# High Harmonic Distortion in a New Building due to a Multitude of Electronic Equipment

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***Abstract*—In modern buildings virtually all electric loads are non-linear. Neither the applicable standards for supply of electrical energy nor those for consumption of electrical energy take into account the replacement of linear loads by non-linear loads. Low power equipment is exempted in standards assuming that all other (linear) loads dominate the power quality. In modern buildings there is a huge number of non-linear loads in lighting, monitor, computer and small power supplies and only a very limited number (or no) conventional linear loads. This is causing unacceptable interference with costly consequences.**

**This paper analyzes current standards and the (exemptions for) harmonic current consumption of modern devices. The increase in harmonic distortion in a new building due to a multitude of non-linear equipment is shown. This forced the owner of the building to make costly changes in the power supply network.**

## I. Introduction

The electrical energy supplier, in public systems the utility, is responsible for providing a clean voltage. The customer is responsible for not causing excessive currents. The quality of supply (voltage) and the emission (of current) caused by electrical and electronic equipment has been defined and agreed in standards and often these standards are referred to in legislation. However, these standards have been developed in a time that linear (resistive) consumers damped unwanted effects caused by maybe very few non-linear electronic devices. This is changing very rapidly, because electrical motors are more and more controlled by electronic frequency converters, more electronic equipment is used in offices, factories and houses, and new lighting systems, consuming less energy, have been introduced. Especially the conventional incandescent lamps were useful loads to dampen unwanted effects caused by a few non-linear loads. Inductive loads consuming a high reactive power (VAr) could be compensated in the past by adding capacitors such that the power factor (pf) increased to 1.0, resulting in the same real or consumed power (W) as reactive power. In linear systems the ratio between the apparent power (VA) and real power is only a phase shift between current and voltage (cos φ), and is therefore also called the displacement power factor. This power/displacement factor is taken into account when planning the power capacity for a new building. Also the simultaneity is used. However, modern electronic systems often draw current during a very short period of time. This is causing harmonic distortion in the mains supply, and therefore we do not only talk about cos φ or displacement power factor but we should include the distortion power factor. However, we observed that electrical engineers are not (yet) aware of the distortion power factor. The utilities take into account a maximum level of harmonic distortion, as defined in the standards [1], [2]. Effectively, the utilities use medium-voltage (MV) to low-voltage (LV) transformers with some over-capacity, ranging from 10 up to 20%. Equipment installed in buildings is assumed to fulfill the standards for equipment [3], [4].

Measurements show that due to a multitude of equipment, all of them fulfilling the applicable standard, a high harmonic voltage distortion of the mains supply is occurring. The voltage supplied by the utility was clean, so the users created such a high harmonic current that the voltage at the mains transformers (4 MVA) was heavily distorted. The high harmonic currents resulted in over-heated transformers which forced the owner to upgrade the energy supply system completely, with high costs.

Ironically, own technicians foresaw the problems in the design phase already and advised against the consulting company's recommended 4MVA. However, the owner approved the advice based on estimated costs. After the harmonic distortion problems turned up, the consulting company was not available…

The conventional concepts about power factor do not include the impact of a multitude of non-linear loads in today's mains supply. A revision of these conventional concepts is needed urgently, considering the Smart Grid, Green Energy, and eMobility trends. Recommended practices for installing and using non-linear loads were already discussed two decades ago [5]. At that time, linear loads were the standard. References [6], [7] discuss the

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effect on power quality parameters when replacing incandescent lamps by energy saving lamps. The main focus is on the effect of these parameters on the public supply grid. The power supply in buildings is not taken into account. Reference [8] discusses the EN 61000-3-2 standard and provides methods for power factor correction for limiting the harmonic distortion and complying with this standard. However, a future edition of IEC 61000-3-2 has to take into account the factor 'number of pieces of equipment in use' [3] to prevent interference and reduce the risk of fire in neutral conductors and transformers.

This paper identifies the (serious) gaps in power quality (voltage) and electromagnetic compatibility (EMC) (current) standards. The measured harmonic current consumption of equipment installed in a new building will be shown. The increase of voltage total harmonic distortion (V-THD) in a new huge office building at our university due to a large amount of electronic equipment is shown, and the costly consequence is described.

