Harmonics and high-frequency emission by small end-user equipment

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***Abstract*-- This paper discusses different treatments of harmonics in three phase systems, especially passive and active power factor correction (PFC). The change from harmonics below 2 kHz to above 2 kHz is described. Measurements have been carried out with two types of computer load together with LCD and florescent light driven by electronic ballast: on a large number of devices during a LAN party and on individual devices in the laboratory. Also some aspects of increasing numbers of equipment are illustrated.**

***Index Terms*--Electromagnetic compatibility; power quality; conducted disturbances; power-quality and EMC standards.**

I. Introduction

HIGH power density, small losses and low weight are some of the advantages in using power electronics. A disadvantage of this type of load is however that it often creates high levels of harmonics. The use of fast switching techniques also creates high-frequency disturbances on the low-voltage grid.

A simple two-pulse diode rectifier forms the interface to the vast majority of computing and consumer-electronics equipment. The resulting current taken from the supply consists of all odd harmonics up to order 9 to 15 [1]. Third-harmonic currents may be as high as 80% of the fundamental component.

International standards have been introduced to limit the harmonic currents produced by small and large equipment. Before use, the equipment has to fulfill the product standard, tested one by one, in a controlled laboratory environment.

Other equipment, noticeable energy-saving lamps and some advanced power-electronic driven electrical machines, are equipped with a so-called "controlled rectifier" or "active front-end" as interface. These produce significantly less distortion in the frequency band up to about 1 kHz. However they produce instead waveform distortion at higher frequencies, typically at the switching frequency and at harmonics of the switching frequency.

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II. Power Supplies

A. Harmonics and high-frequency harmonics

The interest of low weight together with high power density and small losses has resulted in a basic change in power converter construction. Instead of a 50/60 Hz transformer followed of a diode bridge, a storage capacitor and a voltage regulator, the diode bridge is first, followed by a storage capacitor, a dc/ac converter feeding the transformer with a frequency of tens of kilohertz and a voltage step down dc/dc converter and regulator.

This solution, named switch mode power supply (SMPS), has besides a number of benefits two basic drawbacks: the fundamental frequency harmonic generation in the input diode rectifier and so called "high-frequency harmonics" from the switching units.

B. Power factor corrector

The origin and spread of fundamental frequency harmonics and its disadvantages are well known, also some of the solutions like passive and active filters [2]. One of these solutions, power factor correction (PFC), allows for a wide input voltage range, a displacement power factor close to 1.0 in combination with almost sinusoidal input current.

A passive PFC is often an inductor before the storage capacitor smoothing the capacitor charging current, often enough for computers [2]. An active PFC uses a switching element together with an inductor, a switched-mode boost converter, before the storage capacitor to force the current, like in a resistor, to follow the shape of the voltage.

The switching frequency and its harmonics in the PFC are generated independently, i.e. uncorrelated, to the frequencies and its harmonics generated in other switching unit's like dc/ac converters, dc/dc converters or other PFC, connected to the same power grid.

The origin for the PFC switching frequency is also generated independent to the 50/60 Hz fundamental frequency and its harmonic. But, as long as the frequency origin is not the same, two identical converters will differ in switching frequency. These harmonics of the switching frequency are called high-frequency harmonics (HF-harmonics), in distinction from the fundamental frequency harmonics. In the case there is a summation of lots of switching frequencies and their harmonics the expression, high-frequency noise, HF-noise, is also used.

The treatment of the fundamental frequency harmonics is often based on their steady state behavior and the "phase locking" between the three phases and between the harmonics. This makes it possible to create tuned filters at a certain harmonic frequency and to create phase-shift filters using transformer windings.

The difference in frequency origin, between 50/60 Hz fundamental frequencies and the switching frequency, is an important piece of knowledge in understanding the behavior and the treatments of this switching frequency and its harmonics, to achieve electromagnetic compatibility EMC.

