

Measurement & Analysis of Harmonics & Flicker

Part 1: Harmonics

Mandatory Requirements and Premises



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1. Origin and Effects

1.1 Definition:

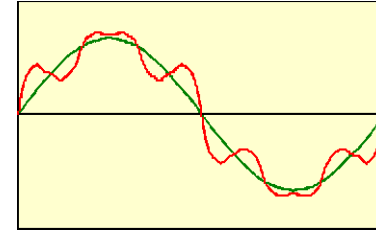
- **HARMONICS**

Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g. 50Hz or 60 Hz).



1.2 Additional Definition & Origin:

A 250 Hz sine-wave signal, superposed onto the fundamental 50 Hz mains frequency, will be designated as the 5th harmonic or as the harmonic of 5th order (5 x 50 Hz).

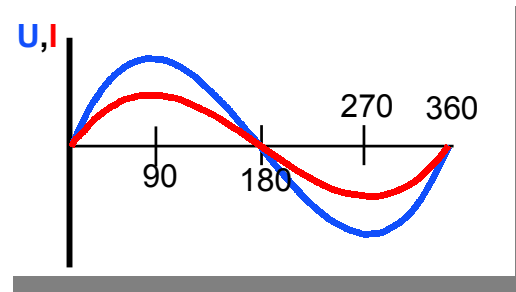
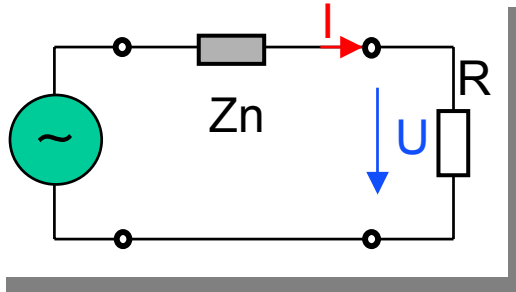


Any signal component having a frequency which is not an integer multiple of the fundamental frequency is designated as an interharmonic component or referred to more simply as an interharmonic.

Harmonics and interharmonics are basically the result of modern developments in electricity utilization and the use of electronic power conditioning modules. Using switching power supplies to control loads and to reduce power consumption results in unwanted frequencies superimposed on the supply voltage. The presence of voltage at other frequencies is, as far as possible, to be avoided.



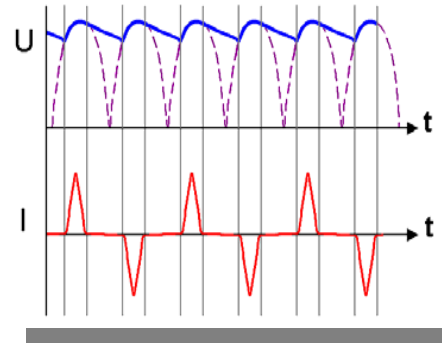
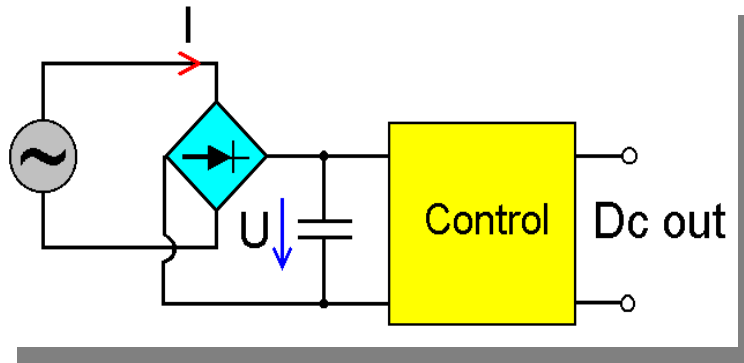
1.3 Linear System



In a linear system (e.g. a circuit, with ideal resistors, capacitors and/or inductors), the characteristics of the voltage and the current are sinusoidal in nature. The current contains only one frequency, the mains frequency or the so called fundamental. Beside this 50 Hz component there are no other frequencies and therefore there are no harmonic components.

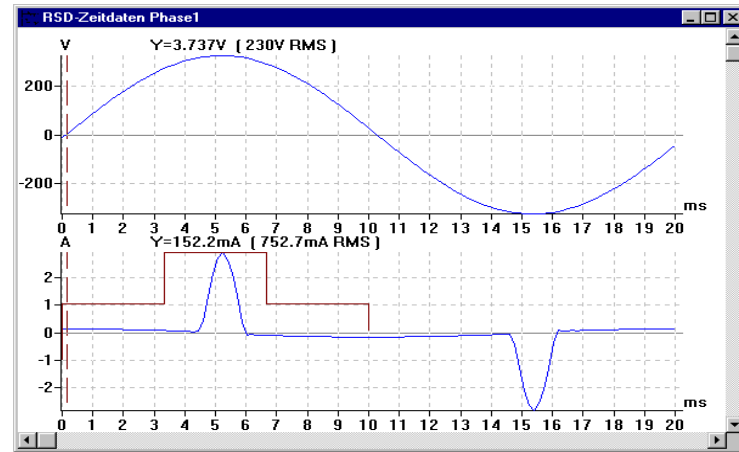
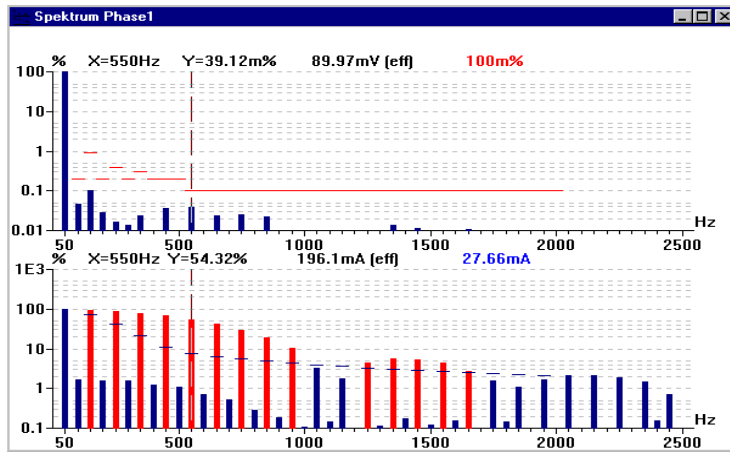


