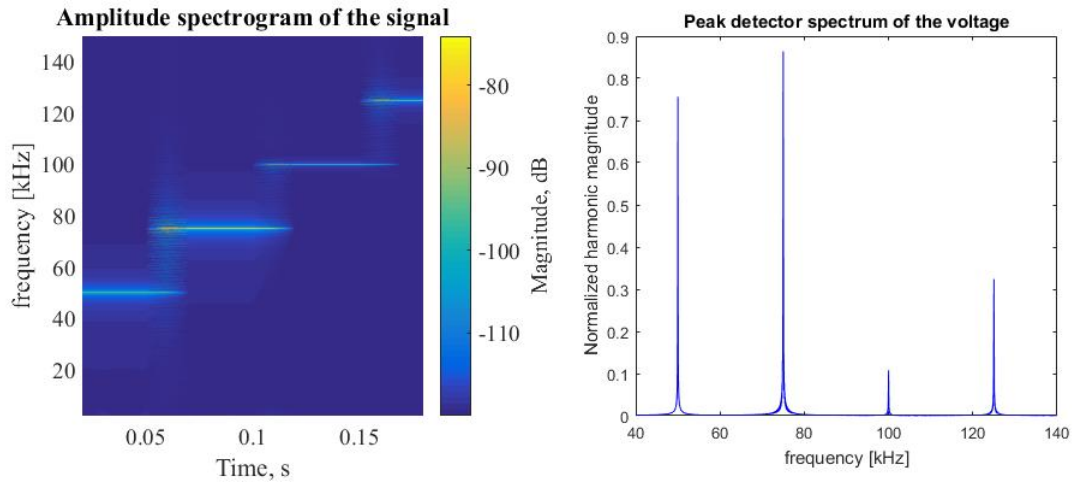


Figure A.6: On the right figure, spectrogram of the signal; on the left figure, the spectrum showing the four peaks of the signal, at 50, 75, 100 and 125 kHz, with 0.76, 0.82, 0.1 and 0.3 of amplitude, obtained by the peak detector

On figure A.6, two graphs are present. The first one gives the spectrogram of the signal representing the signal evolution with the time. The second simply shows the four peaks that are present on the signal written above. The spectrogram is very interesting to observe the signal non-stationarity.

Slight differences between the computed and theoretical amplitudes of the test signal can be observed on table A.1. Those differences could come from the STFT computation stage. In fact,

	Theoretical	Computed
$ Uh_{50kHz} $	0.7	0.76
$ Uh_{75kHz} $	0.8	0.864
$ Uh_{100kHz} $	0.1	0.108
$ Uh_{125kHz} $	0.3	0.324

Table A.1: Comparison between the theoretical and computed values given by the peak detector

one parameter is used to specify the **overlap** of the successive windows. This overlap impact directly the value given by the STFT. More informations are given in [section 2.2](#).

A.3.2 Quasi-peak detector - Validation

Like for the previous methods, validation test is done to check if the result with synthesized signal is correct. The signal used can be written as follow

$$v(t) = 0.65 * \sin(2\pi 700 * 50t) \quad (\text{A.10})$$

The obtained spectrum can be seen on figure A.7.

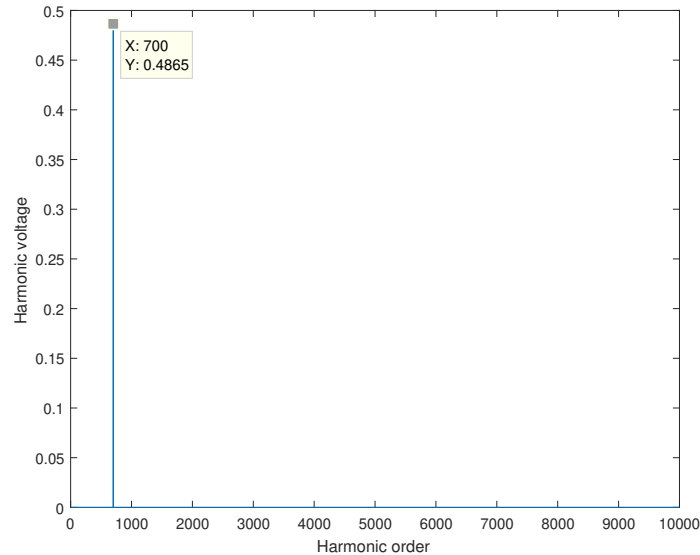


Figure A.7: Spectrum result, given for the quasi-peak detectors. Harmonic with 0.49 V of magnitude, at 35 kHz. The voltage harmonic magnitude is given, in function of the frequency (the axis is expressed in term of the harmonic order, since the program is built like that)