C. Instability

It has been reported that high-frequency harmonics causes new problems. Distribution transformer failure due to high energy spikes and switching transients [3] and disturbances from PWM converters have been reported [4] giving "malfunction of electronic office equipment, blown power supply units, malfunction of electronic controls or unacceptable noise."

Since more than 10 years it is also known that the connection of PFC to certain ac sources and line conditioners can cause system instability. [5]. This early study pointed out that "*PFC supplies on the other hand can be unstable below 60Hz when powered by an AC source that exhibits high output impedance characteristics in that frequency range*." Later research has pointed out switching frequency instability "near the zero crossing of the PFC input current" [6], [7], [8].

The construction of the PFC can vary depending on relative cost, volume, weight and applicable power range [2]. It makes it possible to have all kind of combinations of solutions according to the power electronic and to the regulator circuit. This regulator circuit is tested according to stability but normally only connected to a passive AC sources and seldom in parallel with other equipment.

III. NEUTRAL CURRENTS

The total resulting current in the neutral conductor in a balanced three-phase system without harmonics is, as known, zero.

In the presence of zero-sequence harmonics (odd triplen harmonics, 3rd, 9th, 15th, and so on) in a balanced three-phase system, there will be a current in the neutral.

In time domain: the current pulses in the three phases do not overlap at all or overlap only partly so that the return current has to close via the neutral.

The root-mean-square (RMS) value, I_{rms} of a current, $i(t)$ is:

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)} \qquad [1]$$

The total resulting RMS value of the current in the neutral conductor, I_N in a balanced three-phase system with no overlap (see figure3 and text below), is the arithmetic sum of the contribution from each phase I_A, I_B, I_C:

$$I_N = \sqrt{I_A^2 + I_B^2 + I_C^2} \qquad [2]$$

Calculation on a per unit basis results for the maximum neutral current:

$$I_{N\max} = \sqrt{1^2 + 1^2 + 1^2} = \sqrt{3} \approx 1{,}73 \qquad [3]$$

When the current pulses show overlap in time, the RMS of the neutral current becomes less and requires a time-domain or frequency-domain calculation to be quantified.

The ratio, N between the neutral current and the mean phase current is:

$$N = I_N / ((I_A + I_B + I_C)/3) \qquad [4]$$

The maximum ratio, $N_{\max}$ is:

$$N_{\max} = I_{N\max} / ((I_A + I_B + I_C)/3) \qquad [5]$$

Calculation for the maximum neutral current and no overlap in the per unit basis gives:

$$N_{\max} = \sqrt{3} / ((1+1+1)/3) = \sqrt{3} \approx 1{,}73 \qquad [6]$$

The factor $\sqrt{3}$ is the maximum possible ratio, between the neutral current and the phase current in a three-phase system.

IV. IEC 61000-3-2 STANDARD

International standards have been introduced to limit the harmonic currents produced by small and large equipment.

Each device itself has been designed to fulfill the standard requirements against minimum costs. The design of equipment has not been aimed at limiting the overall distortion level.

Only when the equipment is installed and in use, will the result of the standard and the tests become clear. It will also become clear only then if the increasing numbers of similar and non similar equipment together creates new electromagnetic compatibility (EMC) problems like spurious trips, reduced lifetime and ageing [9]

IEC 61000-3-2 [10] sets limits for common equipment in domestic, commercial and industrial buildings, like computers, CRT, LCD, fluorescent lamps, etc.

The standard categorizes equipment in four classes A, B, C and D. The limits for Class C (lighting equipment having an active input greater than 25 W) are summarized in Table I.

TABLE I
LIMITS FOR CLASS C EQUIPMENT

Harmonic order (n)	Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency %
2	2
3	30×λ*
5	10
7	7
9	5
13≤n≤39 (odd harmonics only)	3
	* λ is the circuit power factor

Class D, valid for all applications having an active power between 75 and 600 W, and includes personal computers, personal computers monitors and televisions receivers. The relevant limits are shown in Table II.