1.4 Harmonic current source



voltage & current flow into the capacitor

Display of voltage and current



Spectrum or frequency domain

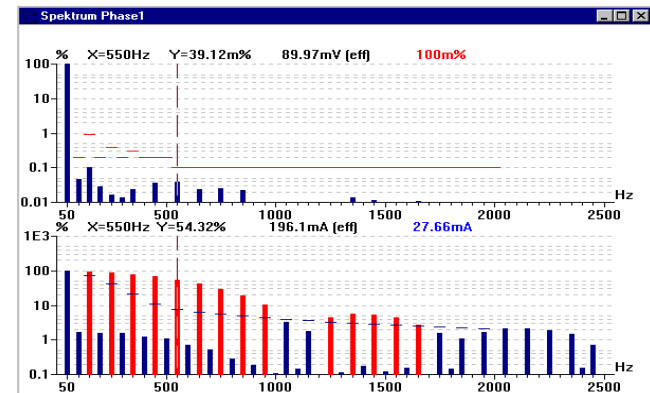
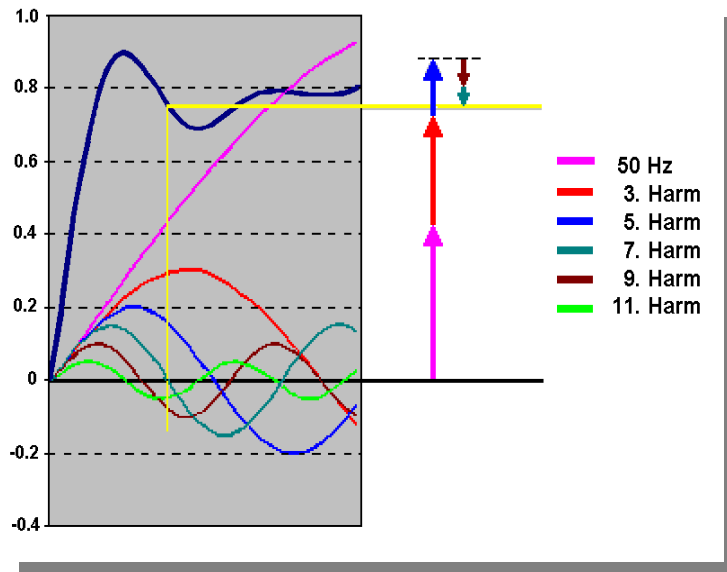
Time domain



1.5 Fourier Transformation:

- Fourier Transformation:**

Any periodic or non periodic waveform can be resolved into truly sinusoidal components (the fundamental frequency and the associated harmonics of higher order).



Decomposition of a waveform in the time domain into sine-wave signals of higher order (harmonics).

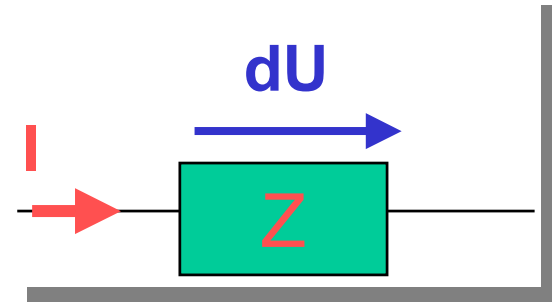
1.6 Potential Sources of Harmonics

- Switched mode power supplies
- Dimmer's
- Current Regulators
- Frequency Converters
- Voltage source inverters with pulse width modulated converters
- Low power consumption lamps
- Electrical arc-furnaces
- Arc welding machines
- Induction motors with irregular magnetizing current associated with saturation of the iron
- All equipment with built-in switching devices or with internal loads with non-linear voltage/current characteristics



1.7 Description of phenomenon:

- Harmonic disturbances are generally caused by equipment with nonlinear voltage/current characteristic and are mainly the result of modern electronic controlled power consumption.



- The harmonic current from different sources produces harmonics voltage drops across the impedance of network. The result of all the single harmonics coming from different sources is obtained by the vector addition of the single elements.
- The reactive loads in conjunction with cable capacitance's can result in shunt and series resonance's in the network. This can cause a voltage magnification, which can appear at a point remote from the distorting load.



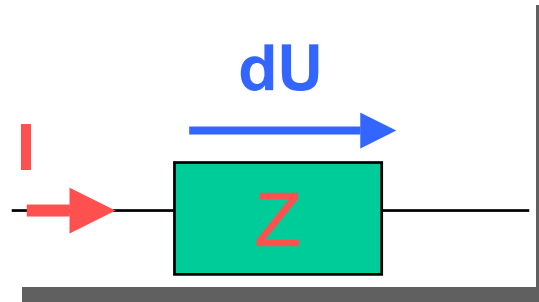
1.8 Effects of Harmonics on Mains supplies :

- Distortion of main supply voltage, unwanted currents flowing in the supply network generate additional energy losses.
- Defective operation of regulating devices, disturbed operation of florescent lamps, television receivers or other equipment.
- Malfunction of ripple control and other mains signaling systems, protective relays and, possibly, other of control systems.
- Additional losses in capacitors and rotating machines.
- Additional acoustic noise from motors and other apparatus, reducing the efficiency of motors.
- Telephone interference.
- High harmonic amplitudes may not only cause malfunctions, additional losses and overheating, but also overload the power distribution network and overheat the neutral conductor and cause it to burn out.