The simulation time is 1.5 seconds. Due to the weighting factor added by the quasi-peak detector, the final value obtained is lower (0.49) than the one expected (0.65). One of the problem

with this method is the speed of simulation which is very slow, due to Simulink. One way to solve that problem would be to use the digital implementation of the quasi-peak detector.

APPENDIX B

SCRIPT MATLAB

B.1 FFT-based methods

B.1.1 IEC 61000-4-7

```

1 function [U_fft,I_fft,b,G_Ub,G_Ib,f_interh,G_Uib,G_Iib,f_fft] =
    IEC_4_7(U,I,fs,n_10_cycles)
2 % This function computes the frequency spectrum of the voltage and
    the
3 % current, in accordance with the standard IEC 61000-4-7. This
    function
4 % takes as input
5 %     U, the voltage
6 %     I, the current
7 %     fs, the sampling frequency
8 %     n_10_cycles, the number of 200 ms periods (must be integer)
9 % The program makes the DFT, and the grouping. It can be used on
    signals of
10 % any duration. The output are
11 %     U_fft, I_fft, the fourrier transform of the current and the
        voltage
12 %     G_Ub, G_Ib, the harmonic voltage and current after the
        grouping
13 %     G_Uib, G_Iib, the interharmonic voltage and current value
        after the grouping
14 %     b, the center frequencies of the grouping band
15 %     f_interh, the position of the interharmonic
16
17 % Declaration of the parameters used by the program
18
19 Window = 200e-3;           %Duration of the window used for the DFT
20 n_fft = fs*Window;         %Size of the DFT, used fy the fonction fft
21 U_fft_aggreg = zeros(n_10_cycles,n_fft); U_fft = zeros(1,n_fft);
22 I_fft_aggreg = zeros(n_10_cycles,n_fft); I_fft = zeros(1,n_fft);
23 f_fft = 0:fs/n_fft:fs-fs/n_fft;
24
25 % Computation of the DFT depending if the signal last 200 ms, or

```

```

26 % n_10_cycles*200 ms. For signal longer than 200 ms, an aggregation
    is
27 % done.
28
29 if n_10_cycles == 1
30     U_fft = abs(2*fft(U,n_fft)/n_fft);
31     I_fft = abs(2*fft(I,n_fft)/n_fft);
32 else
33     for j=0:(n_10_cycles-1)
34         U_fft_aggreg(j+1,:) = abs(2.*fft(U(1,j*(length(U)/n_10_cycles
35             )+1:j*(length(U)/n_10_cycles)+...
36                 (length(U)/n_10_cycles)),n_fft)./(n_fft));
37         I_fft_aggreg(j+1,:) = abs(2.*fft(I(1,j*(length(I)/n_10_cycles
38             )+1:j*(length(I)/n_10_cycles)+...
39                 (length(I)/n_10_cycles)),n_fft)./(n_fft));
40     end
41     % Aggregation for each harmonic order
42     for k=1:n_fft
43         U_fft(1,k) = sqrt(sum(U_fft_aggreg(:,k).^2)/n_10_cycles);
44         I_fft(1,k) = sqrt(sum(I_fft_aggreg(:,k).^2)/n_10_cycles);
45     end
46 end
47
48 % Grouping of the harmonic:
49 % Declaration of the variables, and the frequency vector
50
51 f_grouping = 200; %grouping of 2kHz
52 b = find(f_fft == 2000+f_grouping/2):f_grouping*window:find(f_fft
53     ==150e3-f_grouping/2)
54
55 G_Ub = zeros(length(b),1);G_Ib = zeros(length(b),1);
56
57 % Computation of the grouped harmonics (according to the standard)
58
59 for i=1:length(b)
60     G_Ub(i,1) = sqrt(sum(U_fft(1,b(i) - f_grouping*window/2+1 : b(i)+
61         f_grouping*window/2).^2));
62     G_Ib(i,1) = sqrt(sum(I_fft(1,b(i) - f_grouping*window/2+1 : b(i)+
63         f_grouping*window/2).^2));
64 end
65
66 % Grouping of the interharmonics:
67 % Declaration of the variables, and the frequency vector
68
69 f_interh = 1:1:40;
70 G_Uib = zeros(1,length(f_interh));G_Iib = zeros(1,length(f_interh));
71
72 % Computation of the grouped interharmonics (according to the
73     standard)
74
75 for i=1:length(f_interh)