TABLE II
LIMITS FOR CLASS D EQUIPMENT

Harmonic order (n)	Maximum permissible harmonic current per watt (mA/W)	Maximum permissible harmonic current (A)
3	3,4	2,30
5	1,9	1,14
7	1,0	0,77
9	0,5	0,40
11	0,35	0,33
13≤n≤39 (odd harmonics only)	3,85/n	See table-I IEC 610000-3-2

V. MEASUREMENTS

A. Computers

1) Measurements on computers in LAN-parties

Measurements have been carried out at four LAN-parties held in Skellefteå, Sweden, in the years 2002, 2003, 2004, and 2006. During such a LAN-party, people interested in playing computer games get together and connect their computers and LCD/CRT to a dedicate three-phase power distribution system and a wired LAN system.

The phase and neutral currents measured during LAN 2002 are shown in Figure 1. The figure 1 also shows a summation of all three phases, giving a better oversight on the activity despite the unbalance between the phases. The currents harmonics in one phase are shown in figure 2. The lowest activity was around eight o'clock on Saturday morning, with half the maximum current.

The maximum total active power in the three phases during the LAN-party 2002 was about 21kW, and the corresponding neutral current was 66A. The maximum allowed neutral current of harmonic order 3 and 9 according to IEC 610000-3-2 standard [10], table I, is 72.2 A. Corresponding neutral current for only 3:rd harmonic order, is 71.4 A. The measured neutral current during the LAN-party 2002 is lower than what is allowed according to IEC 610000-3-2 standard [10].

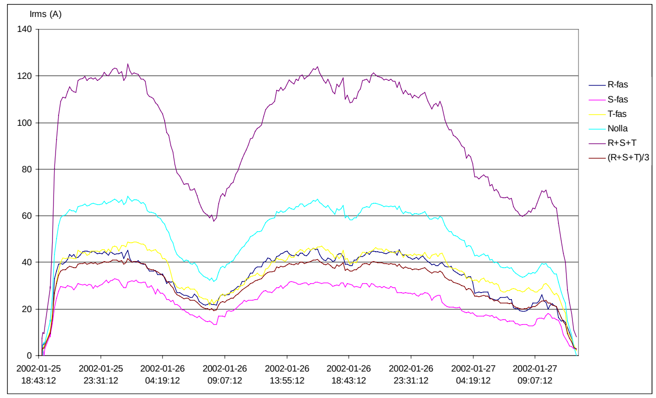

Figure 1. The three phase and the neutral currents during LAN 2002

The ratio in this case between the actual neutral current and the allowed neutral current, according to IEC 610000-3-2 standard [10] is 1.08.

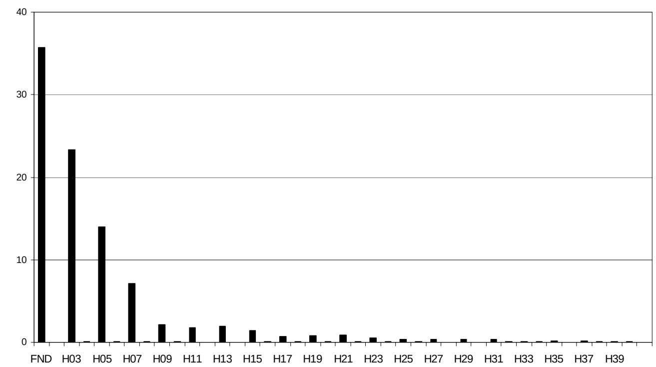

Figure 2. The phase currents harmonics during LAN 2002

A calculation according the ratio, N, between the neutral currents and the mean phase currents using the formula [4] had been made from the measured values during the LAN-party 2002 and the result is shown in figure 3.