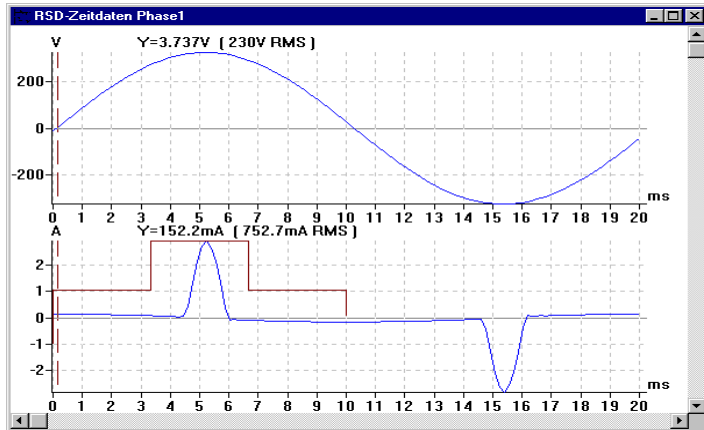


1.9 Harmonics are bad!

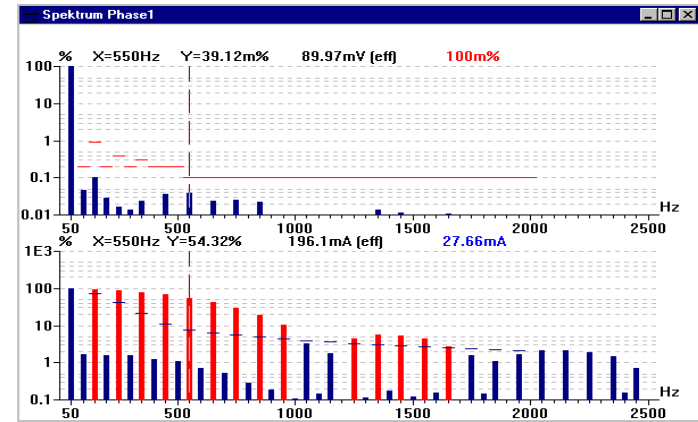
- Poor Power Factor overloads the cables resulting in low real power delivered to the load.



1.10 Why specify mains Harmonics?



Time domain



Spectrum

The main purpose is to limit the distortion created by equipment connected to the mains supply !

The distortion of mains supply voltage can be limited by reducing the current harmonic content delivered by the connected equipment.



1.11 In summary:

Modern power electronics is the state of the art and the tendency to use it more and more is increasing.

Therefore, the generation of current at unwanted frequencies ought not to be allowed to grow without limit, because it may impact the public mains. As a consequence the harmonic content on the public networks has to be limited. Furthermore, the equipment connected to the mains has to show sufficient immunity in order to continue to operate as intended in the presence of a certain allowed harmonic distortion.

The release of international standards is a practicable compromise in order to establish reference levels for the coordination of emission and immunity in the interests of electromagnetic compatibility.

2. European Practice and Standards Used

- **Standards in order to define Harmonic limit values.**

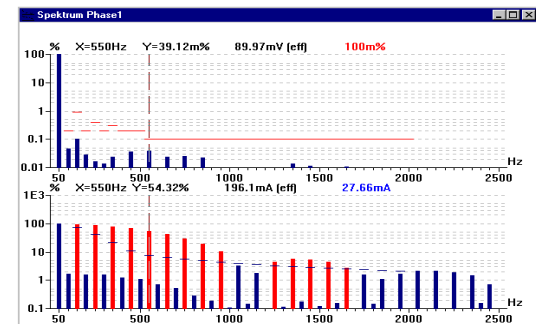
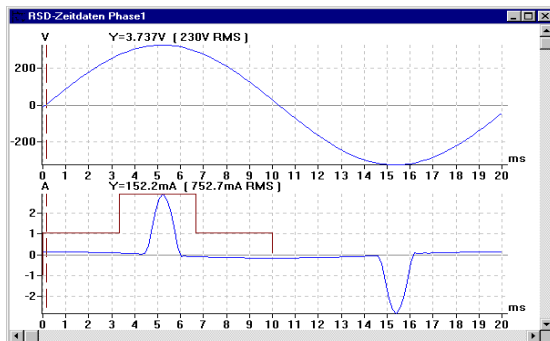
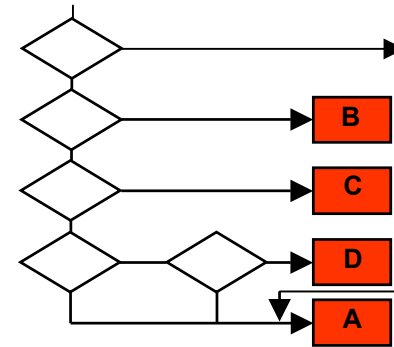
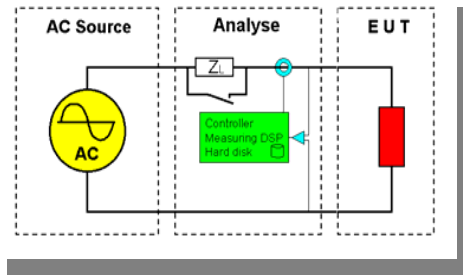
- **IEC/EN 61000-3-2 (1995-03) + (am 1 + am 2 1998-04)**
Limits for harmonic current emissions (equipment input current ≤ 16 A per phase single & 3 phase).
- **IEC/EN 61000-3-2 (2000 (A14))**
Limits for harmonic current emissions (equipment input current ≤ 16 A per phase single & 3 phase).
- **EN 61000-4-7 (1991-08)**
General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.

- **Standards in order to quantify the quality characteristics of the electricity**



3. Harmonic analysis per EN 61000-3-2

Specifications, Characteristics and Commitments to the intention of the standards and the derivable mandatory requirements thereto for set-up, measurement equipment and EUT.



