



## **Virtual FFT Analyser for identification of harmonics and inter-harmonics – metrological aspects**

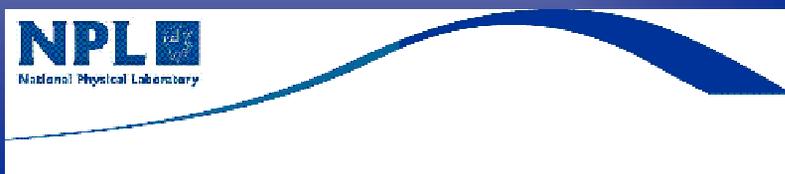
M. Jerzy Korczyński

Institute of Theoretical Electrotechnics, Metrology and Material Science, Metrology Group,  
Technical University of Lodz, ul. B. Stefanowskiego 18/22, 90-924 Lodz, Poland,

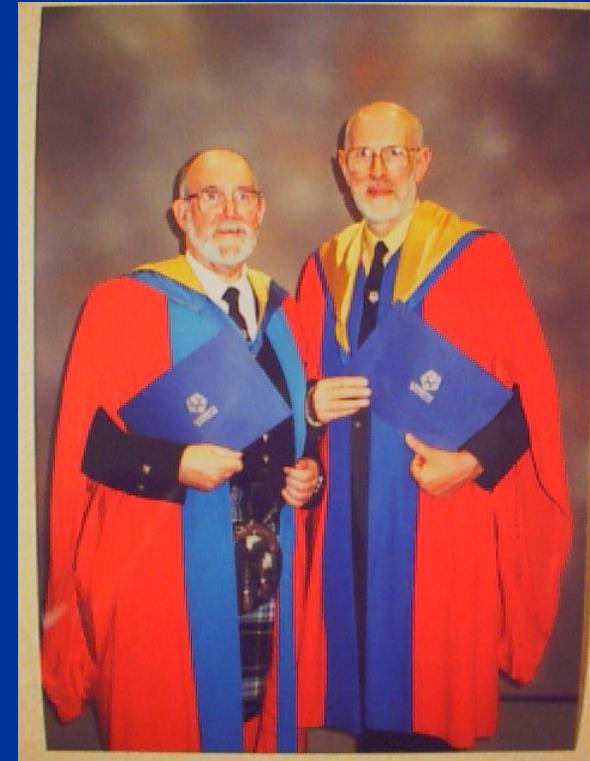
[jerzykor@ck-sg.p.lodz.pl](mailto:jerzykor@ck-sg.p.lodz.pl)



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# British connection



Joseph Mc Ghee & Ian Henderson



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Activities of M&I research group

---

---

## Research subjects:

- **Some aspects of quality of electrical power:**
  - **how to treat non-sinusoidal of current, voltage and as consequence - energy, which not only consists of active, reactive, apparent but one of the element is a deformation caused by harmonics. (DM – FFT, JTFT, modelling of signals)**
- **Virtual Instrumentation – development of new class of instruments**
- **Instrument calibration and traceability problems**
- **Software development supporting measurements**
- **Evaluation of uncertainties:**
  - **Approximation methods**
  - **Fast Fourier Transform based method**
  - **Monte Carlo Method**

## Teaching

- **concern all subjects related to Measurement and Instrumentation**



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Overview:

---

---

- **INTRODUCTION**
- **Why are we interested in sinusoidal voltage and current of electrical power supply and what is disturbing electrical power supply?**
- **Sources of disturbances in electrical power net - loads?**
- **Impact of harmonics and interharmonics on electrical devices**
- **Do really harmonics and interharmonics exist?**
- **Parameters describing signal distortion**
- **Standards related to identification of harmonic contents**
- **Grouping of harmonics and interharmonics**
- **200 ms window is a compromise - advantages and disadvantages of these 200ms window length transient states monitoring , sampling frequency requirements**
- **Uncertainties in grouping harmonics and interharmonic - how far can we be from the reality?**
- **Evaluation of uncertainties due to imperfection of probes, sensors, input transducers, analogue-to-digital converter**
- **How the uncertainty propagates through FFT procedure.**
- **Further work, foreseen development**



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

The logo for the National Physical Laboratory (NPL), featuring the letters 'NPL' in a bold, blue font with a small square icon to the right, and the text 'National Physical Laboratory' below it.

**NPL**  
National Physical Laboratory

# INTRODUCTION:

---

---

The considerations cover the area of applications which concern electrical power net low and high voltage :

current, voltage of 50 Hz ( 60 Hz) in consequence related power components and aggregated parameters , which characterise non-sinusoidal signals

The metrological consequences of imperfections of virtual analyser will be presented for modelling the real world in calculation of:

- Harmonic groups, interharmonic groups, harmonic subgroups and central interharmonic subgroups
- Electrical power measurement

How the compromised windowing of 200 effects measurement above parameters as it is a error due to applied methodology.



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

The logo for the National Physical Laboratory (NPL), consisting of the letters 'NPL' in a bold, blue, sans-serif font, with a small square icon to the right. Below the letters, the full name 'National Physical Laboratory' is written in a smaller, blue, sans-serif font.

**NPL**  
National Physical Laboratory

# Why sinusoidal voltage and current?

- **Ideal conditions for calculation of power consumption**  
(Reactive, active and apparent power) Otherwise we are faced with deformation power,  
No payment so far for deformation in voltage, current
- **All electrical data of electrical equipment are presented for sinusoidal voltage power supply.**
- **Some of instruments may fail if the voltage is too much distorted.**

**What is causing distortion of current and voltage consequently?**



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

**NPL**  
National Physical Laboratory



# Sources of harmonics and inter-harmonics

- **Power drives systems**
  - Cycloconverters
  - Power frequency converters (inverters)
- **Arc devices**
- **ferromagnetic devices (e.g. motors),**
  
- **fluorescent lamps,**
- **all office devices with rectifier at the input**
- **devices consuming power within a short period**

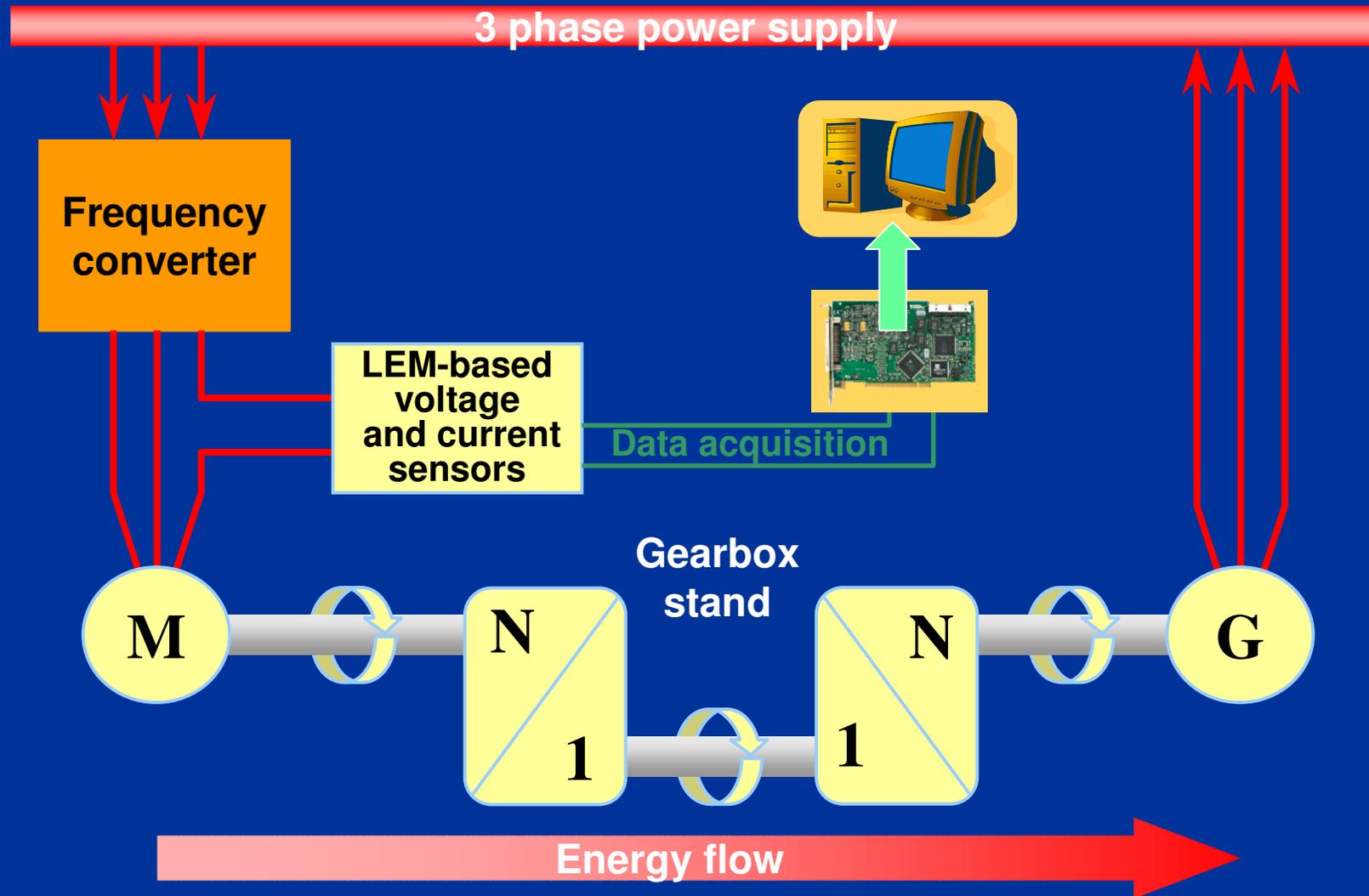
**Typical scheme for frequency converter causing current distortion and how to identify these distortions**



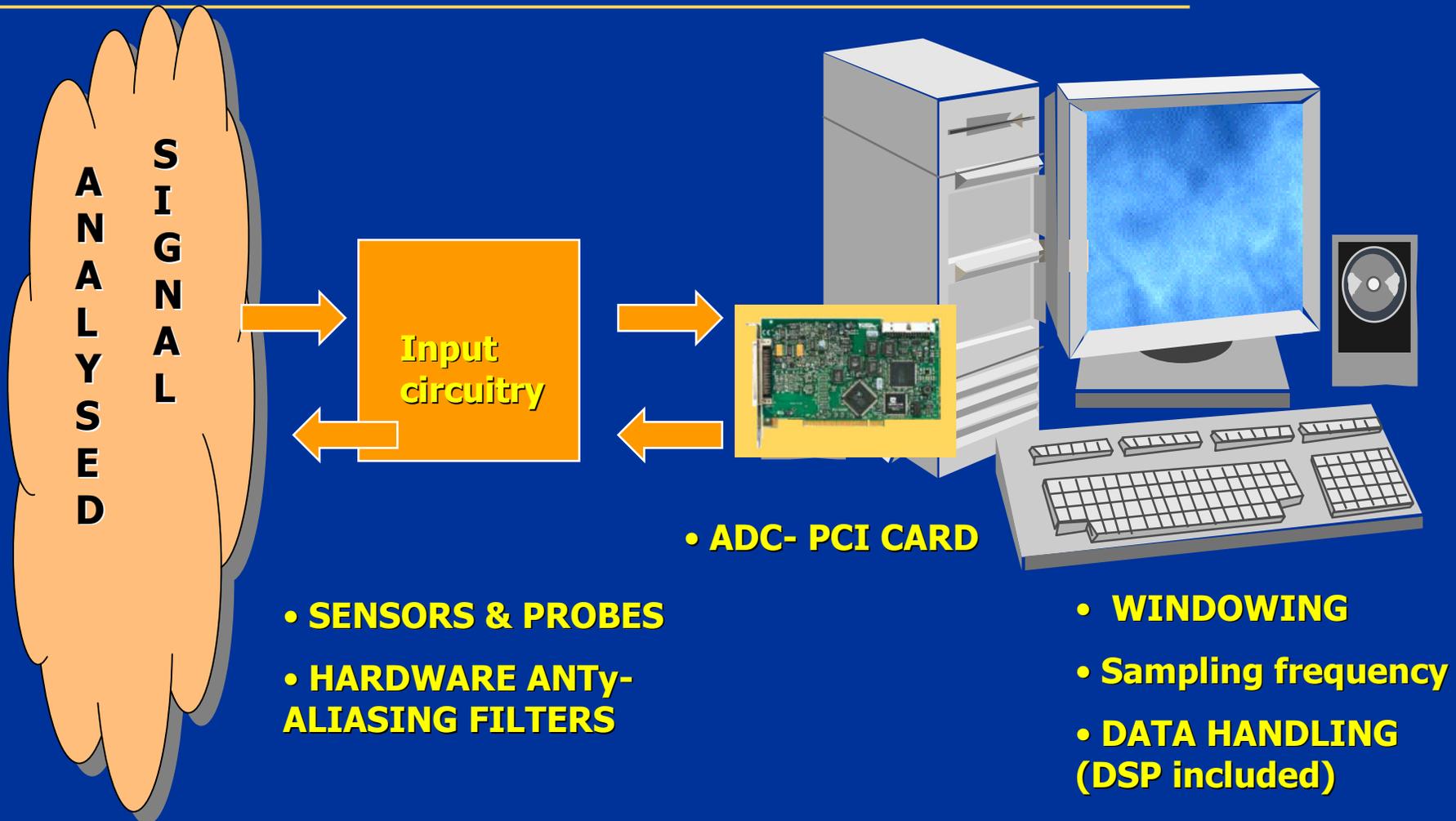
Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Source of distortions (transient states)