## II. Power Voltage Standards

The power supply quality at the Point of Interface (POI) between the public supply grid and the user is defined in Europe in EN 50160, 'Voltage characteristics of electricity supplied by public distribution systems' [1]. An updated version is in preparation, EN 50160:2010/FprAA:2010 [9]. In the USA IEEE 519:1992 is being used [2]. For ground based military systems STANAG 4133, 4134, 4135, MIL-STD 1275, Def-Stan 61-5 are being used, and for military naval systems STANAG 1008, MIL-STD 1399, GAM EG13 E509, Def-Stan 61-5 and other national standards. The scope of these standards are confined to the electricity supplied at the supply terminals and does not deal with the supply system of the installation or equipment, the Power Distribution User Network (PDUN). The topology of public supply grid, POI, and PDUN is shown in Fig. 1.

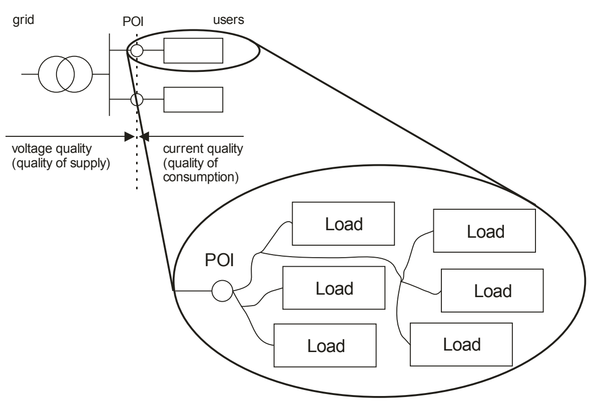


Fig. 1. The power supply and power distribution user network

The EN 50160 assumes the voltage characteristics by reference to the nominal voltage, but IEC 61000-4-30 references harmonic measurements to the value of the fundamental voltage component at the time of measurement [10]. In the CLC/TR 50422 [11] it is mentioned that it is typical for measuring instruments to reference harmonic measurements to the RMS voltage. Furthermore, it states that many measuring instruments, especially those indicating Total Harmonic Distortion (THD), reference harmonic measurements to the fundamental voltage component. In situations with a low THD the difference will be negligible. Measurements are being performed up to the 17$^{th}$, 20$^{th}$, 40$^{th}$ or sometimes even 50$^{th}$ harmonic, depending of the standard considered.

EN 50160 requires a V-THD of less than 8% for 95% of the 10 minutes mean RMS values during each period of one week. Furthermore, for each individual harmonic, up to the 25$^{th}$ order, a limit is defined of the same kind as for the THD. Table I lists a subset of these limits.

TABLE I
EN 50160 Harmonic Voltage Limits up to the 13$^{th}$ Order

| Harmonic Order n | Limit Mean RMS values (%) | Harmonic Order n | Limit Mean RMS values (%) |
|---|---|---|---|
| 2 | 2 | 8 | 0.5 |
| 3 | 5 | 9 | 1.5 |
| 4 | 1 | 10 | 0.5 |
| 5 | 6 | 11 | 3.5 |
| 6 | 0.5 | 12 | 0.5 |
| 7 | 5 | 13 | 3 |

The IEEE 519:1992 has different voltage harmonic limits. The V-THD is limited to 5% while each individual harmonic voltage distortion shall be less than 3%.

## III. Power Current Standards

The harmonic currents generated by electronic equipment will influence the voltage harmonic level. The level of the disturbance is a function of the magnitude of both the current and impedance. The emission limits of equipment are described in IEC 61000-3-2 [3] and IEC 61000-3-12 [4], IEEE519:1992 [2] and several of the military standards described in section II, and are established on the basis of a reference network impedance as defined in IEC 60725 [12]. As most standards developed by the power distribution people, this standard also contains only the network impedance defined for 50Hz. For The Netherlands, 95% of the users are assumed to see an impedance lower than 0.7+j0.25 ohm, which is equivalent to 0.7 Ω in series with 0.8 mH. The generic network impedance is defined as 0.24+j0.15 ohm for phase and 0.16+j0.1 ohm for neutral.