3.1 Distinctions between standard edition 2000 (A14) and the previous version 1995 of EN61000-3-2

1. New Classification of Equipment

Class D equipment are related to PC's, Monitors and TV's. The special envelope for current wave shape verification is obsolete now.

2. New Observation Period

Instead of steady state and fluctuating state, there are now four different type of observation periods.

3. Measurement Procedure

- The 1.5 sec smoothing filter is applied during all observation periods.
- The arithmetic average of the measured values from the DFT time windows is calculated over the entire observation period.



Additional distinctions between standard edition 2000 (A14) and the version 1995 of EN 61000-3-2:

4. Application of Limits

- Only the average value for the individual harmonic current, taken over the entire observation period, shall be less than or equal to the applicable limits. The 1.5 sec smoothed r.m.s. harmonic current values can rise up to 150% of the applicable limits for unlimited time duration.
- Facilitation for the 21st and higher odd order harmonics.

5. Determination of Maximum Input Power, Fundamental Current and Power Factor

These values are used for establishing limits when limits are specified in terms of power (Class D), fundamental current or power factor (Class C).

6. Separation of categories of equipment for which limits are not specified in this standard

New list with categories of equipment which the standard is not applicable, or in other words for equipment for those no limits have been affixed so far.



3.2 Important Aspects of IEC 61000-3-2 edition 1995 including amendment 1 & 2 of 1998

3.2.1 Classification of Equipment

For the purpose of harmonic current limitation, equipment is classified as follows:

- Class A:** Balanced three-phase equipment and all other equipment except that stated in one of the following classes;
- Class B:** Portable tools;
- Class C:** Lighting equipment including dimming devices;
- Class D:** Equipment having an input current with a "special wave shape" and an active input power P between (50) 75600W.



3.3 Important Aspects of new IEC 61000-3-2 edition (A14)

3.3.1 New Equipment Classification:

Class A: - Balanced three-phase equipment;
- Household appliances excluding equipment identified as Class D;
- Tools excluding portable tools;
- Dimmers for incandescent lamps;
- Audio equipment;
- Equipment not specified in one of the three other classes shall be considered as Class A equipment.

Class B: - Portable tools.

Class C: - Lighting equipment.

Class D: - Equipment having a specified power $\leq 600\text{W}$ of the following types:
- Personal computers and personal monitors;
- Television receivers.



3.3.2 New observation duration:

Quasi-stationary T_{obs} of sufficient duration to meet the requirements for repeatability ($\pm 5\%$)

Short cyclic $T_{\text{obs}} \geq 10$ cycles (reference method) or T_{obs} of ($T_{\text{cycle}} \leq 2.5$ min) sufficient duration or synchronization to meet the requirements for repeatability ($\pm 5\%$)

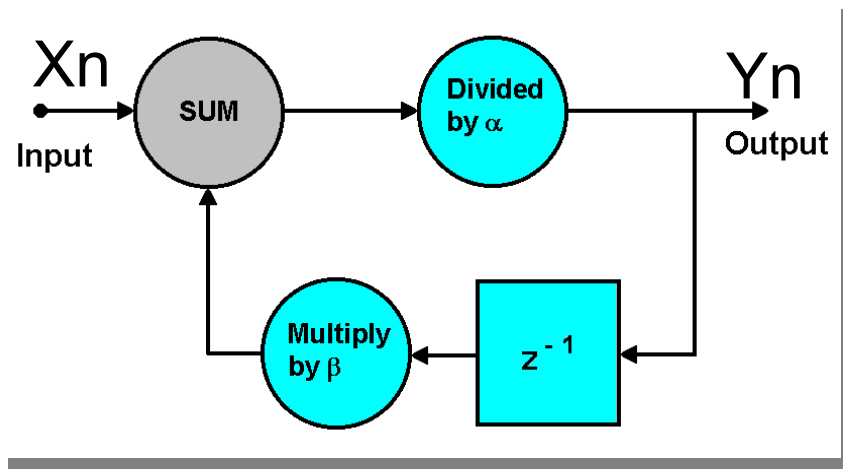
Random T_{obs} of sufficient duration to meet the requirements for repeatability ($\pm 5\%$)

Long cyclic Full equipment program cycle (reference method) $T_{\text{cycle}} > 2.5$ min) or a representative 2.5 min period considered by the manufacturer as the operating period with highest THC.



3.3.3 Measurement of harmonic current:

- For each harmonic order, measure the 1.5 sec smoothed r.m.s. harmonic current in each DFT time window.



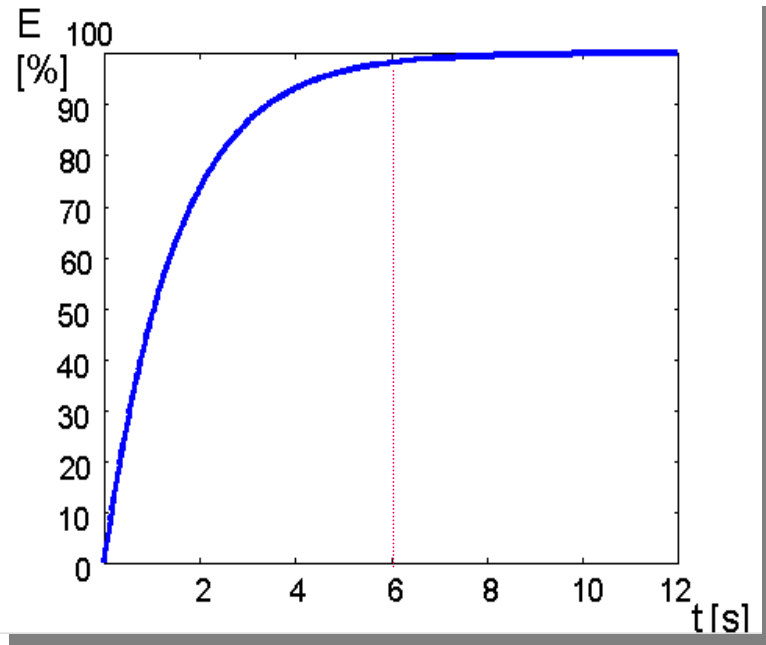
Digital filter

$$Y_n = \frac{X_n + \beta \cdot z^{-1}}{\alpha}$$

- Calculate the arithmetic average of the measured values from the DFT time windows over the entire observation period.
- The harmonic currents and the active input power shall be measured under the same test conditions but need not be measured simultaneously.