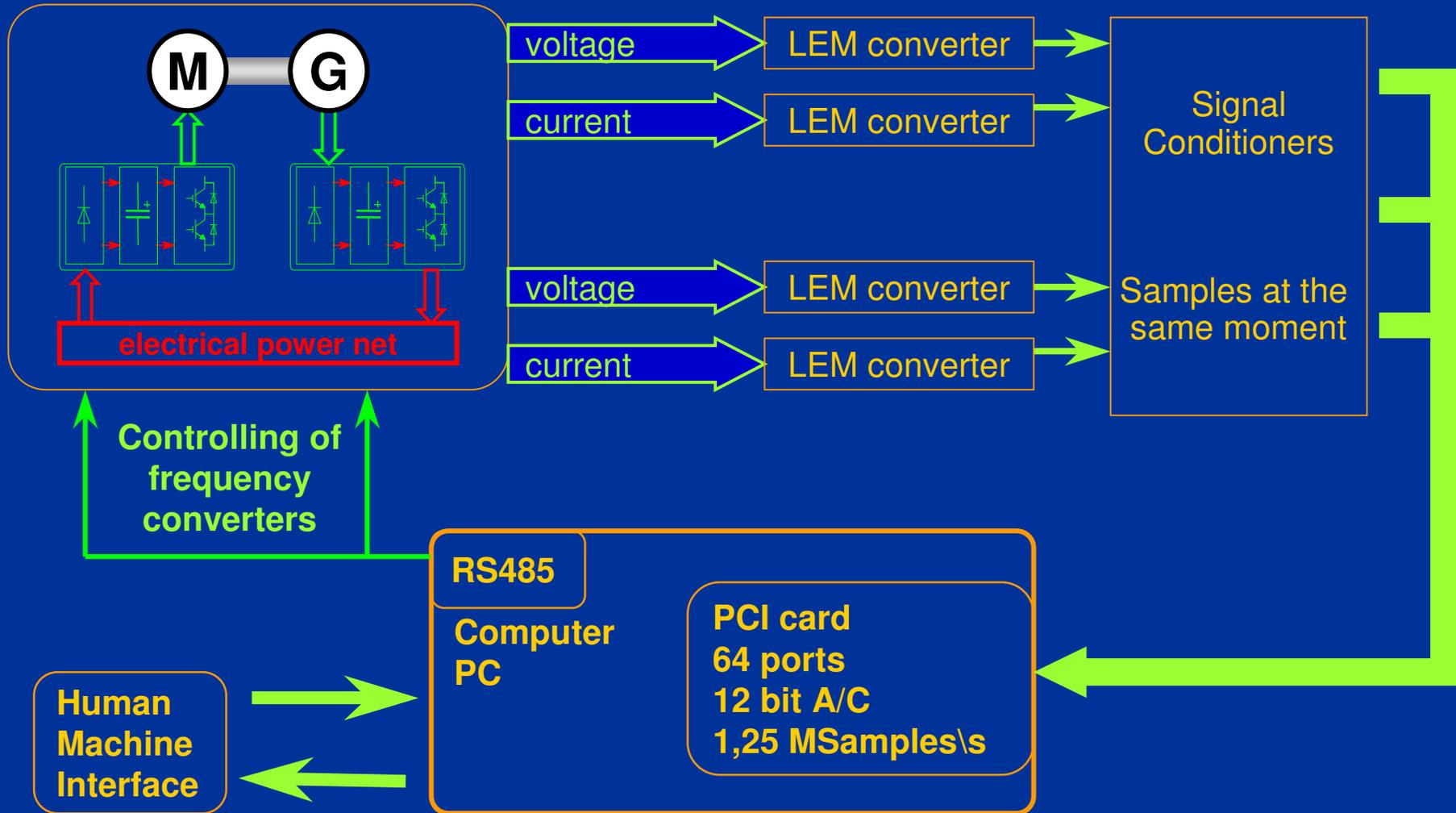
# Virtual Instrument to calculate harmonics



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Circuitry for steady or transient state analysis



# Taxonomy of applied to harmonics (50 Hz)

**Higher harmonics whose frequencies are integer multiples of fundamental frequency**

**Interharmonics harmonics whose frequencies are non-integer multiples of fundamental frequency and**

**Sub-harmonics - harmonics non whose frequencies are below the fundamental frequency**

**Steady state, quasi-stationary state and rapidly change states.**

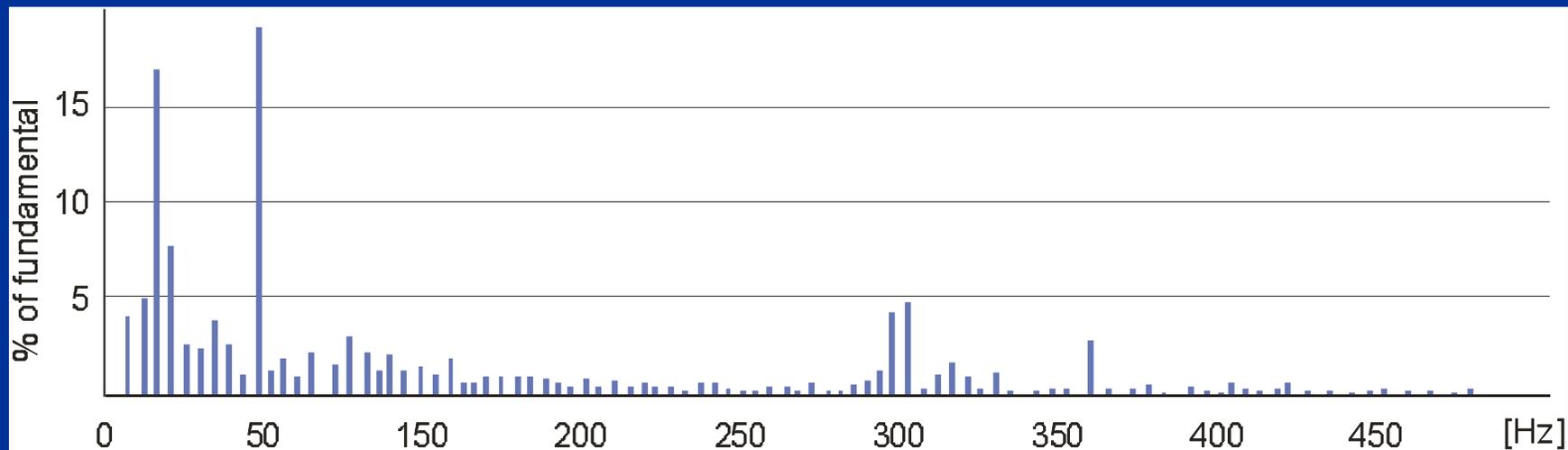
$$f_n = n * f_1$$



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



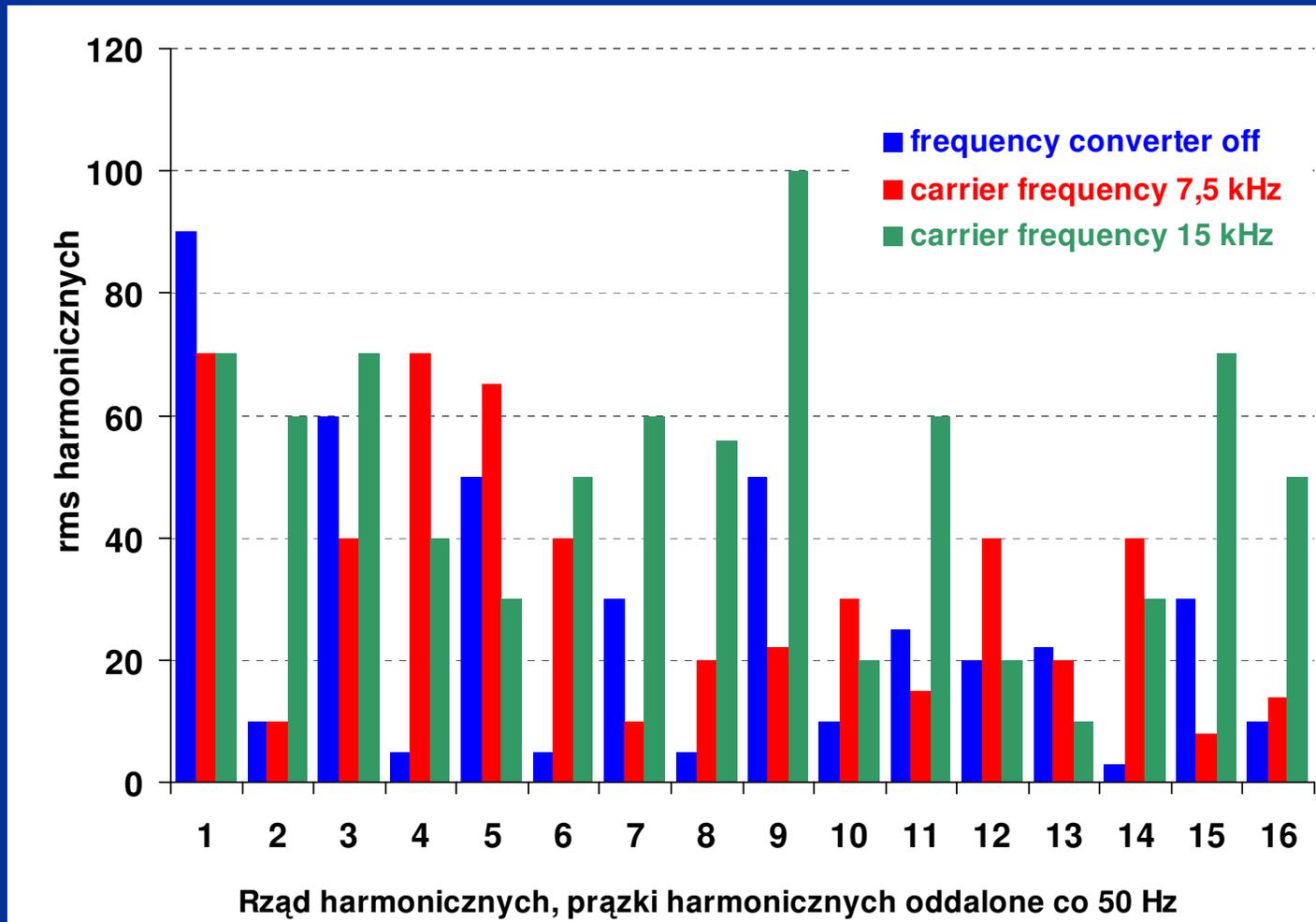
# Harmonics and interharmonics in real world



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



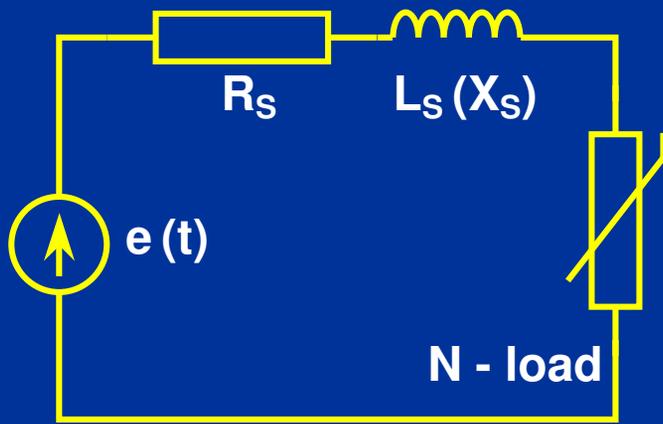
# Example of harmonic contents



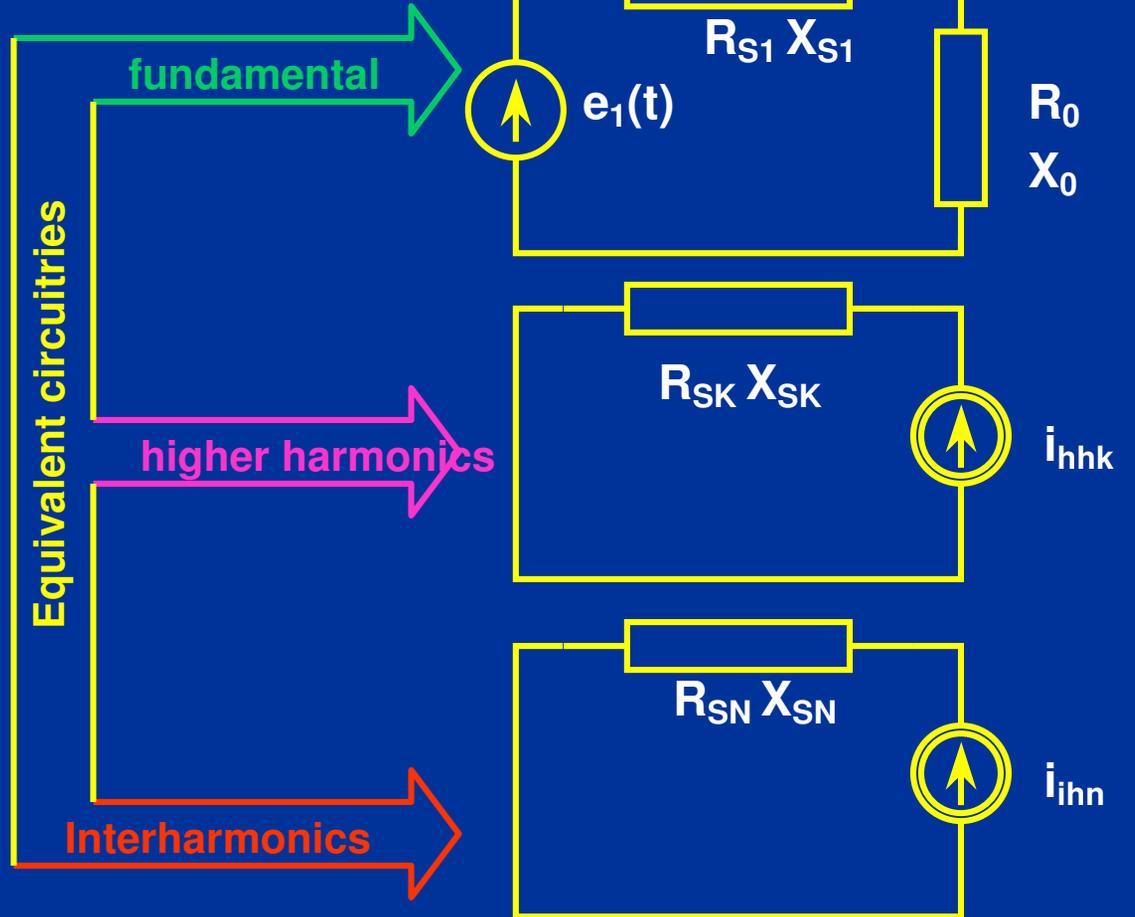
Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# FIZYCZNY MODEL ODBIORNIKA NIELINIOWEGO