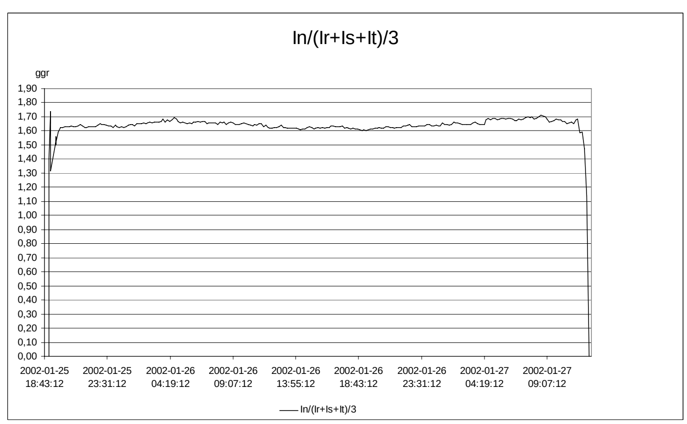

Figure 3. The three phase and the neutral currents during LAN 2002

The ratio is almost constant, around 1.65 although the phase currents vary, and close to the maximum value:

$$N_{\max} = 1{,}73 \text{ calculated in } [6]$$

The quotient between the maximum value $N_{\max}$ in formula 6 and the value N_{2002} in the LAN-party 2002 is:

$$\frac{N_{\max}}{N_{2002}} = \frac{1{,}73}{1{,}65} \approx 1{,}05 \qquad [7]$$

A comparison between formula 7 and 8 shown, that in this case, measuring on more than hundred computers and screens in a LAN-party installation, it seems that the IEC 610000-3-2 standard [10] has no consequence, in limiting the neutral current. However the IEC 610000-3-2 standard [10] is made to apply on single equipment and not in installations.

When the current in the neutral is higher than in the phase conductor, overload protection becomes difficult. The factor *N* should be as low as possible to prevent neutral overload and allow for effective overload protection.

TABLE III
FOUR LAN PARTIES

Year	Players + crew	Ratio N (se text)
2002	120+30	1,65
2003	440+30	1,48
2004	140+30	1,49
2006	120+30	1,25

Similar measurements were made during the three following LAN-party's, and together shown in Table II, the ratio N has slowly decreased from, N_{2002}=1,65, until N_{2006} =1,25.

2) *Measurements on computers and LCDs in lab*

Measurements made on three computers and three LCDs connected to three phases system in the laboratory are shown in figures 3-5

In figure 4 measurements made on three LCDs connected to three phases. The result is typical for a two-pulse diode rectifier charging a capacitor, the interface to the vast majority of computing and consumer-electronics equipment.

Comparing the phase voltage, in the top graph, and the corresponding phase current, in the second graph from top, shows the capacitor-charging event. The phase current flows only when the voltage is close to its peak value.

The shape of the current in the three other phases is the same but with a difference of 120° or 6,67 ms in a 50 Hz system. This current "pulse" is short (less than 60° or 3,33 ms, a 50 Hz system) in all three phases, so that there is no overlap and all the current is passing the neutral conductor.

In figure 5 measurements on three computers connected to three phases are shown. Comparing the current shape in figure 5 to the current shape in figure 4 shows a slower rise-time, longer pulse-time and a delay. The easiest way to create this delay is by introducing an inductor in front of the storage capacitor, a way to create passive PFC. The neutral current in figure 5 is continuous.

A combination of three LCDs and three computers connected to three phases is shown in figure 6. The phase current shows two peaks and the neutral current is continuous.

The combination of two types of loads is, as in this case positive, to reduce the neutral current, by increasing the overlap between the phase currents.