3.3.4 Smoothing function with first order low-pass filter having a time constant of $1.5 \text{ s} \pm 10\%$



$$S(t) = E (1 - e^{-t/\tau})$$

$$\text{with } t = 6\tau$$

the following result is obtained:

$$S(t) = 0.9975 E$$

Response time of Low-pass filter

In order to let the smoothing function achieve it's full operation, a minimal observation duration of 10 seconds is to be applied.



3.3.5 Determination of input power value for the limit calculation of class D equipment:

The harmonic currents and the active input power shall be measured under the same test conditions but need not be measured simultaneously. Based on this, proceed as follow:

- Measure the 1.5 s smoothed active input power in each DFT time window.
- Determine the maximum of the measured values of power from the DFT time windows over the entire duration of the test.

The value for power, measured as defined above, shall be specified by the manufacturer and documented in the test report. Moreover, in order not to specify a power at which limits change abruptly, thus giving rise to doubt as to which limits apply, the manufacturer may specify any value which is within $\pm 10\%$ of the actual measured value.



3.3.6 Determination of the fundamental and the power factor for the limit calculation of class C equipment

The fundamental current and power factor, specified by the manufacturer, shall be used for the calculation of limits.

The fundamental component of the current and the power factor are measured and specified by the manufacturer in the same way as the power is measured and specified for the calculation of class D limits.

Furthermore the standard specifies:

The value used for the power factor shall be obtained from the same DFT measured window as the value for the fundamental component of current.

A better wording would therefore be:

The values for the power factor and fundamental component of current shall be obtained by the same way but need not be produced from the same measured DFT window.



3.3.7 Applicable limits:

The average value for the individual harmonic currents, taken over the entire test observation period shall be less than or equal the applicable limits.

For each harmonic order, all 1.5 s smoothed r.m.s. harmonic current values, shall be less than or equal to 150% of the applicable limits.

For the 21st and higher odd order harmonics, the average values obtained for each individual odd harmonic over the full observation period, calculated from the 1.5 s smoothed r.m.s. values may exceed the applicable limits by 50% provided that the following conditions are met:

- the measured partial odd harmonic current does not exceed the partial odd harmonic current which can be calculated from the applicable limits.
- All 1.5s smoothed individual r.m.s. harmonic current values shall be less or equal to 150% of the applicable limits.

$$\text{Partial Odd Harmonic Current POHC} = \sqrt{\sum_{n=21,23}^{39} I_n^2}$$



3.3.8 Typical products to which this standard may apply

This standard is basically applicable to all electrical and electronic equipment having an input current up to and including 16 A per phase, and intended to be connected to public low-voltage distribution systems.

Excluded from that are the following categories of equipment:

- **Equipment** with a rated power of **75 W or less**, other than lighting equipment
- **Professional equipment** with a total rated power **greater than 1 kW**
- Symmetrically controlled **heating elements** with a rated power less than or equal to 200W
- Independent **dimmers for incandescent lamps** with a rated power **less than or equal to 1 kW**



3.4 Common Aspects

3.4.1 Limits Class A and B

Class A

Odd harmonic	Max. Current	Even harmonic	Max. Current
n	A	1	A
3	2.3	2	1.08
5	1.14	4	0.43
7	0.77	6	0.30
9	0.40		
11	0.33		
13	0.21		
15 - 39	0.15 * 15/n	8 n 40	0.23 * 8/n

Class B

1.5 * Class A



Common Aspects

3.4.1 Limits Class C and D

Class C

Harmonic	Max. % of Current
n	%A
2	2
3	30 * power factor
5	10
7	7
9	5
11 n 39	3

Class D

Harmonic	Max. mA/W
n	mA/W
3	3.4
5	1.9
7	1.0
9	0.5
11	0.35
13 - 39	3.85/n



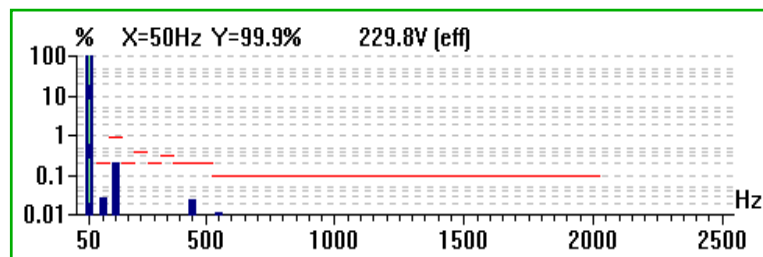
3.4.2 Requirements of voltage source

Key characteristics:

Voltage accuracy/stability:	$\pm 2\%$
Frequency accuracy/stability:	$\pm 0.5\%$
Phase angle shift for 3-phase sources:	$120^\circ \pm 1.5^\circ$
Crest factor:	1.40 - 1.42
Crest factor arriving after zero cross between:	$87^\circ - 93^\circ$

Very low distortion:

Harmonic order	3.	$\leq 0.9\%$
”	5.	$\leq 0.4\%$
”	7.	$\leq 0.3\%$
”	9.	$\leq 0.2\%$
”	2. - 10.	$\leq 0.2\%$
”	11. - 40.	$\leq 0.1\%$



3.4.2. Requirements of AC voltage source

Crest factor:

The crest factor of a power source is defined as:

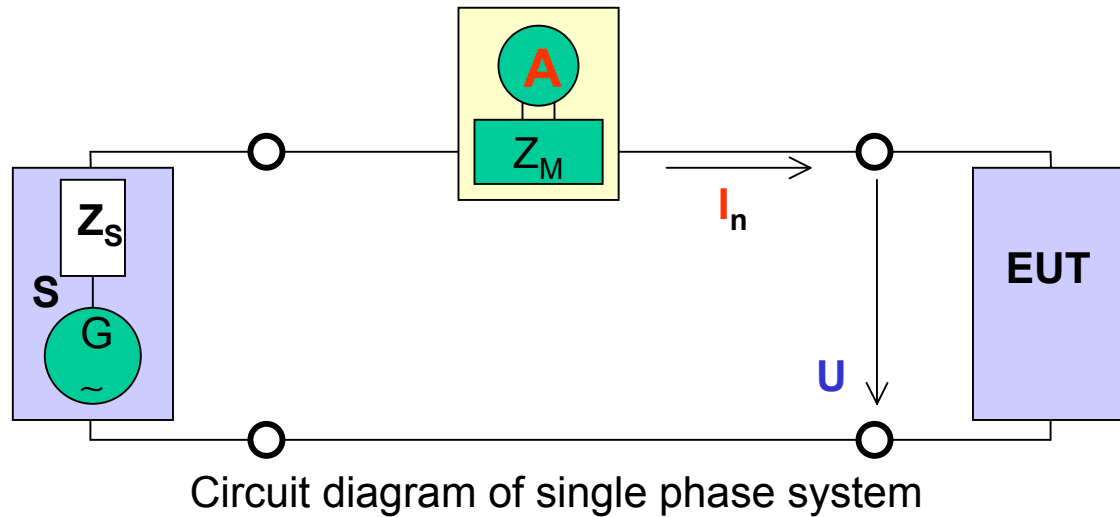
$$\frac{\text{peak}}{\text{RMS}}$$

During transitory events it may happen, that an EUT may need higher peak current. A high crest factor is the only way to forestall clipping effects of test voltage during such events.

Clipping effect may result in incorrect measurements !



3.4.3 Test Setup for harmonic measurement



Current measurement:

Maximum permitted voltage drop along the measuring device Z_M (e.g. shunt) due to the input current : $\leq 0.15 \text{ V}$

Max shunt value = $0.15 \text{ V} / 50 \text{ A} \approx 3 \text{ m}\Omega$

Resolution ADC = 5 % of 5 mA = 0.25 mA

$$\Rightarrow 3 \text{ m}\Omega * 0.25 \text{ mA} = 0.75 \mu\text{V!}$$



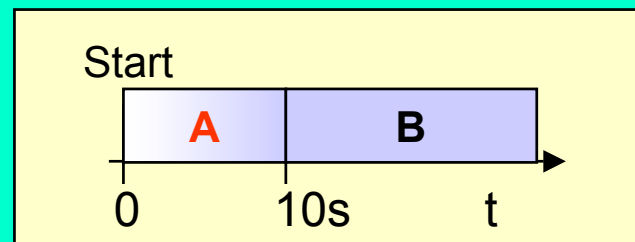
3.4.4 Basic considerations of measurement procedure:

EUT:

During measurements the user's operation controls or automatic programs shall be set in order to produce the maximum harmonic components under normal operating conditions, for each successive harmonic component, in turn.

General Aspects:

- Harmonic current $< 0.6\%$ of the input current or $< 5\text{ mA}$, whichever is greater, are disregarded.
- Harmonic currents lasting for less than 10 seconds when a piece of equipment is brought into operation or is taken out of operation, manually or automatically, are disregarded.



Critical Aspects and Consequences to the Limit Values:

Harmonic currents less than **0.6 % of the input current** measured under the test conditions, or less than **5 mA**, whichever is greater, are disregarded.

Example of a DUT with a current consumption of 16 A:

=> Minimum harmonics content: 0.6 % of 16 A = 96 mA

$$\text{Limits for Class A : } G_{(19-39)} = 0.15 \times 15 / n; \quad n_{\text{ODD}} = (0.15 \times 15) / 0.096 = 23.44;$$
$$G_{(8-40)} = 0.23 \times 8 / n; \quad n_{\text{EVEN}} = (0.23 \times 8) / 0.096 = 19.17$$

The limits for those above the **20th** harmonic for even harmonics and for those above the **25th** for odd harmonics are set to **96 mA** for a 16A DUT. This means that the limits are no longer fixed but vary according to the current consumption!

Input current level at which it will start to influence the limits:

Class A: Limit for harmonic order 40: $0.23 \cdot (8/40)$ in amps:
 $I_{(\text{smoothed value})} \geq (0.23 \cdot (8/40)) / 0.006 \geq 7.66... \text{ Amps}$

Class B: Limit value is value Cl. A multiplied by 1.5:
 $I_{(\text{smoothed value})} \geq 1.5 \cdot 7.66... \text{ A} \geq 11.499... \text{ amps}$



3.4.5 Requirements for Power Analyzer:

Resolution of AD-converter:

Required measurement accuracy 5%

With $L_{\text{value}} (H_{40}) = 0.23 \text{ A} * 8/40 = 0.046 \text{ A}$

Minimal current value to be measured $\Rightarrow 0.046 / 20 = 0.0023 \text{ A}$

This will result in:

For an estimated current measuring range of 50A

$\Rightarrow 50 \text{ A} / 0.0023 \text{ A} = 21,740 \Rightarrow 2^{15}$ or in more practical terms:

AD-converter with **16 Bit** resolution.