Non linear load



# Measurement chain

**Data acquisition:  
sampling frequency  
and windowing**



**Fast Fourier Transform  
FFT**

**Harmonic spectrum  
(harmonics and interharmonics)**



**Grouping of  
harmonics and  
interharmonics**



**Aggregated parameters**



**Active electrical power**



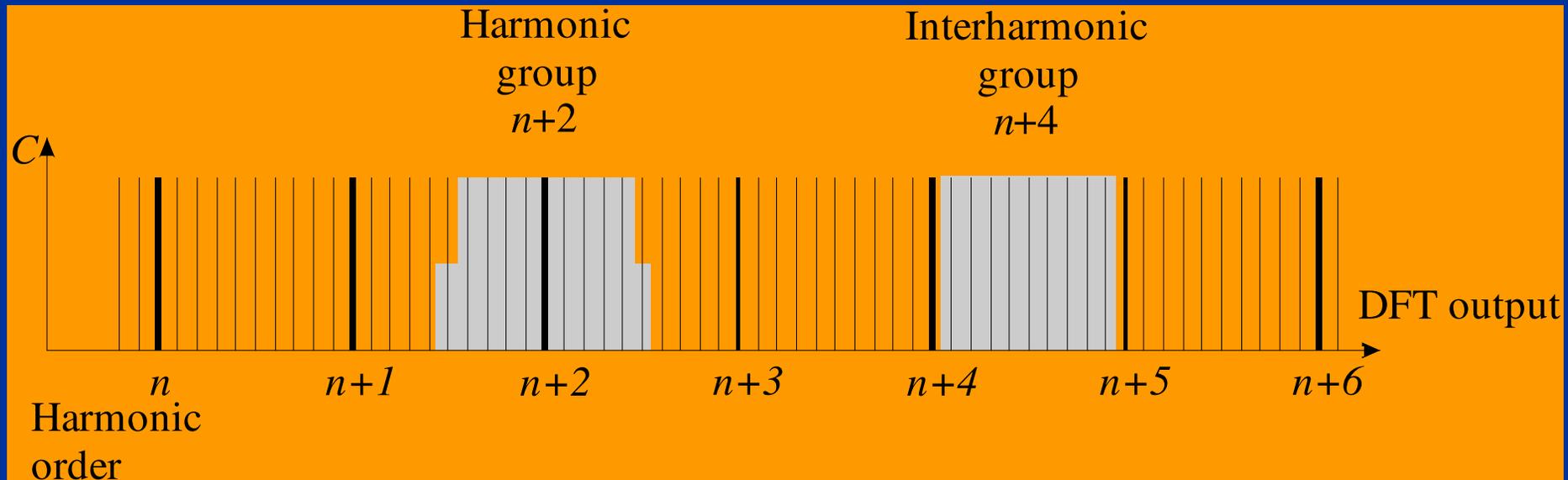
# Permissible errors of instruments

Class	Quantity	Range	Max permissible error
I	Voltage	$U_m \geq 1\%U_n$	$\pm 5\%U_m$
		$U_m < 1\%U_n$	$\pm 0,05\%U_n$
	Current	$I_m < 3\%I_n$	$\pm 5\%I_m$
$I_m \geq 3\%I_n$		$\pm 0,15\%I_n$	
Power	$P_m \geq 150W$	$\pm 1,5W$	
	$P_m < 150W$	$\pm 1\%P_n$	



# Harmonic Group and interharmonic group

r.m.s values of Harmonic Group and Interharmonic Group



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

Harmonic Group

$$G_{ig,n}^2 = \sum_{i=1}^9 C_{k+i}^2$$

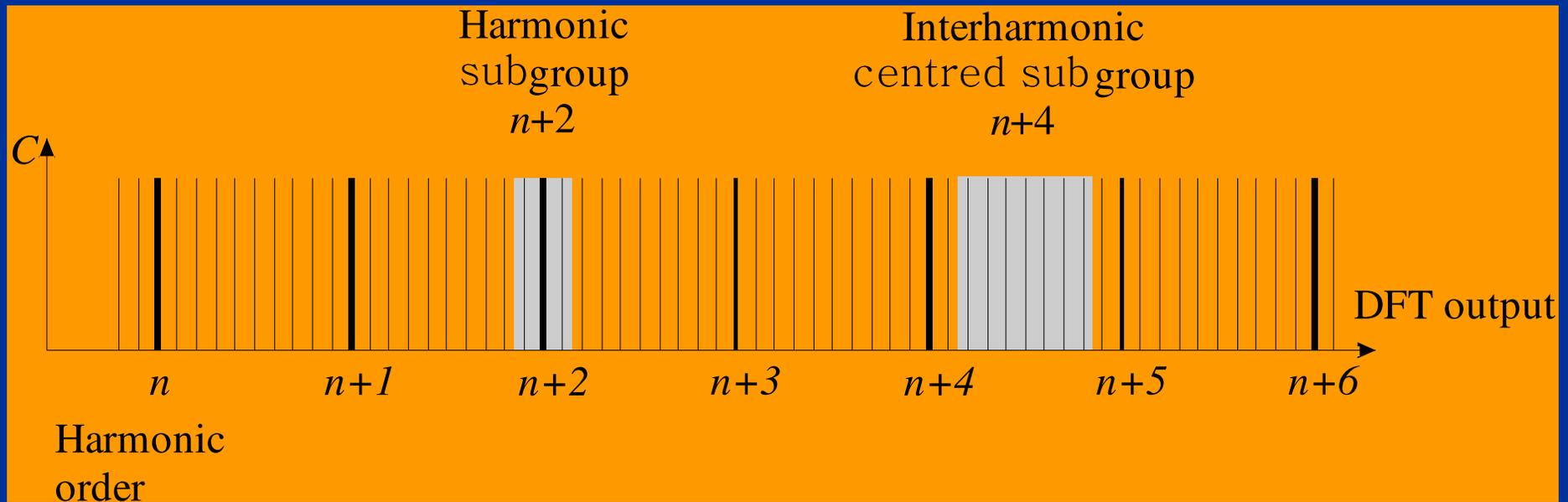
Interharmonic Group



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Grouping harmonics and interharmonics



$$G_{sg,n}^2 = \sum_{i=-1}^1 C_{k+i}^2$$

Harmonic subgroup

$$G_{isg,n}^2 = \sum_{i=2}^8 C_{k+i}^2$$

Interharmonic centered subgroup



# Aggregated parameters of non-sinusoidal signals

According to IEC 61000- series -

Measuring window - 200ms so 5 Hz resolution is assumed

$$THD = \sqrt{\sum_{n=2}^H \left( \frac{G_n}{G_1} \right)^2}$$

**Total Harmonic Distortion**

$$THDG = \sqrt{\sum_{n=2}^H \left( \frac{G_{gn}}{G_{g1}} \right)^2}$$

**Group Total Harmonic Distortion**

$$THDS = \sqrt{\sum_{n=2}^H \left( \frac{G_{sgn}}{G_{sg1}} \right)^2}$$

**Subgroup Total Harmonic Distortion**

$$PWHD = \sqrt{\sum_{n=H_{\min}}^{H_{\max}} n \left( \frac{G_n}{G_1} \right)^2}$$

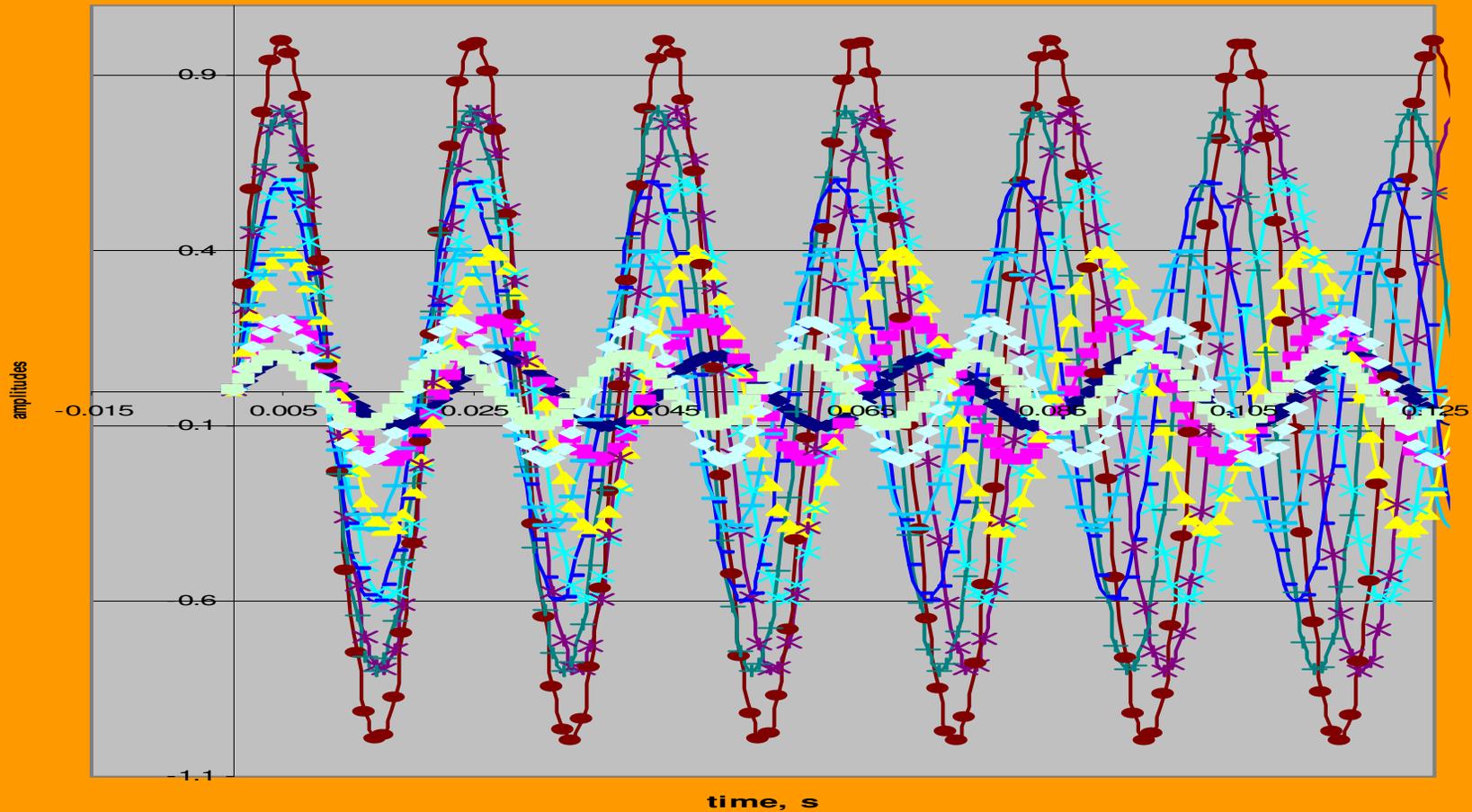
**Partial Weighted Harmonic Distortion**