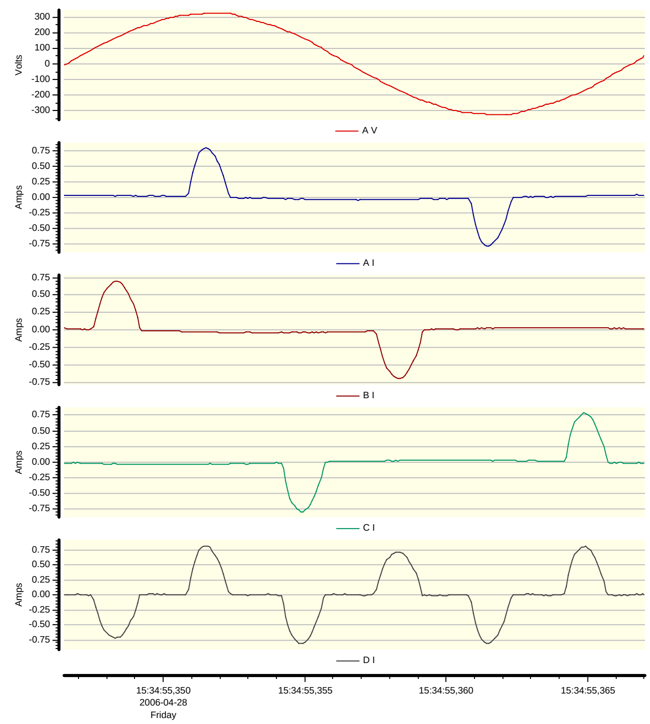

Figure 4. Measurements made on three LCD:s connected to three phases. The two top graphs showing a phase voltage and the corresponding phase current, next the two remaining phase currents and the neutral current.

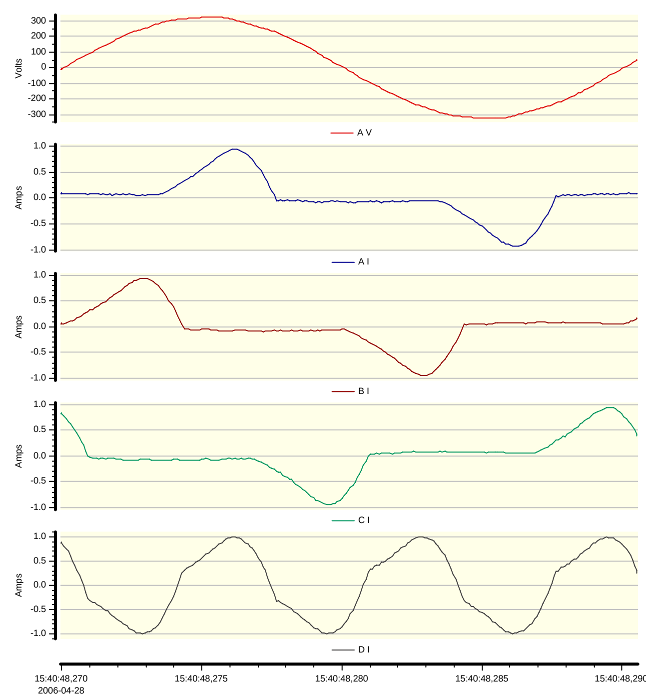

Figure 5. Measurements made on three computers connected to three phases. The two top graphs showing a phase voltage and the corresponding phase current, next the two remaining phase currents and the neutral current.

The measurements shown in figures 1-5 are an example when increasing number of equipment having a difference in construction results in a decreased neutral current. Connecting a increasing number of identical LCDs alone, as in figure 3, to an three phase system gives no reduction on neutral current, even if they comply with IEC 610000-3-2 [10].