```

```
70      G_Uib(1,i) = sqrt(sum(U_fft(1,(i-1)*10+2:(i-1)*10+8).^2));
71      G_Iib(1,i) = sqrt(sum(I_fft(1,(i-1)*10+2:(i-1)*10+8).^2));
72  end
73  end
```

B.1.2 IEC 61000-4-30

```
1 function [U_fft_max,I_fft_max,U_fft_min,I_fft_min,U_fft_RMS,I_fft_RMS
   ] = IEC_4_30_fct_V1(U,I,fs,n_10_cycles)
2 % This function computes the spectrum of the voltage and the current
   according
3 % the standard IEC 61000-4-30.
4 % This function takes as input
5 %     U, the voltage
6 %     I, the current
7 %     fs, the sampling frequency
8 %     n_10_cycles, the number of 200 ms periods (must be integer)
9 % The output are
10 %     U_fft_max, I_fft_max, the harmonic voltage and current (
   maximum value)
11 %     U_fft_rms, I_fft_rms, the harmonic voltage and current (rms
   value)
12 %     U_fft_min, I_fft_min, the harmonic voltage and current (min
   value)
13 % The program computes the harmonic of the voltage and the current,
   based
14 % on the parameters specified by the standards. Depending of the
   value
15 % entered for the parameters, the coverage of the signal used to make
   the computation will change.
16
17 % Definition of the parameters
18
19 Ts=1/fs; % Inverse of the sampling frequency
20 duration=length(U)/fs; % Total duration of the signal
21 t=0:Ts:duration-Ts; % Time interval
22
23 Nbr_intervalle = 32; %Number of intervals
24 duration_intervalle = (0.5e-3); %Duration of the intervals
25 Total_sample_per_intervalle = (fs*duration_intervalle); %Total number
   of samples
26 windows =0.5e-3; %Size of the window used for the DFT (1/window to
   obtain the resolution frequency)
27 n_fft = (fs*windows); %Size of the DFT:
28
29 %Declaration of the result variables
30
31 U_fft_aggreg_RMS = zeros(n_10_cycles,n_fft);
32 U_fft_RMS = zeros(1,n_fft);
33 I_fft_aggreg_RMS = zeros(n_10_cycles,n_fft);
34 I_fft_RMS = zeros(1,n_fft);
35 U_fft_aggreg_min = zeros(n_10_cycles,n_fft);
36 U_fft_min = zeros(1,n_fft);
37 I_fft_aggreg_min = zeros(n_10_cycles,n_fft);
38 I_fft_min = zeros(1,n_fft);
39
40 U_fft_aggreg_max = zeros(n_10_cycles,n_fft);
```

```

41 U_fft_max = zeros(1,n_fft);
42 I_fft_aggreg_max = zeros(n_10_cycles,n_fft);
43 I_fft_max = zeros(1,n_fft);
44
45
46 f = 0: (fs/(n_fft)) : (fs - fs/(n_fft)); f=f./50; % Frequency vector
47
48 % Computation of the DFT depending if the signal lasts 200 ms, or
49 % n_10_cycles*200 ms
50
51 if n_10_cycles==1
52     [U_fft_max,I_fft_max,U_fft_min,I_fft_min,U_fft_RMS,I_fft_RMS] =
53         ...
54         fft_resize(U,I,t,Total_sample_per_intervalle,Nbr_intervalle,
55             fs, windows);
56 else
57     for i=0:(n_10_cycles-1)
58         [U_fft_aggreg_max(i+1,:),I_fft_aggreg_max(i+1,:),
59             U_fft_aggreg_min(i+1,:),I_fft_aggreg_min(i+1,:),
60             U_fft_aggreg_RMS(i+1,:),I_fft_aggreg_RMS(i+1,:)] =
61             fft_resize(...
62                 U(1,i*(length(U)/n_10_cycles)+1:i*(length(U)/n_10_cycles)
63                     +(length(U)/n_10_cycles)),...
64                 I(1,i*(length(U)/n_10_cycles)+1:i*(length(U)/n_10_cycles)
65                     +(length(U)/n_10_cycles)),...
66                 t(1,i*(length(U)/n_10_cycles)+1:i*(length(U)/n_10_cycles)
67                     +(length(U)/n_10_cycles)),...
68                 Total_sample_per_intervalle,Nbr_intervalle,fs, windows);
69     end
70
71 %Aggregation of the harmonic in the case we have more than 1
72 %interval of 200 ms
73
74 for k=1:n_fft
75     U_fft_RMS(1,k) = sqrt(sum(U_fft_aggreg_RMS(:,k).^2)/
76         n_10_cycles);
77     I_fft_RMS(1,k) = sqrt(sum(I_fft_aggreg_RMS(:,k).^2)/
78         n_10_cycles);
79
80     U_fft_max(1,k) = sqrt(sum(U_fft_aggreg_max(:,k).^2)/
81         n_10_cycles);
82     I_fft_max(1,k) = sqrt(sum(I_fft_aggreg_max(:,k).^2)/
83         n_10_cycles);
84
85     U_fft_min(1,k) = sqrt(sum(U_fft_aggreg_min(:,k).^2)/
86         n_10_cycles);
87     I_fft_min(1,k) = sqrt(sum(I_fft_aggreg_min(:,k).^2)/
88         n_10_cycles);
89 end
90 end
91 end