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



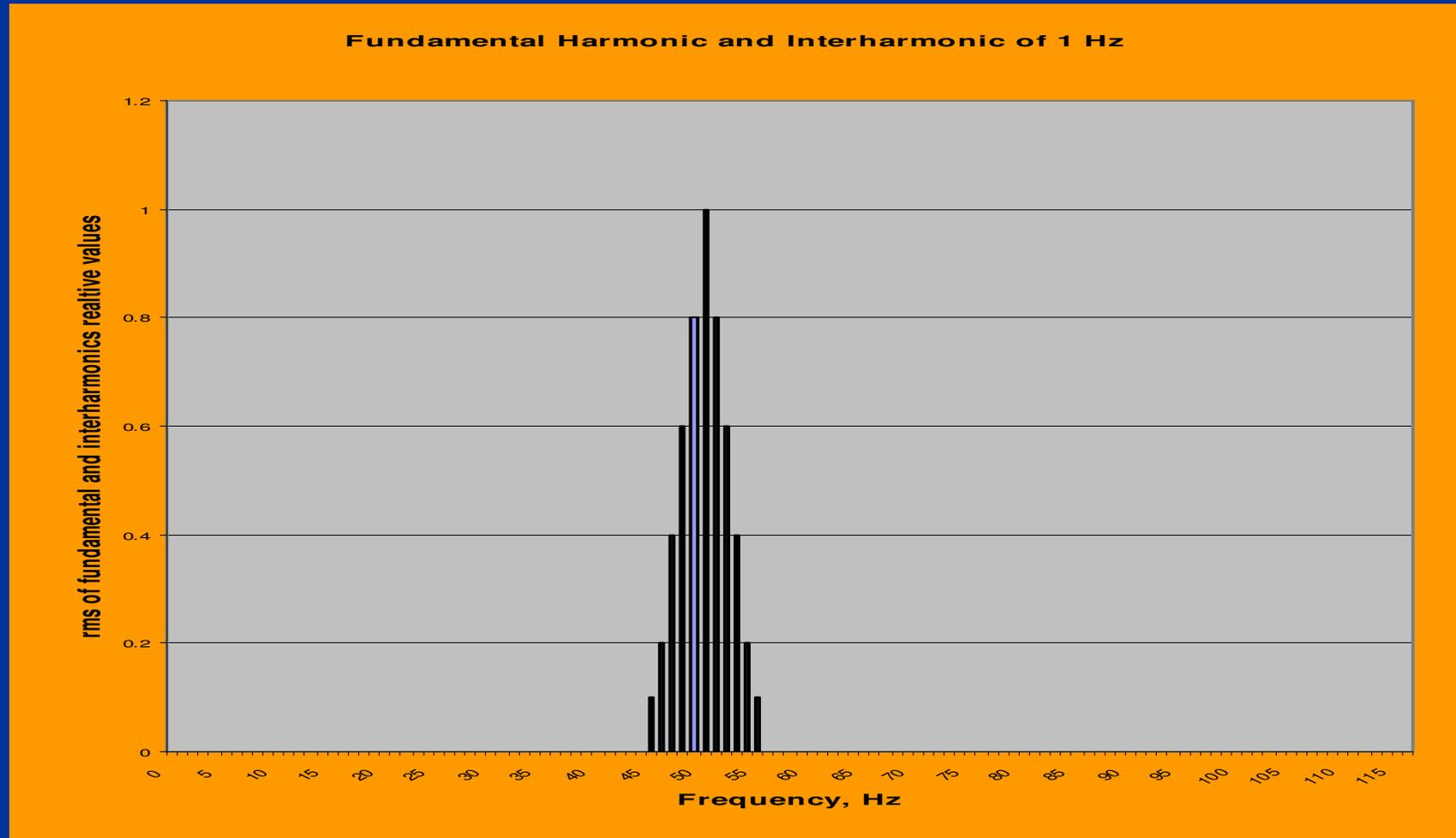
# Calculation Example



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

**NPL**  
National Physical Laboratory

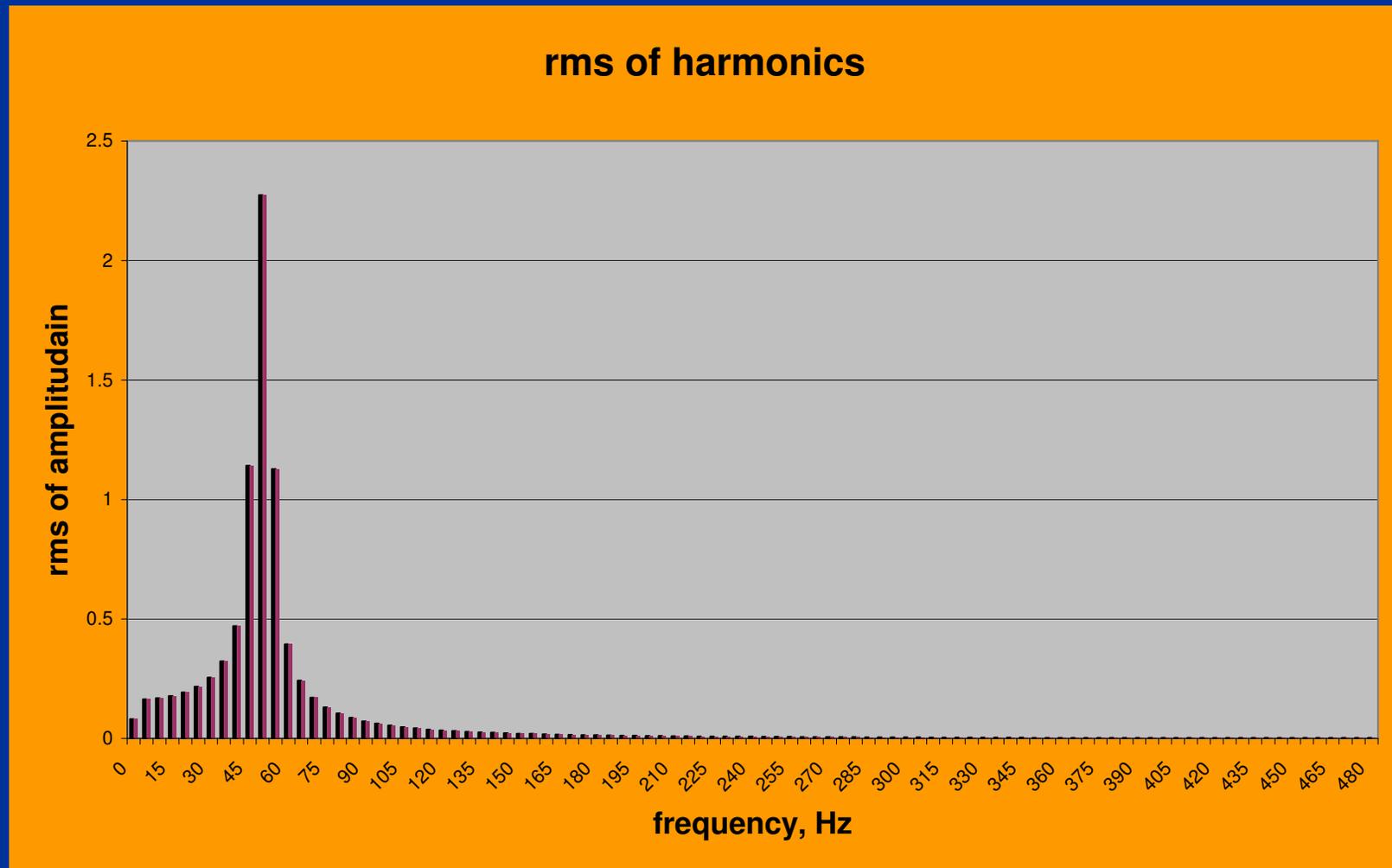
# Harmonic Content window of 1 s



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



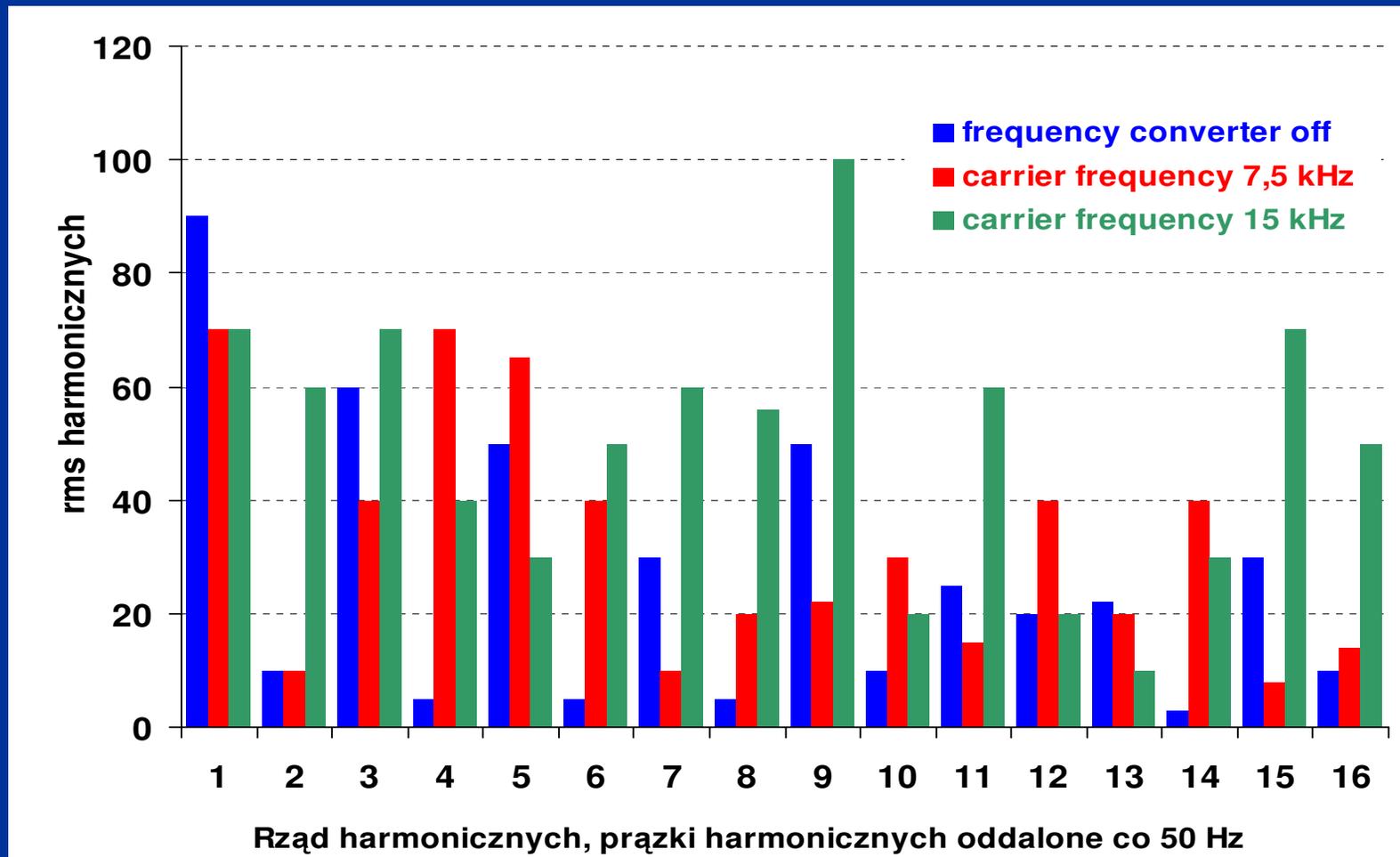
# Harmonic Content window, 0.2 s



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Real example



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

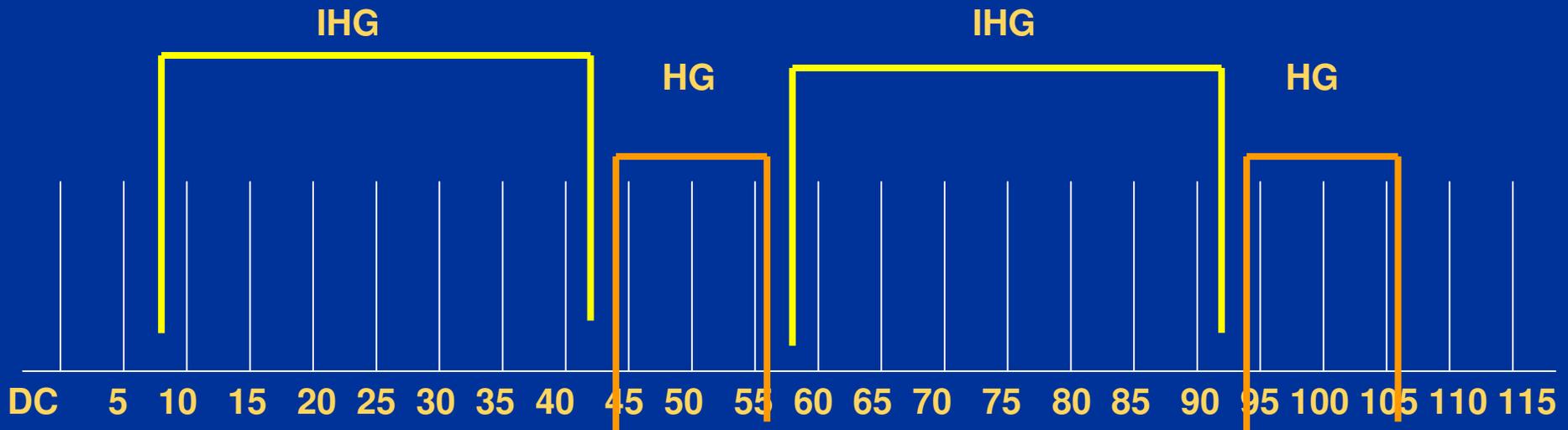


# Example of calculating aggregated and their errors

	True value	True aggregated value	Measured value using window 200 ms	Aggregated measured value	ERROR
Fundamental harmonic	1	1	2.273605	1	127 %
Harmonic group	2.26084788	2.26084788	2.900024	2.900024	28,27 %
Interharmonic group	1.1	0.044537	1.365289	1.853664	19,15 %
	1.1		1.2490059		
	brak		0.100275		
Harmonic subgroup	1.50996689	1.50996689	2.782949	2.784859	84.43 %
	brak		0.095122		
	brak		0.03517		
	brak		0.018689		
Interharmonic cantered subgroup	0.75498344	1.067708	0.730599	0.909296	-14.86 %
	0.754983444		0.5331251		
			0.085557		
			0.038756		

# Definition of Total Harmonic and Inter-harmonic Distortions and numerical example

$$TH \& IHD = \sqrt{\sum (HG)^2 + \sum (IHG)^2}$$



$$TH \& IHD_{ERROR\_rel} = \frac{TH \& IHD - TH \& IHD\_ref}{TH \& IHD\_ref}$$



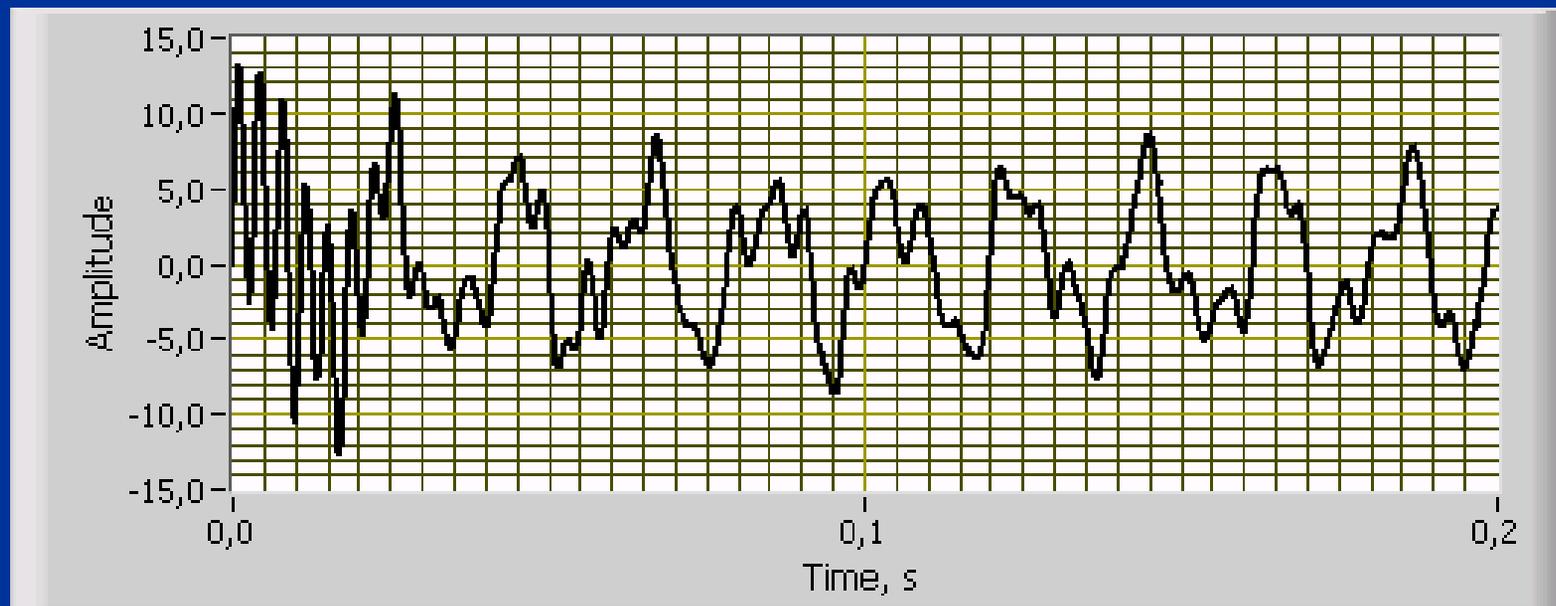
# Numerical example for arbitrary chosen signal