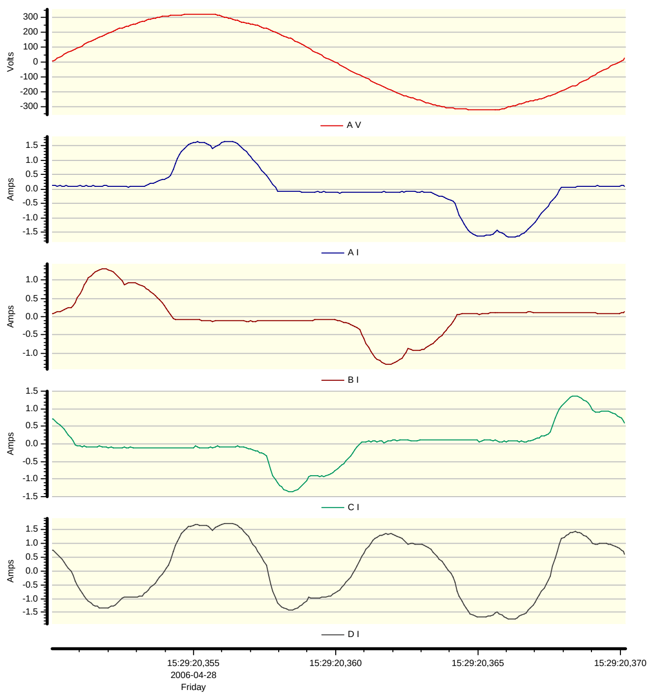

Figure 6. Measurements made on three LCD:s and three computers together connected to three phases. The two top graphs showing a phase voltage and the corresponding phase current, next the two remaining phase currents and the neutral current.

B. Fluorescent lighting

A measurement made on totally 120 fluorescent lamps connected to three phases in a storage depot is shown in figure 6. This lamps follows Class C, Table 1, in the IEC 610000-3-2 standard [10]. Phase L1 (on top) has 55 fittings connected, phase L2 (in the mid) has 56 fittings connected and phase L3 (at the bottom) has 9 fittings connected.

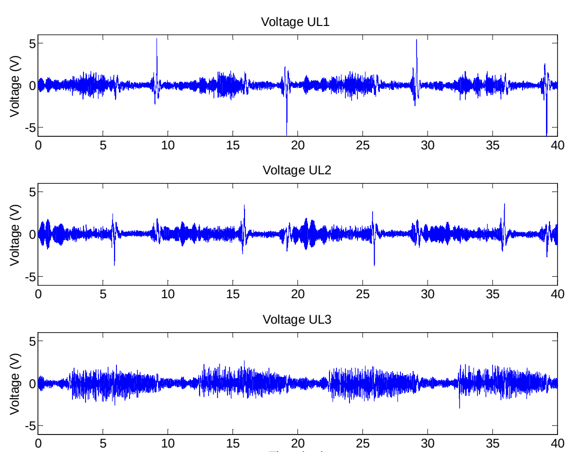

Figure 7. Measurements made on three phases of fluorescent lamps. Phase L1 (on top) has 55 fittings connected, phase L2 (in the mid) has 56 fittings connected and phase L3 (at the bottom) has 9 fittings connected.

The phase voltages are measured using filters having a high attenuation for the fundamental frequency. The filter has 4-dB attenuation in the pass band, shown in figure 8, so that the measured voltage has to be multiplied by 1.5 to get the actual amplitude.

All three phases in figure 7 show "peaks" in the voltages. The peak voltage is higher in phase L1 and L2, (after adjusting for filter loss) approximately 9 V, see figure 9, compared to 2-3V in phase L3. The same time phases L1 and L2 supply six times more lamps.

Similar measurements' at other locations having tens of fluorescent lamps per phase, show the same sort of "peaks", near the zero crossing of the fundamental current. In all these locations, problems with short lifetime of the HF-ballast have been reported.

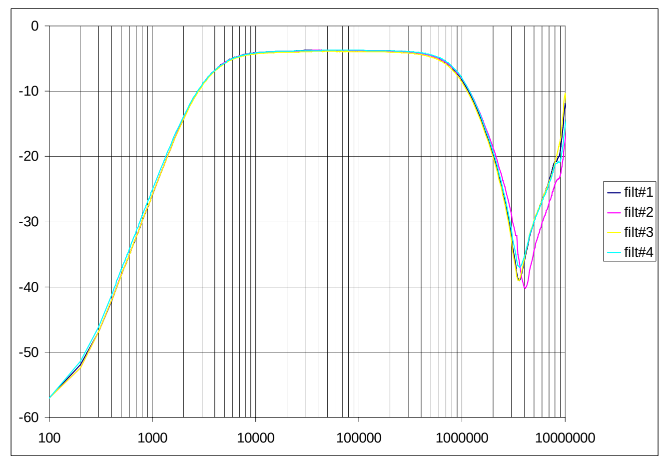

Figure 8. Frequency response in filter used for voltage measurements. The amplitude loss in the pass band is 4 dB