```

fft_resize.m

```
1 function [U_fft_max,I_fft_max,U_fft_min,I_fft_min,U_fft_RMS,I_fft_RMS
   ] = fft_resize(U,I,t,Total_sample_per_intervalle,Nbr_intervalle,fs
   ,windows)
2 % Function used to compute the spectrum with respect to the 4-30.
   Based on the total number of sample
3 % per interval and the number of interval, this code computes the FFT
   of the the voltage and the current (of 200ms duration),
4 % based on the choice of parameters.
5
6 noSamples = length(t); % Number of
   samples
7 a1= (Total_sample_per_intervalle); % Total sample per interval
8 a = (a1)*Nbr_intervalle; % Total sample used in the
   computation
9
10 a_sub = (noSamples-a)/(Nbr_intervalle); % Number of sample that
   are not used to compute the spectrum
11
12 n_fft=windows*fs; %
   Size of the DFT
13
14 %Creation of the different variables, to stock the data
15
16 U_fft_resize = zeros(Nbr_intervalle,n_fft);
17 I_fft_resize = zeros(Nbr_intervalle,n_fft);
18
19 U_fft_RMS = zeros(1,n_fft);
20 I_fft_RMS = zeros(1,n_fft);
21
22 U_fft_max = zeros(1,n_fft);
23 I_fft_max = zeros(1,n_fft);
24
25 U_fft_min = zeros(1,n_fft);
26 I_fft_min = zeros(1,n_fft);
27
28 % Computation of the DFT on the different interval
29
30 for i=1:Nbr_intervalle
31     I_fft_resize(i,:)=abs(2*(fft(I(1,i*(a_sub)+(i-1)*(a1)+1:i*(
        a_sub)+i*a1),n_fft)))./n_fft;
32     U_fft_resize(i,:)=abs(2*(fft(U(1,i*(a_sub)+(i-1)*(a1)+1:i*(
        a_sub)+i*a1),n_fft)))./n_fft;
33 end
34
35 % For each harmonic, on each 200ms interval, takes the max,
   rms and min values
36
37 for j=1:n_fft
38     U_fft_max(1,j) = max(U_fft_resize(:,j));
39     I_fft_max(1,j) = max(I_fft_resize(:,j));
```

```

40
41     U_fft_min(1,j) = min(U_fft_resize(:,j));
42     I_fft_min(1,j) = min(I_fft_resize(:,j));
43
44     U_fft_RMS(1,j) = rms(U_fft_resize(:,j));
45     I_fft_RMS(1,j) = rms(I_fft_resize(:,j));
46 end
47
48 end