Fundamental frequency is 50 Hz, of amplitude of 5 units, and:

92 Hz of amplitude 2 units,

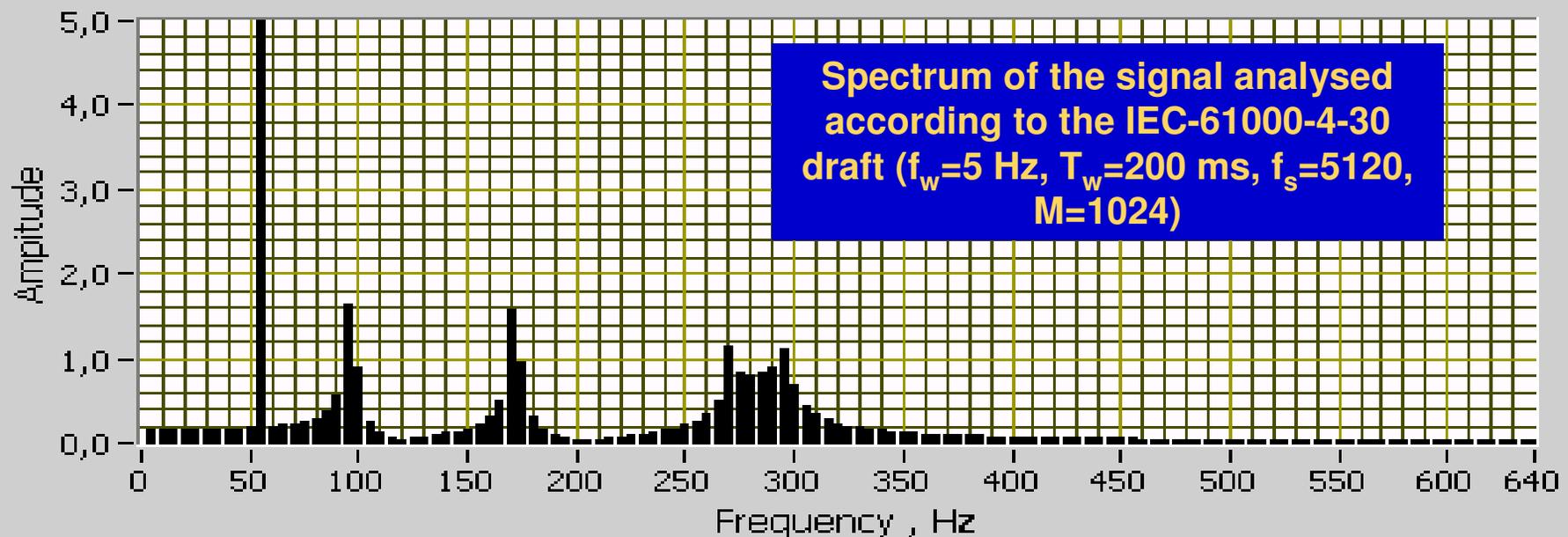
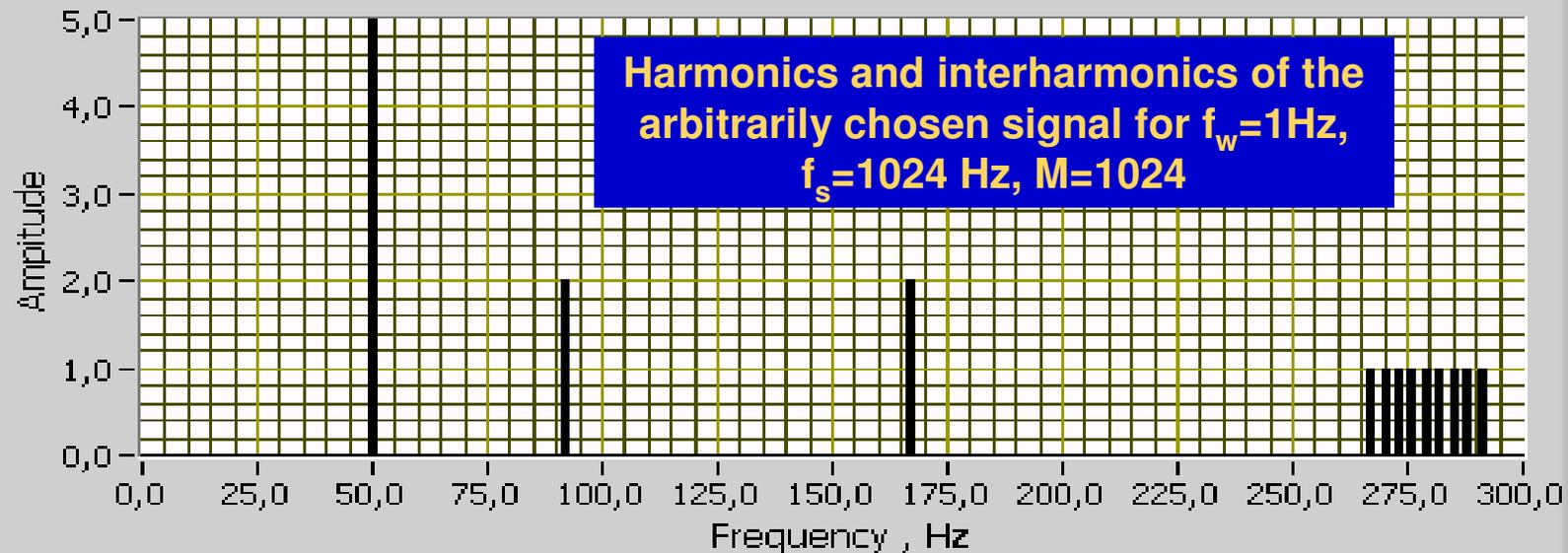
167 Hz of amplitude 2 units and frequencies:

267 Hz, 270 Hz, 273 Hz, 276 Hz, 279 Hz, 282 Hz, 285 Hz, 288 Hz, 291 Hz each of amplitude of 1

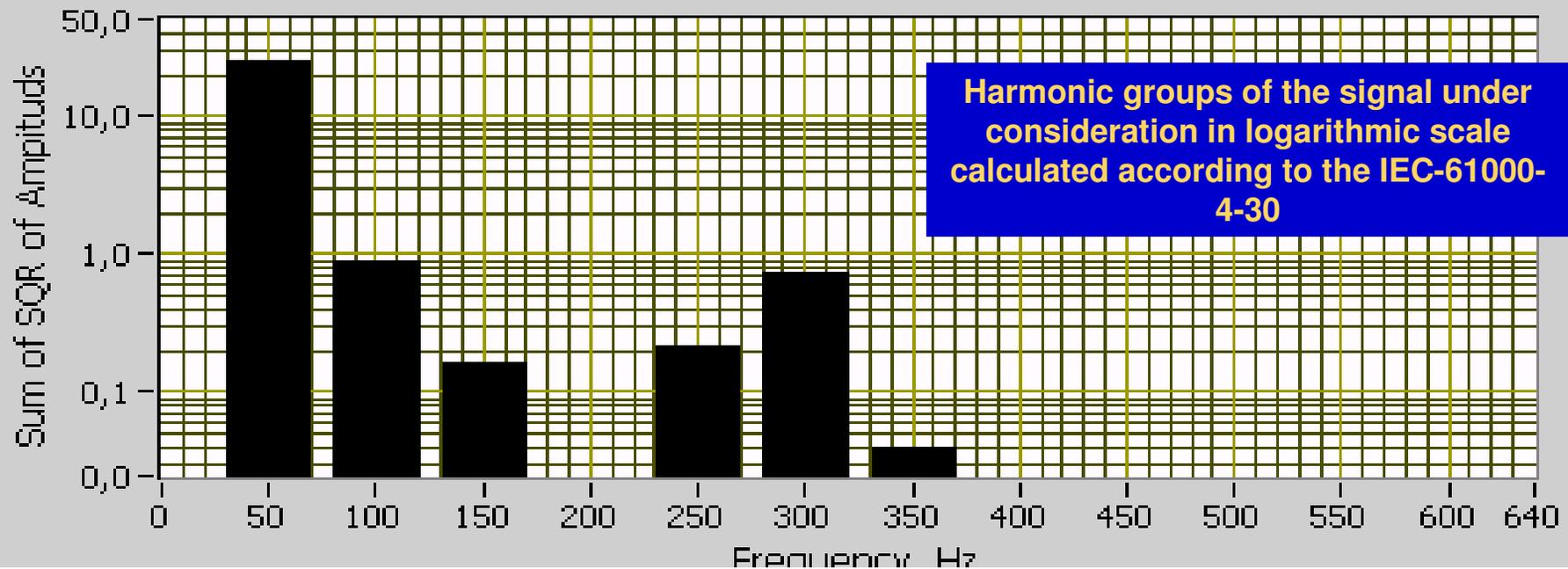
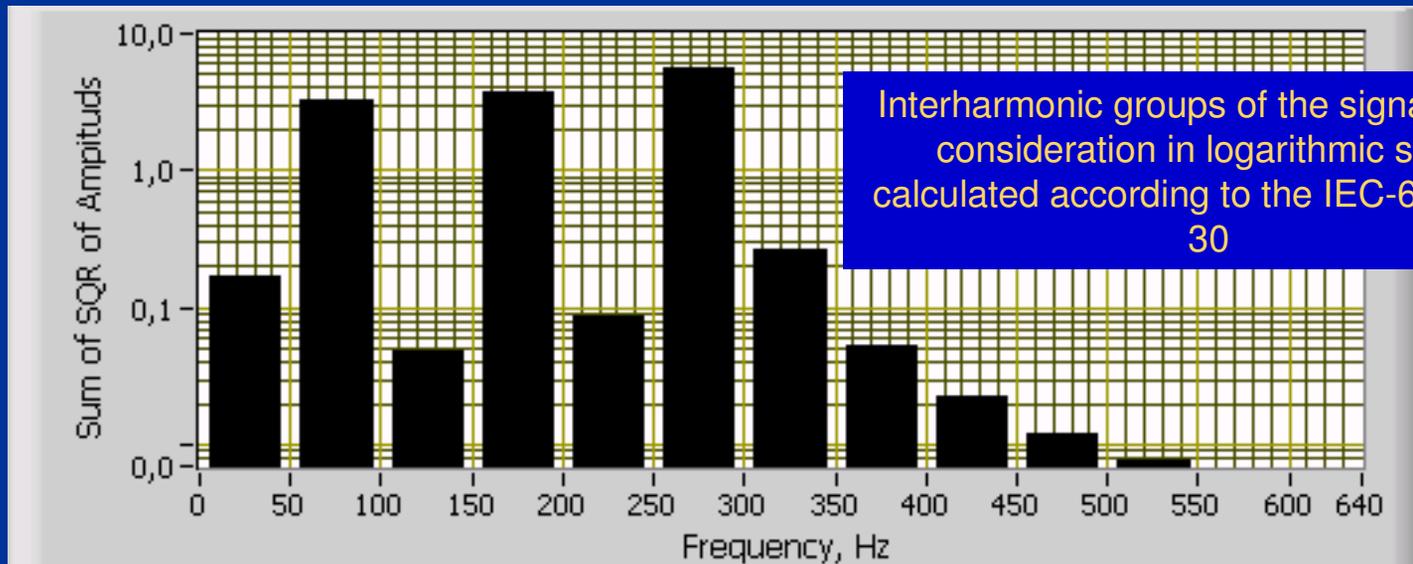


Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

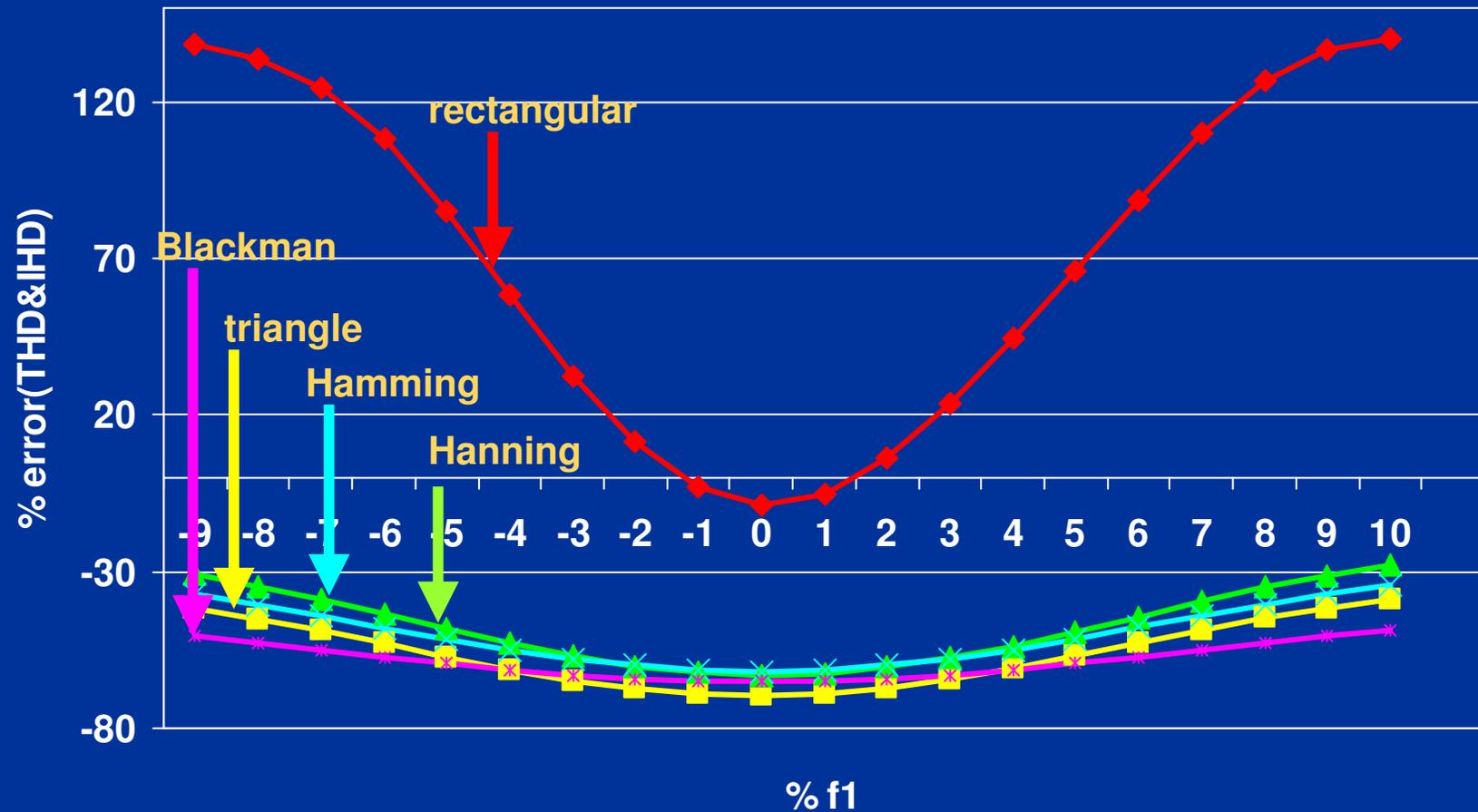
# Ideal FFT of 1 Hz as needed and 5 Hz resolution