The current Total Harmonic Distortion (I-THD) is quantified by the injected harmonics. The relation between the individual harmonics and the I-THD is given by the equation:

$$I\text{-}THD = \sqrt{\sum_{n=2}^{40}\left(\frac{i_n}{i_1}\right)^2}$$

Where $i_n$ is the RMS amplitude of the nth harmonic of the mains current, and $i_1$ is the RMS amplitude of the fundamental component of the mains current.

The distortion power factor describes how the harmonic distortion of a load current decreases the average power transferred to the load. The circuit power factor is defined in IEC 61000-3-2 as the ratio of the measured active input power to the product of the supply RMS voltage and the supply RMS current. According the Directive of the European Parliament DIM1, the circuit power factor, $\lambda$, should be larger than 0.5.

Equipment put on the market within the European Union shall fulfill the essential requirements of the European Directive on EMC [13]. A presumption of conformity with this directive is based on compliance with harmonized standards. The limits in the harmonized standards are set in such a way that voltage distortion limits can be met, assuming certain load diversity. These limits should assure that the transformer that connects customers to the utility does not transport harmonic currents in excess of 5 % of its rated current.

Devices with a rated current smaller than or equal to 16 A per phase have to comply with the standard IEC 61000-3-2:2005 in terms of harmonic current emission. Devices with a rated current higher than 16 A and smaller than or equal to 75 A per phase have to comply with the standard IEC 61000-3-12:2004.

Equipment with a rated current up to 16 A are subdivided into four classes, based on the device type and usage, with separate emission limits for every class.

Class A (normal usage)
- balanced three-phase equipment
- household appliances
- tools
- dimmers for incandescent lamps
- audio equipment

Class B (very short usage)
- portable tools
- arc welding equipment

Class C (continuous usage)
- lighting equipment

Class D (normal usage but special current wave shape)
- PC's
- PC monitors
- TV-sets

Depending on the rated power of the equipment, limits are specified as absolute (in amperes), relative (as a percentage of the fundamental current or rated active power times a constant). As an example, the limits for Class C equipment are listed in Table II.

The limits from the standard IEC 61000-3-12:2004 are divided into three categories: balanced three-phase devices, balanced three-phase devices under specified conditions, and other devices. All limits from this standard are specified as relative (percentage of the fundamental current), but the main difference to the approach in the standard IEC 61000-3-2:2005 is that the limits are dependent on the short circuit ratio of the system at the point of intended connection and the device. The higher this ratio is, the higher is the allowed emission of the device in percents. The short circuit ratio is defined as the ratio of the short circuit power of the system and the equivalent apparent power of the device. The equivalent apparent power is defined as the maximum phase apparent power of the device (for single-phase equipment it is the apparent power of the device, for devices with two or three phases it is the highest of its phase values) multiplied by three. In the case of balanced three-phase equipment it is equal to the rated apparent power of the device.

TABLE II
CURRENT 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 | $30\cdot\lambda$ |
| 5 | 10 |
| 7 | 7 |
| 9 | 5 |
| $11\leq n\leq 39$ | 3 |

* $\lambda$ is the circuit power factor

## IV. GAPS IN STANDARDS

The number of harmonic sources is rapidly increasing while at the same time the portion of purely resistive loads (heating loads) which functions as damping elements is decreasing in relation to the overall load. Furthermore, the number of phase lagging loads like motors and transformers which are linear is also decreasing and are being replaced by non-linear switching front-ends. Therefore, increasing harmonic levels are observed in power supply systems.

We can observe a mismatch between the voltage THD for the utility and the current THD of the connected electronic equipment, the loads. First, the interface between the POI and the load is not taken into account. Also, the number of (non-linear) loads is not considered. A key issue is the exemption for small loads. A large number of small loads is as worse as one large non-linear load.

The standards described in the earlier section are applicable to most equipment, but there are several exceptions. Major exceptions are:

- Equipment (not lighting) < 75W
- Professional equipment > 1000W
- Symmetrical heating control < 200W
- Independent dimmers for incandescent lamps <1000W

Moreover, the limits for LED lamps as well as for fluorescent lamps below 25W are under development, i.e. for the time being there are no limits. There will be no limits below 5W. In Europe all incandescent light bulbs are being replaced at the moment by these highly non-linear and polluting (from an electromagnetic point of view) loads.