Synchronization for sampling rate and max. relative deviation:

The max. permit deviation is: $\leq 0.03 \%$

This can be achieved by using the so called **PLL** technique or by applying a very fast sampling rate. In the latter case this should be at least \Rightarrow

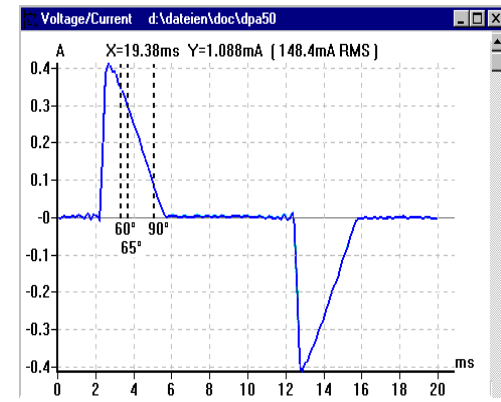
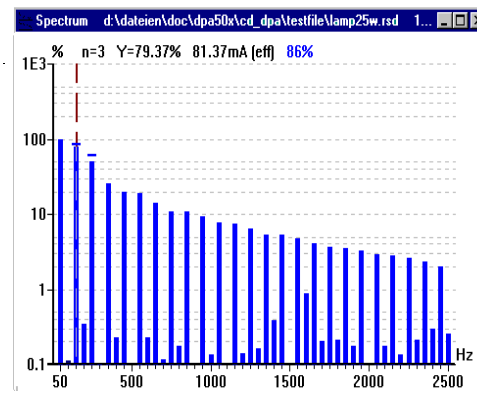
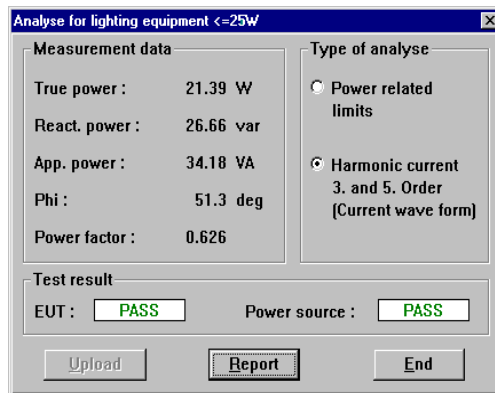
$$1 / (0.020\text{s} * 0.0003) \cong \mathbf{167 \text{ kHz sampling rate}}$$



3.5 Limit application for class C equipment

Lighting equipment having an active input power ≤ 25 W:

- The harmonic currents shall not exceed the power-related limits of table 3, column 3 (\Rightarrow limits of class D) or:
- The **third harmonic current**, expressed as a percentage of the fundamental current, shall not exceed **86%** and the **fifth** shall not exceed **61%** ; moreover, the **waveform** of the input current shall be such that it begins to flow before or at **60°**, has its last peak (if there are several peaks per half period) before or at **65°** and does not stop flowing before **90°**, where the zero crossing of the fundamental supply voltage is assumed to be at 0°



3.6 IEC / EN 61000-4-7 : 2002

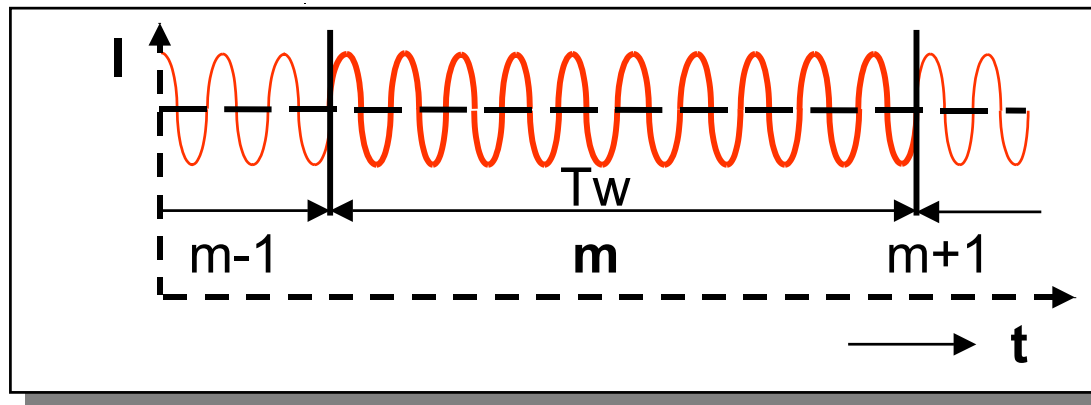
3.6.2 Measuring Window

New measuring window: For new equipment a rectangular window of 10 (50 Hz) or 12 (60 Hz) periods has to be used.

New requirement: rectangular window with 10 (12) cycles of the fundamental will be mandatory and only one applied.

$$\Rightarrow T_w = 200 \text{ ms}$$

Furthermore no gap and no overlapping between successive measuring windows are allowed !



$m-1$, m , $m+1$: number of windows; T_w : Width of the window



3.6.2 Crest Factor current input

Each measuring input must withstand 1.2 * In minimum continuous and 10 * In for short-time (1s).

In general the following crest factors shall be considered as follows:

**Measuring range up to 5A - Crest Factor 4;
up to 10A - Crest Factor 3.5;
up to 20A - Crest Factor 2.5.**

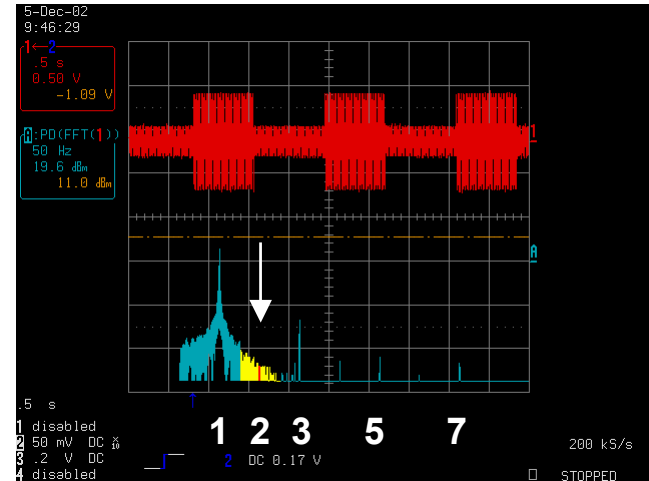
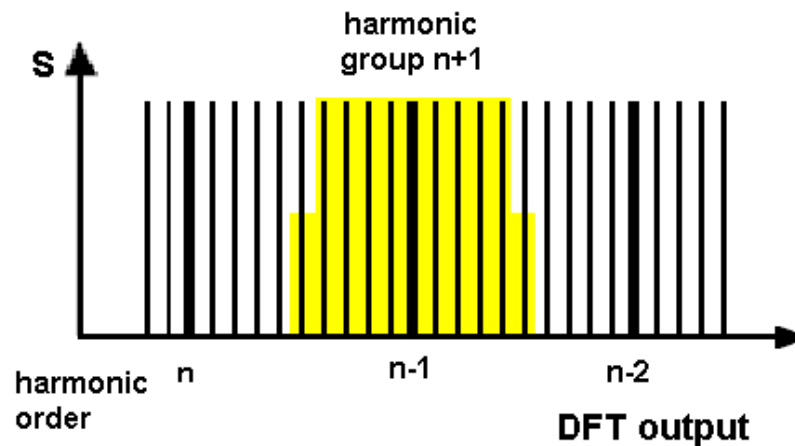
$$\text{Crest Factor} = \frac{\text{peak}}{\text{RMS}}$$



Other changes : IEC / EN 61000-4-7 : 2002

3.6.2 Grouping and Averaging procedures

The new standard edition specifies so called grouping and averaging procedures for interharmonic measurement.



$$C_{ng}^2 = \frac{C_{10ng-5}^2}{2} + \sum_{i=-4}^4 C_{10ng+i}^2 + \frac{C_{10ng+5}^2}{2} \quad \{50 \text{ Hz system}\}$$

$$C_{ng}^2 = \frac{C_{12ng-6}^2}{2} + \sum_{i=-5}^5 C_{12ng+i}^2 + \frac{C_{12ng+6}^2}{2} \quad \{60 \text{ Hz system}\}$$

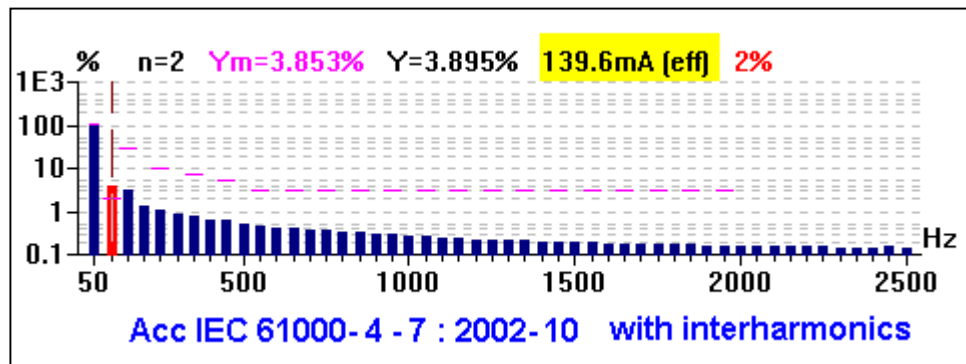
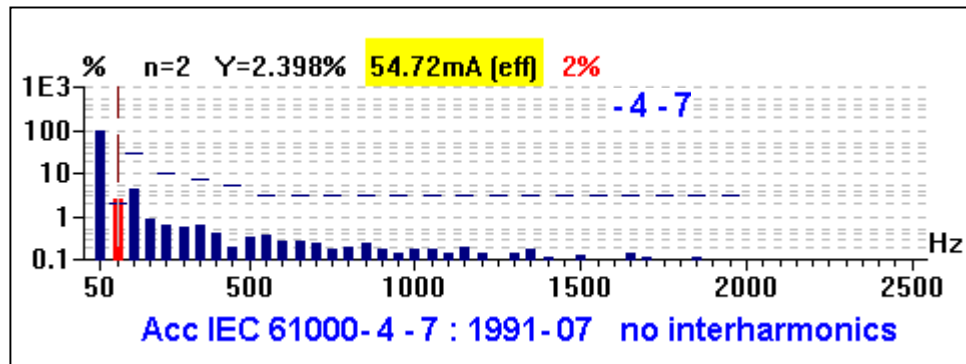
FFT with Scope

Other changes : IEC / EN 61000-4-7 : 2002

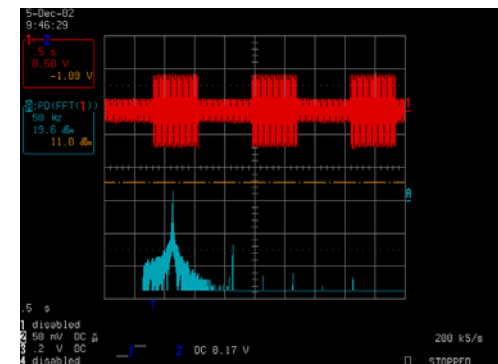
Effect of interharmonic measurements:

A device with intermittent current consumption shows higher harmonic currents with interharmonic measurements .

DPA 500 analyser



Oscilloscope



6.1. Conclusion of IEC 61000-4-7 :2002

Important to know in this context:

Measuring devices being based on the new directives IEC 61000- 4- 7 : 2002 are considered as **Reference Devices.**

Devices being based on the former directive may still be used for a certain period of time until the next revision of the standard. However, all measurements taken with older equipment must be fully proven accordingly.

It is entirely up to the user how to avoid any discrepancies and to obtain the required accuracy.



5. Test Equipment Examples

- **Harmonic and Flicker Test Equipment including Analyzer, AC Source & Lumped Impedance**

Demonstration to show typical Harmonics

- **measurement**