# Inter and Harmonic Grouping IHG & HG



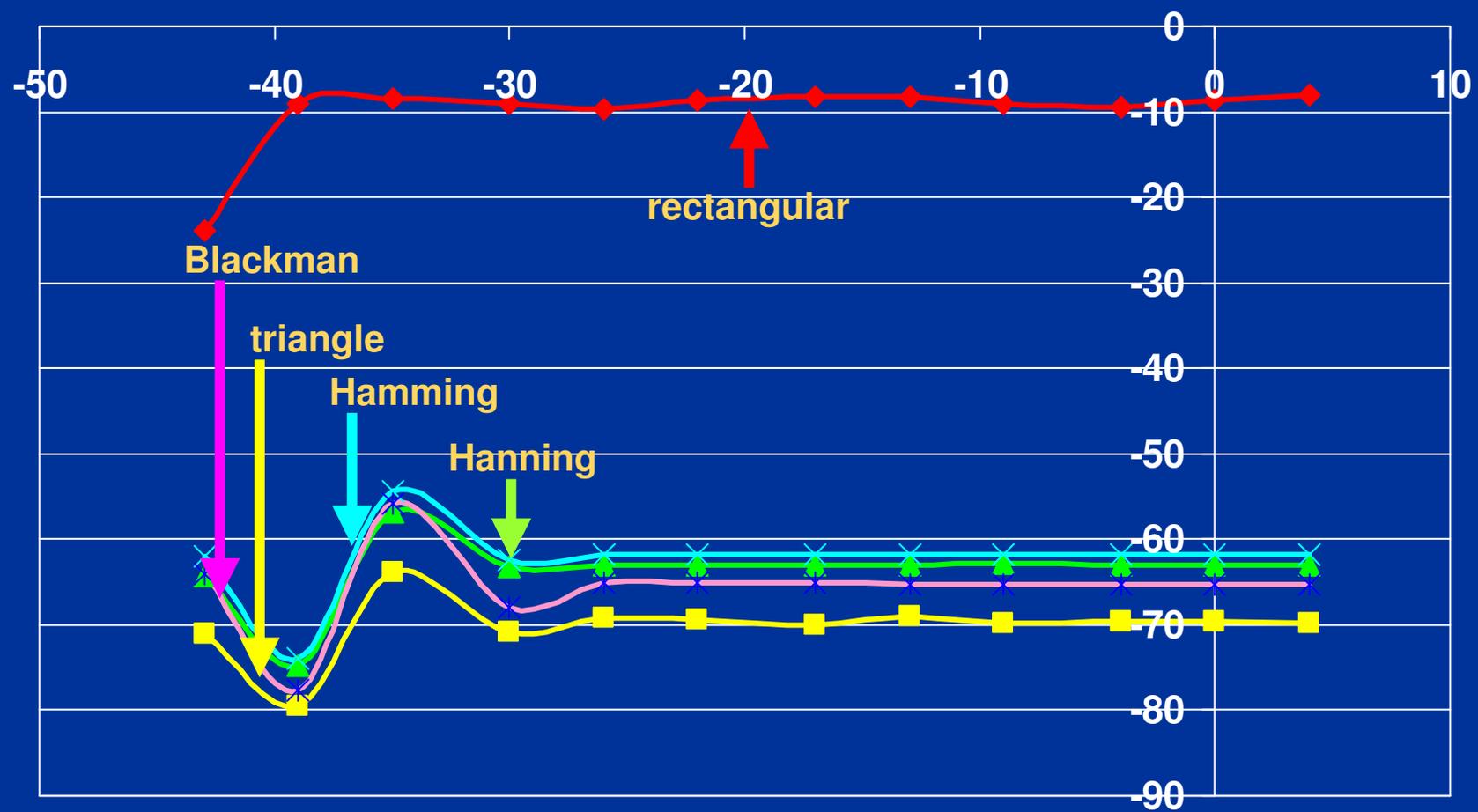
# TH&IH<sub>ERROR\_rel</sub> vs. variation of the fundamental



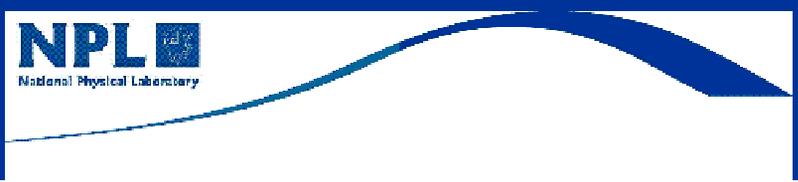
Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



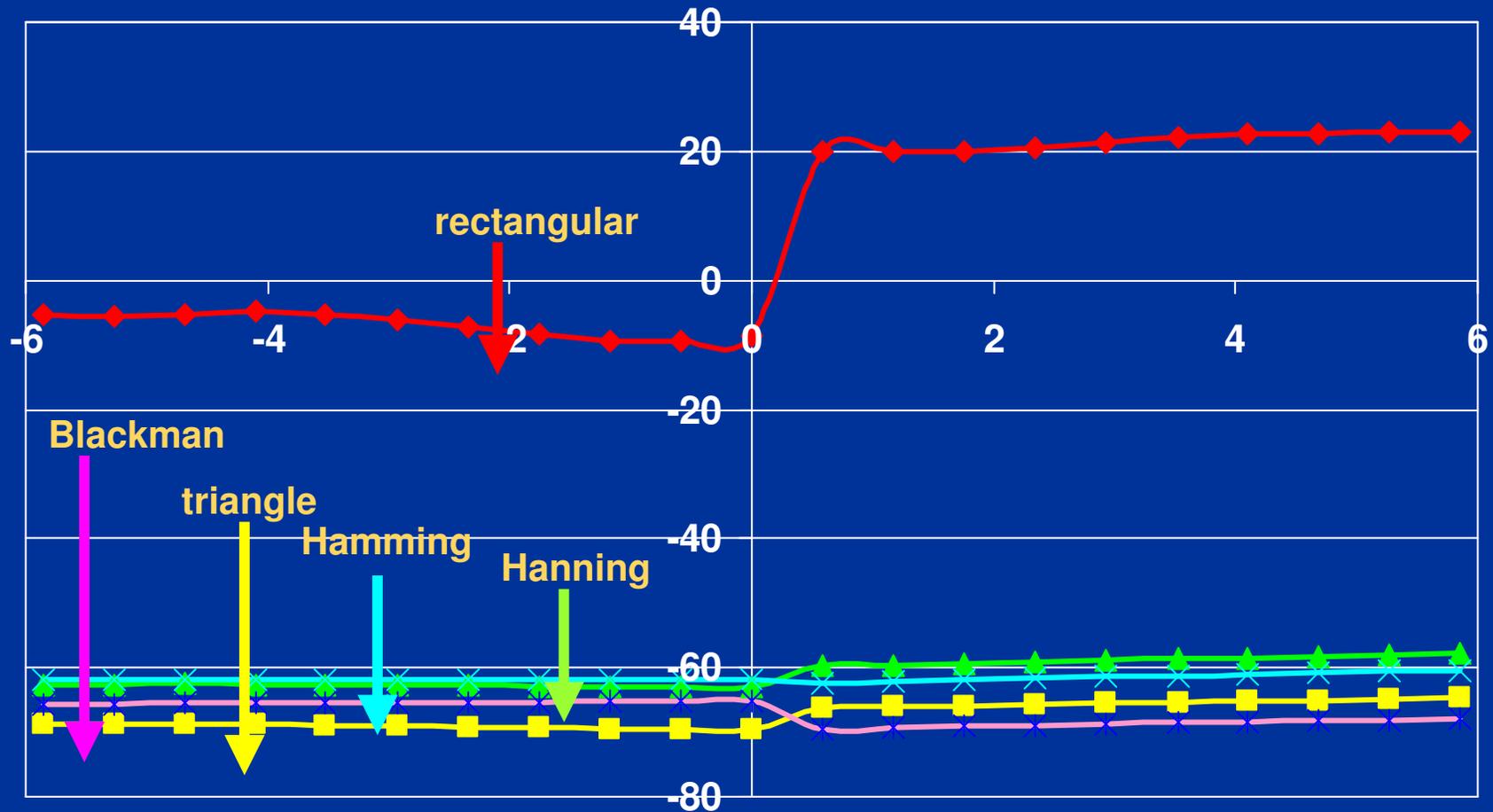
# TH&I<sub>ERROR\_rel</sub> vs. variation of a single interharmonic frequency



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# TH&IH $ERROR_{rel}$ vs. variation of percentage of missing samples



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Conclusion from example

---

---

Defined TH&IHD parameter is a aggregated parameter which can be used for characterising of distortion in electrical power voltage and current, can be used to billing consumers for distortion of electrical power.

The analysis of arbitrary chosen signals depicts that the rectangular window is most adequate but also most sensitive to variations of tested parameters. By applying the windows, the sensitivity is reduced significantly, but a displacement is observed. The displacement has a systematic character, hence it may be corrected.



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

The logo for the National Physical Laboratory (NPL), featuring the letters 'NPL' in a bold, blue font with a small square icon to the right, and the text 'National Physical Laboratory' below it.

**NPL**  
National Physical Laboratory

# Evaluation of uncertainties ....

---

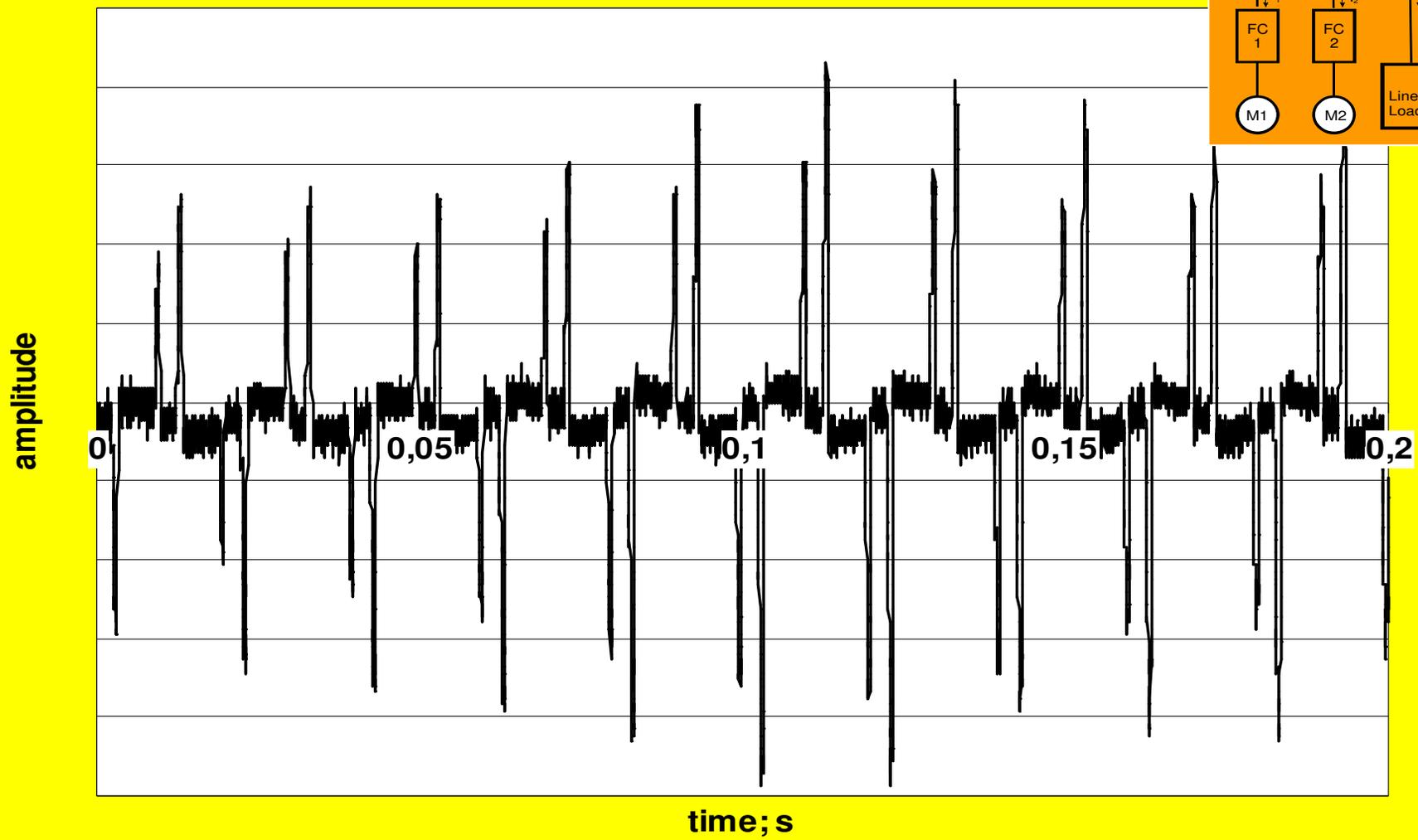
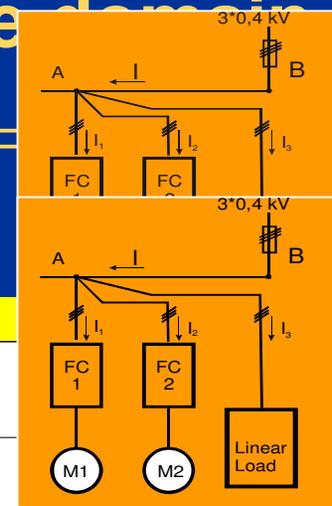
---