```

B.2 STFT-based method

B.2.1 Peak detector

```
1 function [Peak_value_v,Peak_value_i,f_peak] = peak_detection(I,V,fs)
2
3 % This program computes the spectrum of the voltage and the current
  according
4 % to the standard CISPR 16-2-1. This function takes as input
5 %           -V, I, the voltage and the current
6 %           -fs, the sampling frequency
7 % The program compute the STFT of the signal according to the
  standard
8 % parameter, and give as output
9 %           -Peak_value_v, Peak_value_i, the resulting peak
  harmonic for the voltage and the current
10 %           -f_peak, the frequency were the peak value were taken
  , to plot the final resulting
11
12
13 %% Declaration of the variable and set of the parameters
14
15     nfft = fs*20e-3;
16     wlen = 40e-3*fs; % Size of the window used for the STFT
17     hop = wlen/4; % Overlap of the window
18     [Sv, fv, t] = stft(V, wlen, hop, nfft, fs); %Computation of the
  STFT for the voltage
19     [Si, fi, t] = stft(I, wlen, hop, nfft, fs); %Computation of the
  STFT for the current
20     f=fv./1e3;
21     Sv = abs(Sv); % Module of the
  spectrum for the voltage
22     Si = abs(Si); % Module of the
  spectrum for the current
23
24 %% Peak detection for each harmonic calculated for all the duration
  of the signal
25
26 %Declaration of the variables
27
28     f_peak = 40:1:3000;
29
30     Peak_value_v = zeros(1,length(f_peak));
31     Average_value_v = zeros(1,length(f_peak));
32     RMS_value_v = zeros(1,length(f_peak));
33
34     Peak_value_i = zeros(1,length(f_peak));
35     Average_value_i = zeros(1,length(f_peak));
36     RMS_value_i = zeros(1,length(f_peak));
37
38 % Each max value, for each harmonics is taken, on all the time span
39
```

```

40     for i=1:length(f_peak)
41         Peak_value_v(1,i) = max(Sv(i+40,:));
42         Average_value_v(1,i) = mean(Sv(i+40,:));
43         RMS_value_v(1,i) = rms(Sv(i+40,:));
44
45         Peak_value_i(1,i) = max(Si(i+40,:));
46         Average_value_i(1,i) = mean(Si(i+40,:));
47         RMS_value_i(1,i) = rms(Si(i+40,:));
48     end
49
50 % Reshaping of the output variables , to put the results in db micro V
  /A
51
52     Peak_value_v = 20.*log10(Peak_value_v./1e-6);
53     Peak_value_i = 20.*log10(Peak_value_i./1e-6);
54
55 end