These gaps are causing an increasing number of problems now. The non-linear switching front-ends of frequency converters have a conventional rectifier diodebridge, such as shown in Fig. 2, and only in the top of the sine a current pulse is drawn to charge the capacitor. The measured current consumption of a dimmer is shown in Fig. 3.

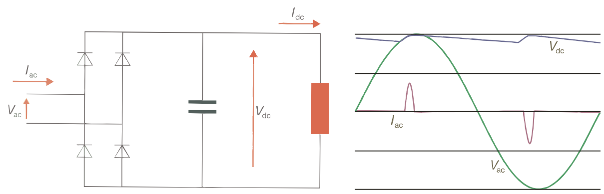


Fig. 2. Conventional rectifier (left) and its terminal voltages and currents (right) [14]

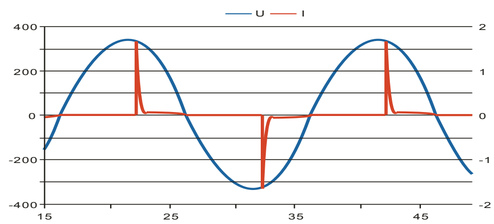


Fig. 3. Current consumption (red) of dimmer

Fig. 4 and Fig. 5 show measured waveforms for an 11W CF light and a 1.2W LED. The incandescent light bulb generated zero harmonics, while the 'energy saving' electronic lighting equipment creates high 3$^{rd}$ and 9$^{th}$ harmonic currents which appear in the neutral conductor (neutral is not neutral anymore). The CF, giving the same amount of visible light of a 60W incandescent light bulb, needs an apparent power of 19VA and draws a peak-to-peak current of 0.58A. The 1.2W LED, giving the same lumens as a 10W incandescent light bulb, needs an apparent power of 4.5VA and draws a peak-to-peak current of 0.10A. Because the utility has to deliver the VA, the 'energy saving' is limited…

The high I-THD of many loads, combined with the PDUN impedance caused a high V-THD at the end of a line in a user installation, such as shown in Fig. 6. The dual crossing of the 0 V line caused some other equipment to trip.

## V. Consequences of High THD

The non-linear loads with an identical harmonic spectrum, connected to a three-phase "wye" distribution network, caused a cumulation of the 3rd harmonic and its uneven multiples (9th, 15th, 21st, etc.) in the neutral or Protective Earth Neutral (PEN) conductor. This can cause an overload of these conductors. As the current in those conductors is normally not monitored, there is a danger that they will overheat and catch fire.

Mains power supply filters with large Y-capacitors connected to a power supply with high V-THD, result in large leakage currents. These will cause malfunctioning of the RCD (residual current devices). Furthermore, the distortion degrades the lifetime of the Y-capacitors.

A third consequence of high I-THD is overheating of transformers. In general, the utility and building owner design a medium-to-low voltage transformer based on power factor (displacement), and use of the building. In modern buildings with many non-linear loads the distortion factor shall also have to be taken into account.