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Evaluation of uncertainties - current in time domain 34



# Input samples, their imperfection

---

---

**Input samples, their imperfection – probability distribution functions of every input data**

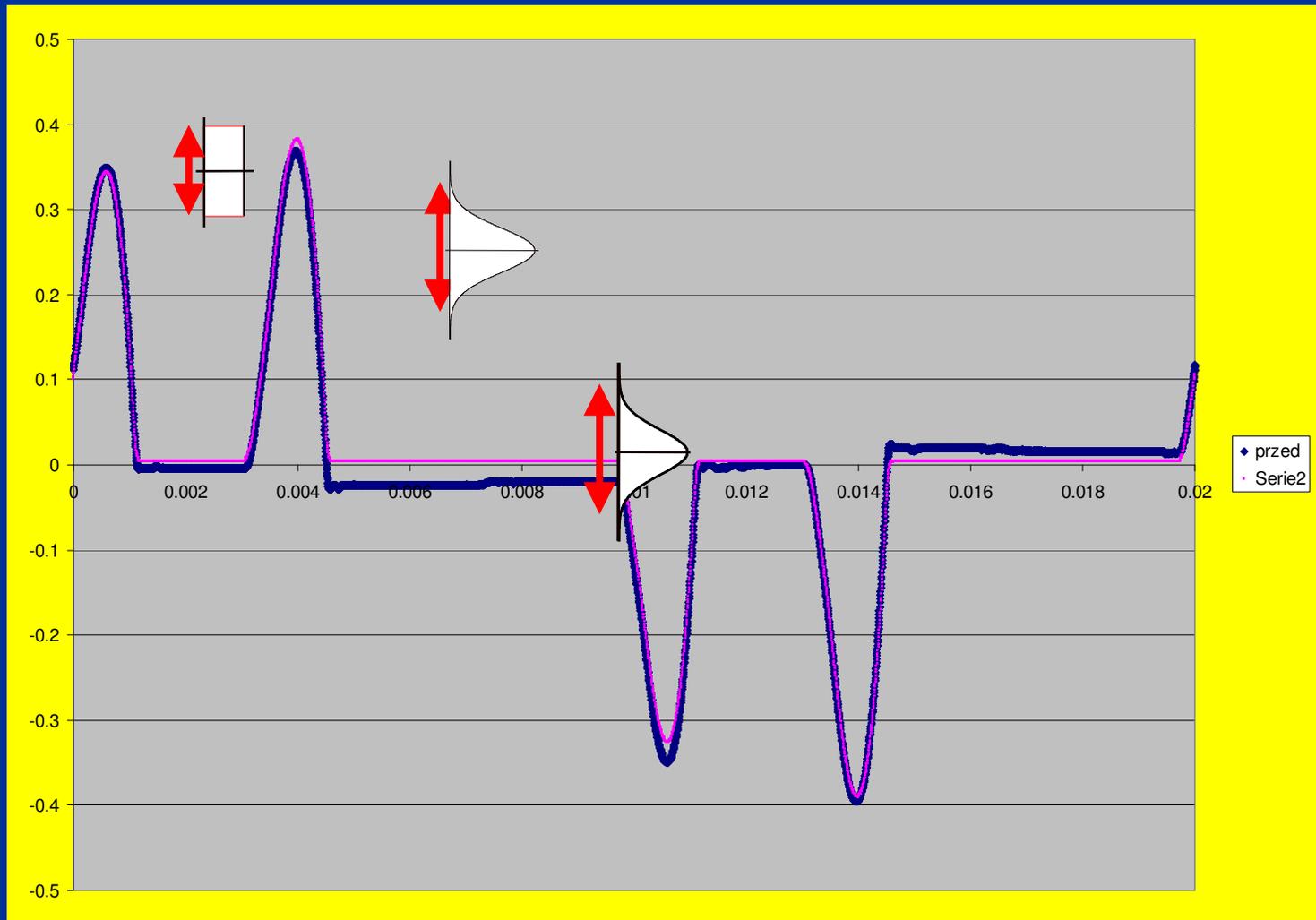
- 1. All sensors: current and voltage transformers**
- 2. ADC converters (gain offset and quantisation)**
- 3. and what left - FFT**



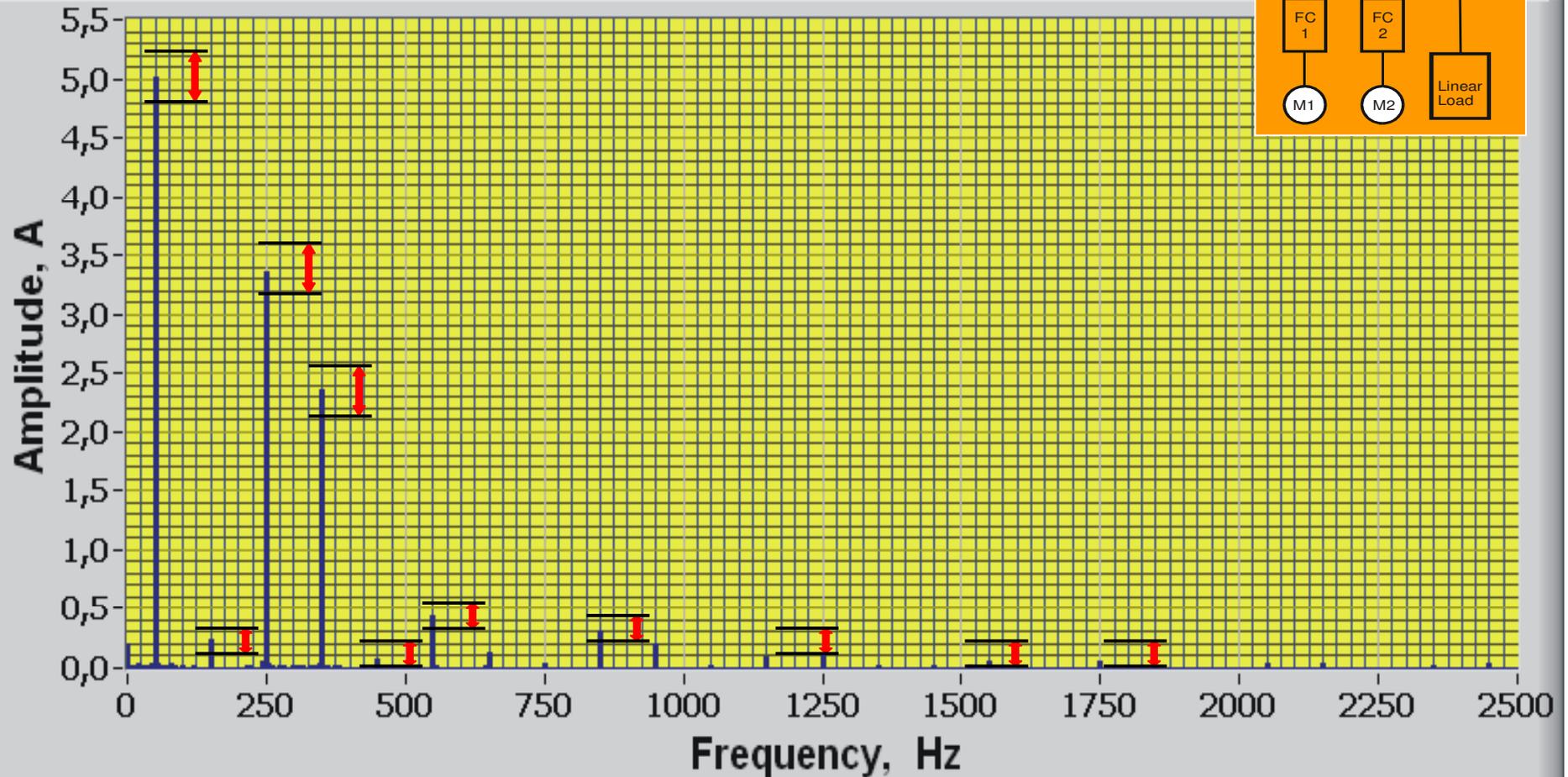
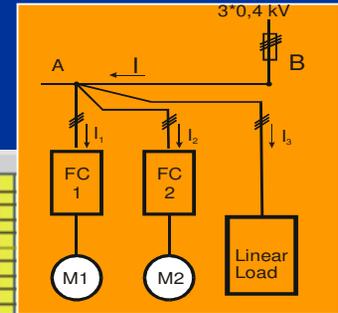
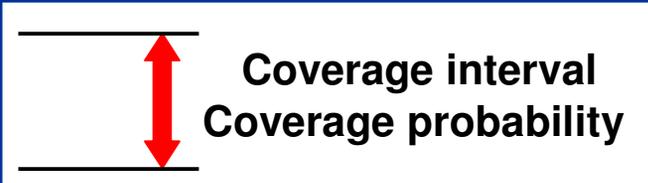
Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Evaluation of uncertainties - current in time domain



# Evaluation of uncertainties - Harmonic content



# Distribution of uncertainties through FFT procedure

FFT algorithm - very well known, but the problem of calculation of uncertainties in harmonic contents is a problem

What methods can be used?

Calculation of standard uncertainty – for type A and B? - discrete model is measurement equation - and k-factor?

1. Application of Law of Propagation of Uncertainty through measurement model to calculate uncertainties - Monte Carlo Method ?

Disadvantages and advantages

Two components were distinguished in input sampled data.

The uniform distribution of errors and Normal and combing

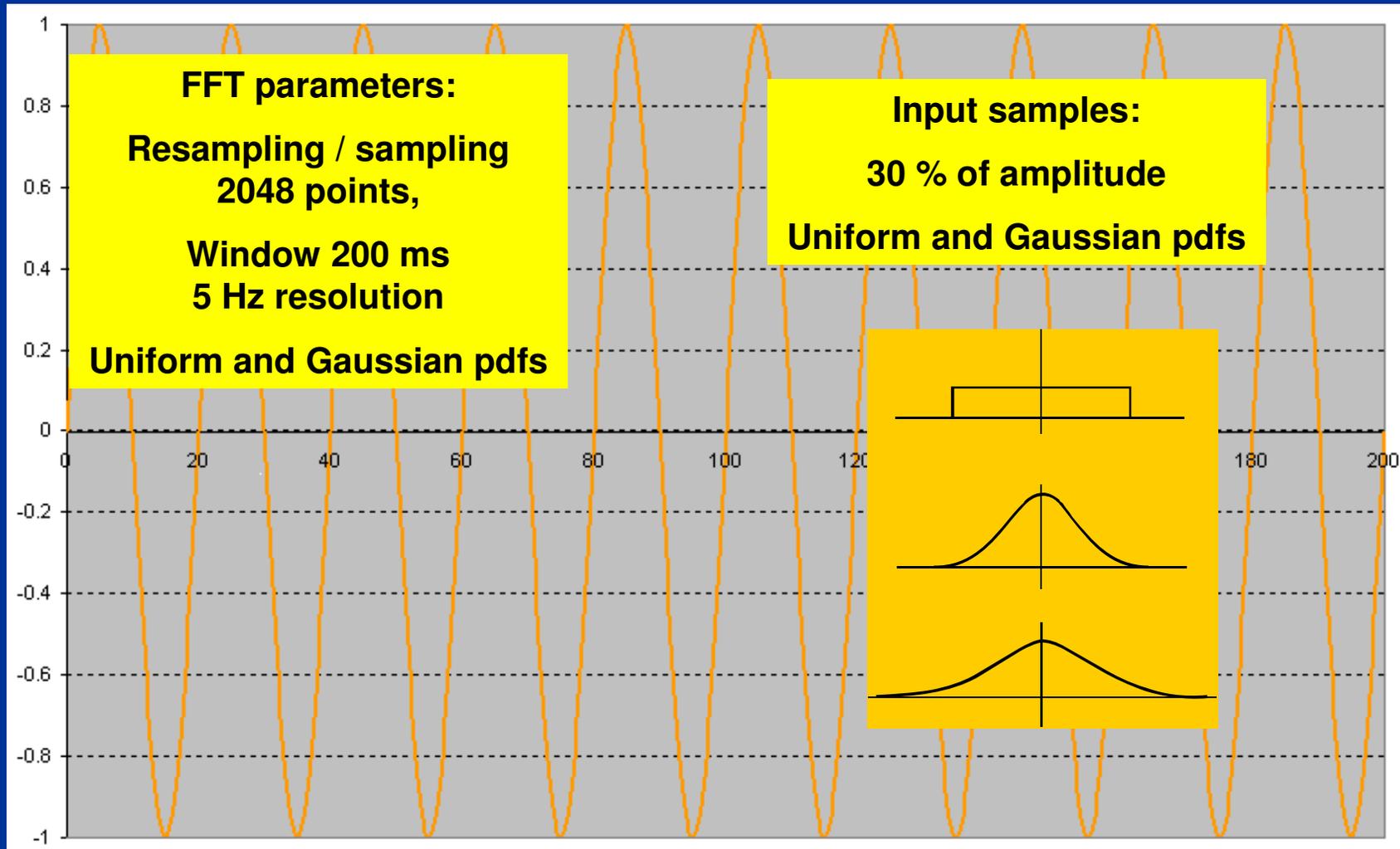
- Type A and type B
- How it propagate through the digital calculation process.