```

B.2.2 Quasi-peak detector (Simulink)

```
1 %Quasi-peak detector script
2 %*****
3 % This is the script used to compute the spectrum of signals using
   the
4 % quasi-peak model implemented on Simulink ("QPK.slx").
5 %
6 % The quasi-peak model takes as input
7 %   - The spectrum of the voltage or the current return by the STFT
8 %   - The frequency and time vector returned after the computation of
   the STFT
9 %
10 % As output, it gives a vector with the resulting spectrum after the
11 % quasi-peak detection in the variable "detect_result". The sizing of
12 % the different components use in the Simulink model
13 % (resistor, capacitor,...) is done with respect to the CISPR 16-2-1
   standard
14
15 % enable to clear the data and command window at the beginning of the
   simulation
16
17 clear all;close all;clc;
18
19 % Importation of the measured voltage or current from the CSV-file
20
21 value1 = csvread('mesure_CFL_18W.csv');
22
23 % Definition of the parameter based on the measures, the sampling
24 % frequency, the voltage, current, and time
25
26 fs = 1/2e-7;
27 Unom1 = value1(:,2)*500;
28 Inom1 = value1(:,3);
29 time1 = value1(:,1);
30
31 Ts = 1/fs;      % Sampling period [s]
32 fNy = fs / 2;  % Nyquist frequency [Hz]
33 duration = 1.5; % Duration [s]
34 t = 0 : Ts : duration-Ts; % Time vector
35 noSamples = length(t);    % Number of samples
36
37 % Parameter used by the STFT, the size of the FFT, the size of the
38 % time window,and the overlap of the window
39
40 nfft = fs*20e-3;
41 wlen = 40e-3*fs;
42 hop = wlen/4.1;
43
44 % Result of the STFT, the returned value are used by the Simulink
45 % model, the voltage or current spectrum is calculated, in this
46 % case, it is the current
```

```

47
48 [Si, fv, t] = stft(Inom1, wlen, hop, nfft, fs);
49 fv=fv/50;
50 Si = 20.*log10(Si/1e-6); % conversion in dB micro A
51
52 % Definition of the output variables
53
54 value = zeros(1,length(t));
55 detect_result = zeros(1,length(fv));
56
57 % Quasi-peak detection of the spectrum, the range of HARMONIC which
58 % will be considered by the model need to be specified, to speed up
59 % the execution of the program. The resulting spectrum at the end
60 % of the loop, is placed in the variable named "detect_result"
61
62 for i=1940:2100
63     value = Si(i,:);
64     sim('QPK');
65     detect_result(i+1) = max(result.signals.values);
66 end
67
68 % Graph part, which enables the user to check the resulting spectra
69 % after the quasi-peak
70
71 figure();
72 plot(fv*50/1e3, detect_result);
73 xlim([95 105]);
74 xlabel('Frequency [kHz]');
75 ylabel('Harmonic current [dB \mu A]');
76
77 figure();
78 plot(ScopeData.time, ScopeData.signals.values, '-b', result.time, result.
    signals.values, '-r');
79 legend('Input signal', 'Quasi-peak detector signal');
80 xlabel('time [s]');
81 ylabel('Signal [V]');

```

stft.m

```
1 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2 %                               Short-Time Fourier Transform           %
3 %                               with MATLAB Implementation             %
4 %                               %                                       %
5 % Author: M.Sc. Eng. Hristo Zhivomirov          12/21/13 %
6 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
7
8 function [stft , f , t] = stft(x, wlen, hop, nfft , fs)
9
10 % function: [stft , f , t] = stft(x, wlen, hop, nfft , fs)
11 % x – signal in the time domain
12 % wlen – length of the analysis Hamming window
13 % hop – hop size (overlap)
14 % nfft – number of FFT points
15 % fs – sampling frequency, Hz
16 % stft – STFT matrix (only unique points, time across columns, freq
    across rows)
17 % f – frequency vector, Hz
18 % t – time vector, s
19
20 % represent x as column-vector
21 x = x(:);
22
23 % length of the signal
24 xlen = length(x);
25
26 % form a periodic hamming window
27 win = hamming(wlen, 'periodic');
28
29 % stft matrix estimation and preallocation
30 rown = ceil((1+nfft)/2); % calculate the total number of
    rows
31 coln = 1+fix((xlen-wlen)/hop); % calculate the total number of
    columns
32 stft = zeros(rown, coln); % form the stft matrix
33
34 % initialize the signal time segment index
35 indx = 0;
36
37 % perform STFT
38 for col = 1:coln
39     % windowing
40     xw = x(indx+1:indx+wlen).*win;
41
42     % FFT
43     %X = abs(2.*(fft(xw, nfft))./nfft);
44     X = abs(2.*(fft(xw, nfft))./nfft);
45     %X = (X./max(X));
46
47     % update the stft matrix
```

```

48         stft(:, col) = X(1:rown);
49
50         % update the index
51         indx = indx + hop;
52     end
53
54     % calculate the time and frequency vectors
55     t = (wlen/2:hop:wlen/2+(coln-1)*hop)/fs;
56     f = (0:rown-1)*fs/nfft;
57
58 end

```

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