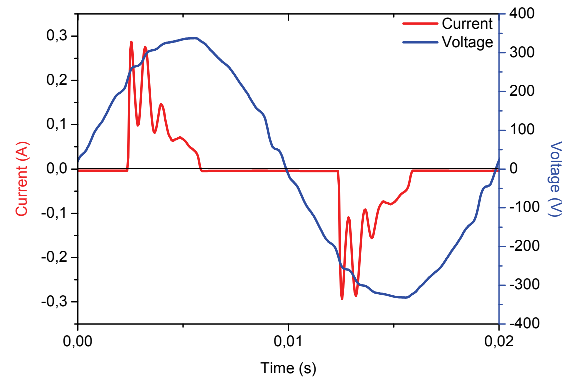


Fig. 4. Measured waveforms 11W CF light

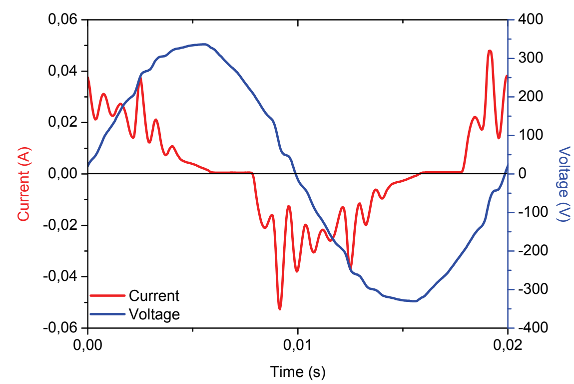


Fig. 5. Measured waveforms 1.2W LED

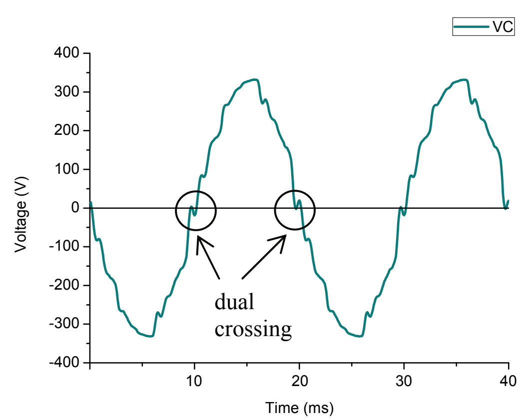


Fig. 6. Measured distorted voltage waveform

## VI. THD in Large Building

Because of the high V-THD of the mains supply, measurements have been performed on the PDUN of a new office building, Carré, at our university. The building is 5 storeys high and has a total floor area of 36,000m$^2$. This large floor area is divided up by lecture, study, office, meeting and laboratory rooms. A picture of the Carré building is shown in Fig. 7.

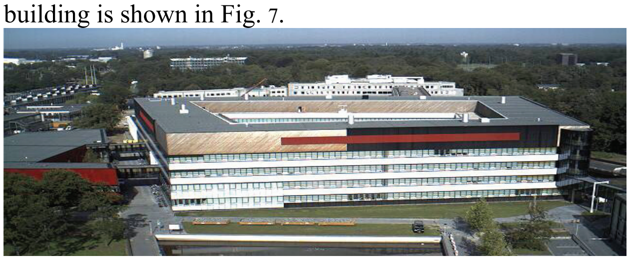

Fig. 7. The east side of the new office building

The electrical supply of the Carré building consists of 4 transformers each having an apparent power of 1000 kVA. The capacity was based on the conventional approach, including aspects like displacement factor and simultaneity. In the design only a 'standard' harmonic distortion was taken into consideration.

From the main switchboard the electrical supply is divided over the five floors. At each floor a couple of distribution boards divide the electrical supply over the rooms. A redeveloped lecture and conference hall was also fed from the Carré building supply.

The voltage total harmonic distortion (V-THD) is measured at three locations ($M_1$, $M_2$, $M_3$) along the path from main switchboard via distribution board to office in the Carré building. A schematic of this path is shown in Fig. 8.

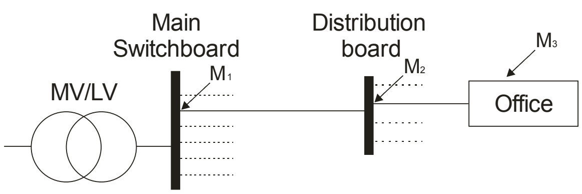


Fig. 8. Schematic of distribution of power supply in Carré: $M_1$, $M_2$ and $M_3$ designate the measurement locations

Two measurement devices are used in this measurement, the PSL PQube and the Dranetz PowerXplorer PX5-400. During the measurement, the PQube is used as reference and measures the voltage in the office. The PowerXplorer is moved along the path to measure the voltage at the three different locations.

At the main switchboard, the low voltage side of the connected feeding transformer is directly measured. This gives the opportunity to measure the voltage of an unloaded transformer while its load is temporarily connected to another transformer. A window of 10 periods is recorded just before and after switching the load. The results are shown in Table III as well as in Fig. 9 and Fig. 10. They show that the voltage supplied by the utility is clean. When the loads are disconnected from the transformer, the VTHD is around 1% for all three phases, while the RMS voltage differs at maximum 5V from the load-connected condition.