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

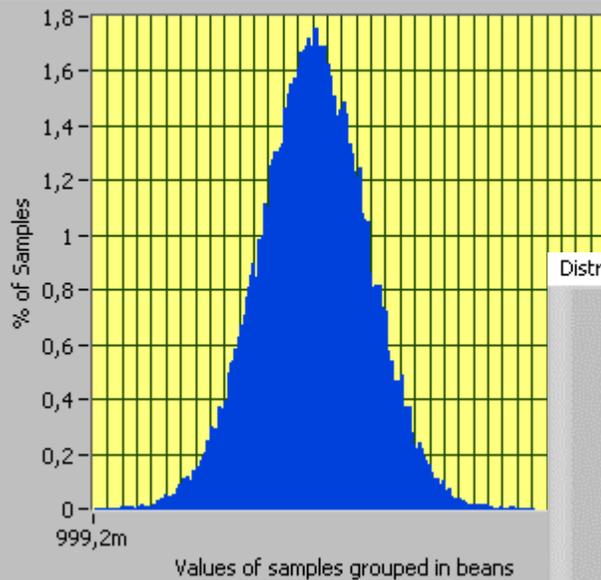


# What kind of signal was tested under MC method?

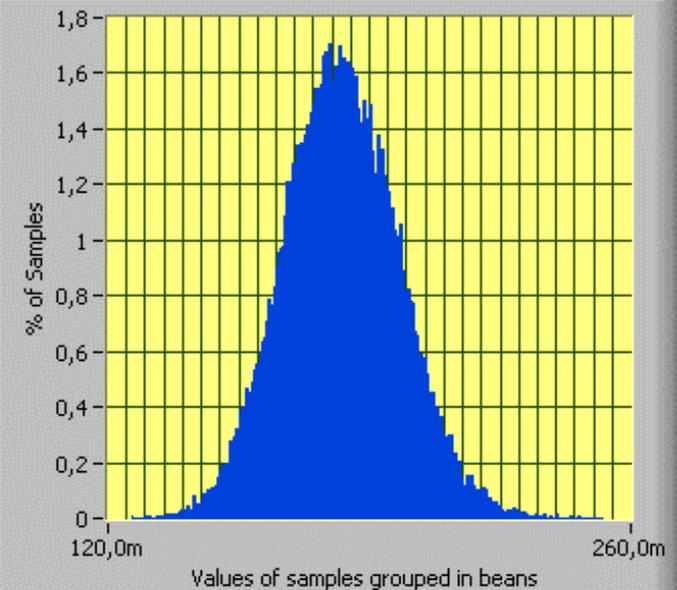


# Result of propagation of uncertainties through FFT procedure (uniform)

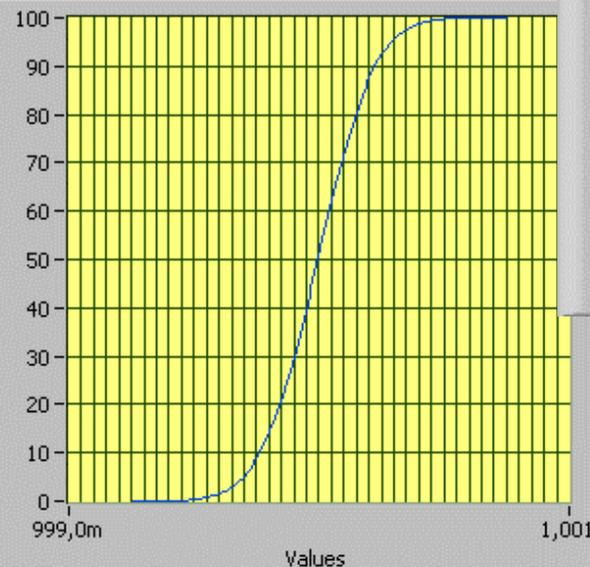
Fundamental harmonic



THD histogram



Distribuant



For 95 % of coverage probability the coverage interval for fundamental harmonic is  $\langle 0,9993; 1,0007 \rangle$  (mean value equals to true value which is 1) and for THD rms coverage interval is  $\langle 0,13 0,25 \rangle$  mean value 0,18%

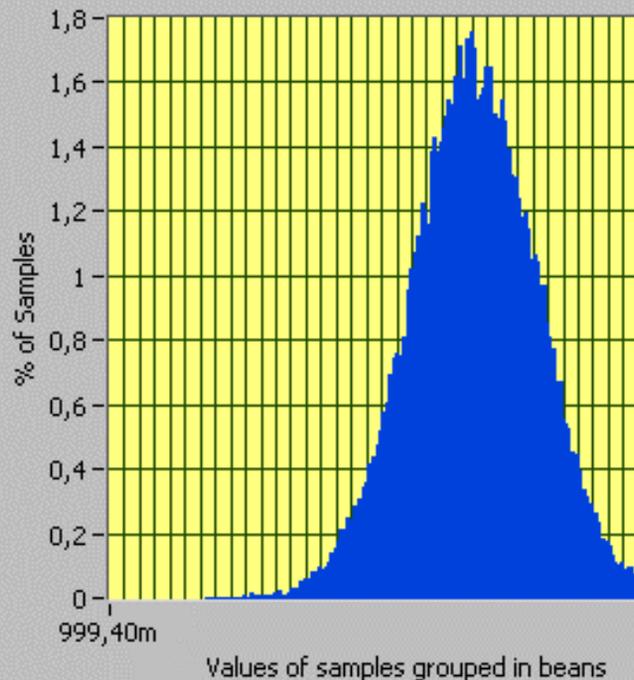


Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

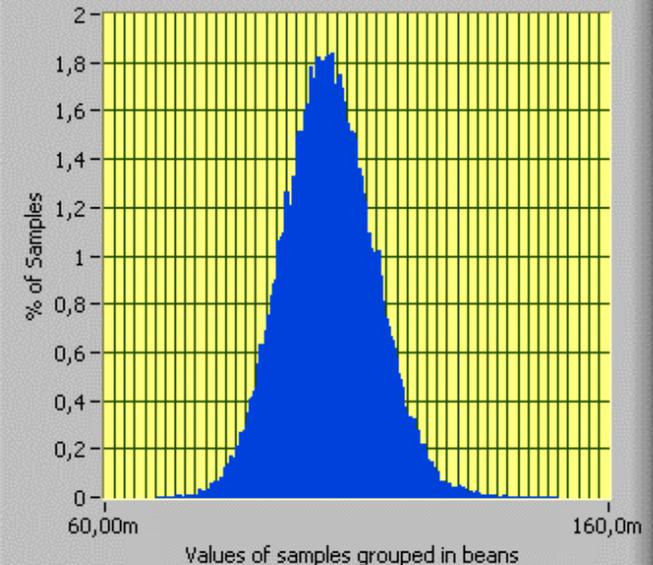


## Result of propagation of uncertainties through FFT procedure (Normal)

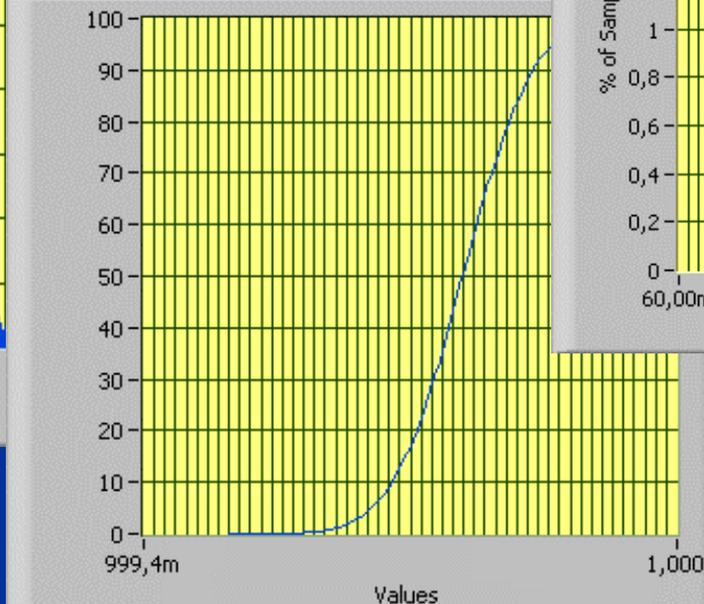
Fundamental harmonic



THD histogram



Distribuant



**Normally distributed error over samples. For 95 % of coverage probability the coverage interval for fundamental harmonic is  $\langle 0,9996 - 1,0004 \rangle$  (mean value equals to true value =1) and for THDrms coverage interval is 0,073 - 0,15 mean 0,10%**



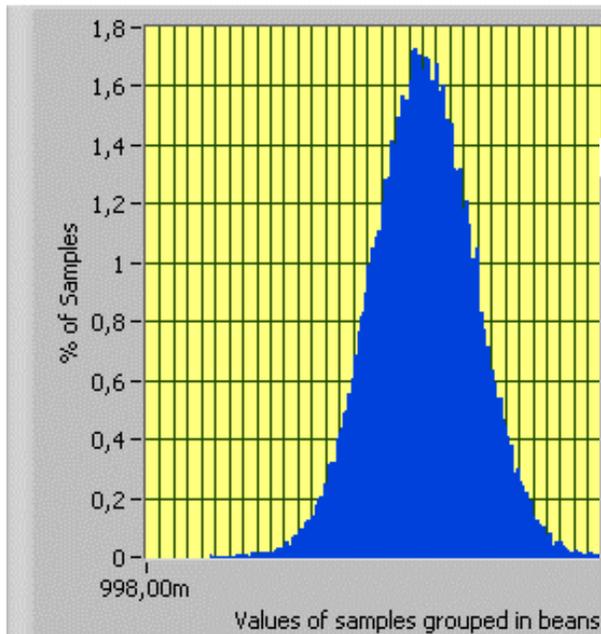
Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



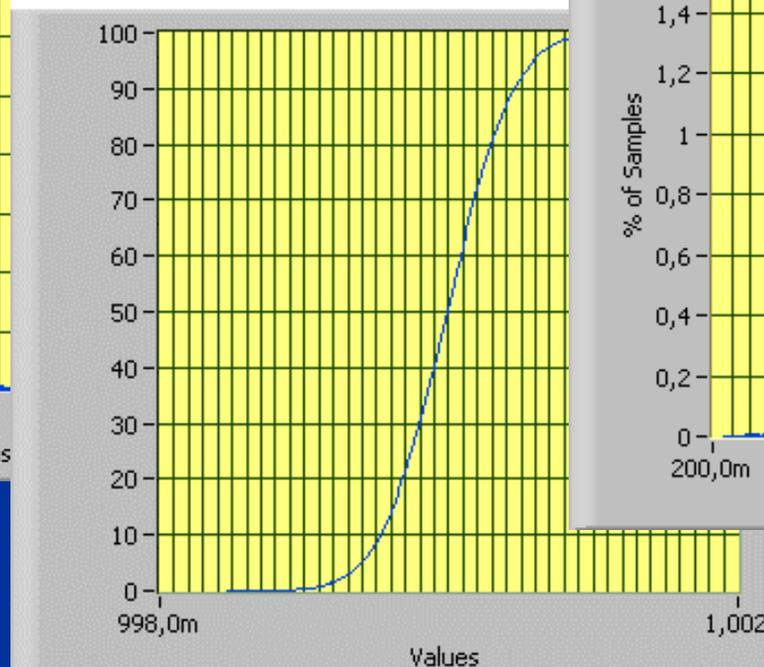
National Physical Laboratory

# 1 % of additive and 2 % of multiplicative components of errors distributed over samples.

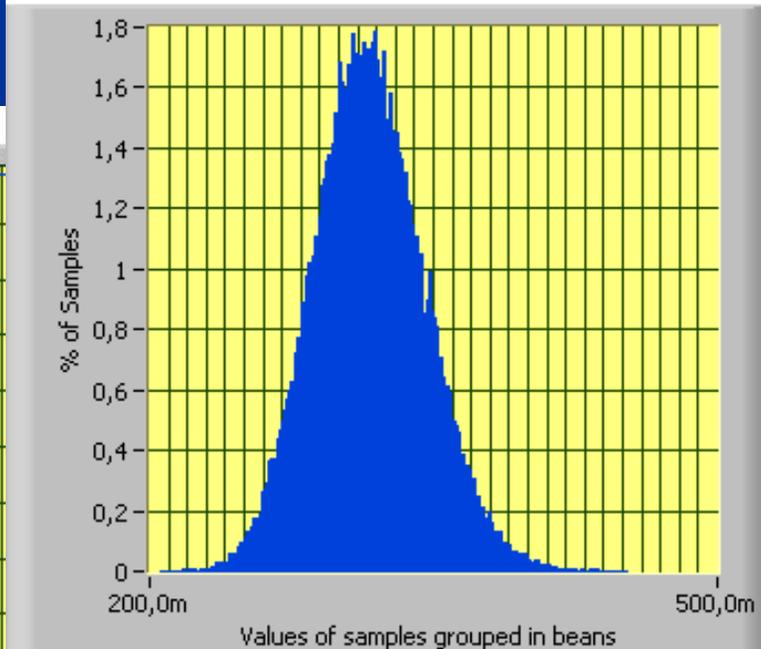
Fundamental harmonic



Distribuant



THD histogram



For 95 % of coverage probability the coverage interval for fundamental harmonic is  $\langle 0,998 - 1,002 \rangle$  (mean value equals to true value which is 1) and for THDrms coverage interval is  $\langle 0,21 - 0,45 \rangle$ , at mean 0,32 %.



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Conclusion regarding evaluation of uncertainties

---

---

- ✓ **Evaluate how uncertainties propagate through model**
- ✓ **To find a simpler method than MCM (as MCM is time consuming)**
- ✓ **The harmonic contents should be presented with coverage interval at certain coverage probability**



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Conclusion

---

---

## Grouping harmonics and interharmonics

---

- 200 ms – window is a compromise, still 5 Hz bins are the assumed resolution
- This is an engineering approach resulting that sometimes we are far away from perfect modelling of a real world, have advantages of unification if widely applied.
- The transient stated in electrical power is still waiting for unification, but 200 ms window can be also used.



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK



# Further investigations

---

---

- Total Harmonic and Inter-harmonic Distortions may be present as relative coefficients (similar to THD) in relation to rms value or fundamental frequency.
- TH&IHD for both steady states and transient states as a measure of non-linearity, induced by some devices in the net.
- Investigation of signals, which can be used for testing instruments to validate build up procedures for analysing harmonics contents
- Development of instruments, which can effectively measure distortion induced in the net by different devices
- Estimation of uncertainties



Digital Signal Processing Workshop and Seminar;  
30th of November 2005, Teddington, UK