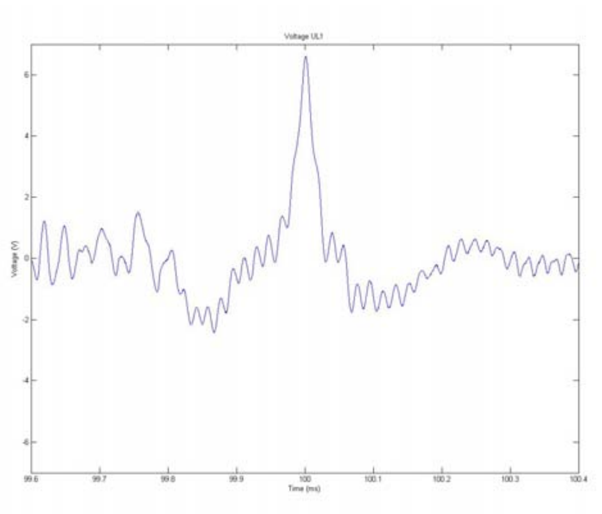

Figure 9. Detail of figure7, measurements made on fluorescent lamps.

Measurements on individual lamps and the relation between the number of fluorescent lamps and the peak voltage are studied in [9].

VI. Conclusions

The interest of low weight together with high power density and small losses in power converters has resulted in the use of diode rectifiers and fast switching techniques. This solution has besides a number of benefits two basic drawbacks: the fundamental frequency harmonic generation in the input diode rectifier and high-frequency harmonics from the switching units in the DC-DC converter.

IEC 61000-3-2 [10] sets limits, for the first drawback, current harmonics up to order 40, i.e. 2 kHz in a 50-Hz system or 2.4 kHz in a 60-Hz system. The use of an inductor [2], passive PFC, is often enough for computers, while the HF-ballast in fluorescent lamps often needs an active PFC.

Measurements and calculations are made on more than hundred computers and LCD/CRT in a dedicated three phase grid, and on three computers and LCDs in laboratory. It shows a ratio, between the neutral currents and the mean phase currents, being between 1.65 and 1.25. This result is close to maximum possible rate, 1.73, and the result is possible even though the equipment fulfill the IEC 61000-3-2 [10].

An active PFC allows a wide input voltage range, a displacement power factor close to 1.0 in combination with almost sinusoidal input current, but adds even more of the high-frequency harmonics. Besides the risk of interference there is a risk for equipment damage, especially with resonances.

Normally, resonances in the power grid are between passive components like inductors and capacitors at harmonic of the power-system frequency. Instability in active PFC circuits may also occur at other frequencies, and has been described as a switching-frequency instability "near the zero crossing of the input current" [6], [7], [8]. One fundamental reason to this "electronic instability" is a combination of the active PFC converters nonlinear behaviour and the choices of parameter values in the regulator [8].

The ac source influence on the stability has been shown for frequencies below 60 Hz [5]. Studies after the ac source influence near the switch frequency and the influence on numbers of parallel active PFC converters connected together are difficult to find. Although it is common to use SMPS and active PFC together in increasing numbers.

Measurement made on totally 120 fluorescent lamps connected to three phases in a storage depot, show "peaks" in the voltages near the zero crossing of the fundamental current. In these locations, and in others, problems with reduced lifetime of the HF-ballast have been reported. The amplitude of the "peaks" shows the tendency to increase with increasing number of fluorescent lamps [9].

If problems should occur, like equipment mal-functioning, damage, or reduced lifetime, when the number of units on a network increases, some sort of adjustment is needed.

This adjustment could be part of the product standards (for the emitting source, for the equipment showing problems, or for both), limiting the numbers of devices connected close together [11], or both.

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VIII. Biographies

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