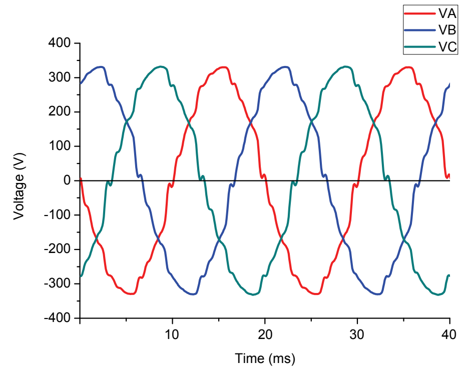


Fig. 9. Measured voltage waveforms transformer with load

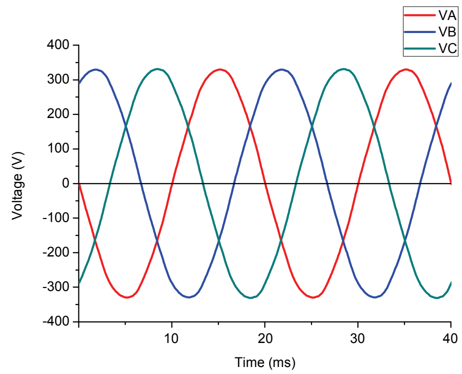


Fig. 10. Measured voltage waveforms transformer without load

TABLE III
MEASUREMENT RESULTS I

| Location | VTHD (% FUND) Transformer with load | | | VTHD (% FUND) Transformer without load | | |
|---|---|---|---|---|---|---|
| | VA | VB | VC | VA | VB | VC |
| Main Switchboard $M_1$ | 5.4 | 5.4 | 5.7 | 1.2 | 0.9 | 1.0 |

The results of the measurements at the three different locations along the path are listed in Table IV. To reduce the high distortion level the lecture and conference hall was disconnected from the Carré building supply and got its own supply. For this, two extra 1600 kVA transformers had to be installed. The measurement was repeated and the results are also shown in Table IV.

TABLE IV
MEASUREMENT RESULTS II

| Location | VTHD (95% limit) Lecture and conference hall connected | | | VTHD (95% limit) Lecture and conference hall disconnected | | |
|---|---|---|---|---|---|---|
| | VA | VB | VC | VA | VB | VC |
| Main Switchboard $M_1$ | 5.3 | 5.4 | 5.7 | 2.4 | 2.3 | 2.3 |
| Distribution board $M_2$ | 5.8 | 5.9 | 6.7 | x | x | X |
| Office $M_3$ | | | 6.7 | | | 3.1 |

Both the construction of the modern Carré building as the redevelopment of the lecture and conference hall are enforced to comply the applicable directives and regulations. However, as a result of the I-THD of a multitude of modern ('energy saving') equipment, the V-THD was much higher than expected. The distorted current due to the non-linear loads results in a voltage drop across the transformers and feeding lines in the installation, resulting in a distorted voltage inside the installation and overheating of transformers. After removing the redeveloped lecture and conference hall from the Carré building supply the V-THD dropped by a factor 2. The total supply apparent power amounts to 7.2 MVA, while it was reckoned with 4.0 MVA. The real power consumption is still below 3 MW.

## VII. Conclusion

Actual standards for power delivery and consumption fails to take into account the effect of connecting a multitude of modern equipment to the mains supply. While modern equipment are non-linear low power consumers and therefore reducing the overall energy consumption, the summation of all these sources are causing a rapidly increasing harmonic distortion of the mains supply. This resulted in higher currents in neutral conductors (assumed to conduct zero current), overheated transformers and redesign of the power supply network. The conventional approach is to use the displacement (power) factor and simultaneity to determine the power supply. These methods cannot be applied anymore, because the distortion factor will determine the total apparent power. The 'energy saving' lighting do reduce the consumed real power, but will still cause a high apparent power connection. The conventional concepts of power factor, displacement factor, distortion factor and determination of needed power need to be revised. We should also re-consider the standards in which low-energy consumers have been excluded.

## Acknowledgment

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