THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# On Harmonic Distortion in Power Systems

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Cover:
Voltage and current distortion caused by a modern six pulse diode rectifier.
See further in Chapter 3.

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## Abstract

The research presented in this thesis concerns the sources of distortion (loads) and the interaction between those and the propagation of the distortion in the power system. Effects on the power system are also studied, e.g. additional losses, harmonic resonance and related financial costs to this. Further, mechanisms affecting the harmonic active power flow, in a certain point, are shown. A new mechanism concerning harmonic current interaction in high voltage transmission systems, due to a difference in the fundamental voltage phase angle between two nodes, is addressed.

The conclusions are that non-linear loads generates current distortion up to 200 % THD. The tendency for modern loads is a reduction of the lower order harmonics, below 1 kHz, and an increase of higher frequency components, up to 100 kHz. The current distortion decreases at higher voltage levels, around 5 % THD, mainly due to mixing with passive loads but also due to current interaction between single and three phase non-linear loads. The voltage distortion is also highest at low voltage levels, mostly below 6 % THD, and decreases down below 2 % at higher voltage levels. A dominating source of distortion, at all public voltage levels, is the use of television receivers at evening time with dominating 5:th and 7:th harmonics, up to 0.5 % of the fundamental component at 130 kV and 400 kV levels.

Other phenomena affecting the distortion is series and parallel resonance, around harmonic order 7 at low voltage levels and around order 10 at high voltage levels. Further, long line resonance, current interaction due to difference of the fundamental voltage phase angle between nodes and fundamental voltage unbalance also affects.

Additional losses are globally small, below one tenth of a percent of the total active power flow, but can locally be some percent.

**Keywords:** Power Quality, Harmonic Distortion, Power System Monitoring, Rectifiers, Drives, Converters, Voltage Notching, Active power, Losses, Harmonic Propagation, Resonance, Harmonic Filter, Unbalance.

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Finally, I owe the nearest standing me my deepest gratitude, especially my family, for understanding and encouragement throughout this work. Thank you Christina and our two sons, Julius and Oskar, for always letting me sit and write in the cellar. Now there will be some more time for skiing and sailing…

# Contents

# 1 Introduction

The use of electric energy is, in developed countries around the world, a natural part of life. It is used everywhere for living, work and travelling, at any residence, commercial building, industry and so on. The number of electrical devices connected to the power system, during the century, has increased enormously, with the main increase having been during the last 20 – 25 years. The total power demand has also increased but not at the same rate as the number of devices connected. This is due to more power efficient equipment being used, both for new devices and older replaced devices. The power system itself has been enlarged to meet the increased consumption but for many regions it was built in the early beginning of the increase. There are differences for different voltage levels and of course a large variation among different countries. Large electrical hydro production units are also from this early period. Nuclear power stations came later. Today renewable energy sources are more and more popular, like wind turbines and solar power.

With the good aim to introduce new techniques, to achieve better performance, to be able to control and to transfer more power over the power system and to reduce the power consumption of the loads, also a new topic was introduced: Power Quality. These new techniques consist of non-linear components that are used to control the load current. The current became distorted, i.e. deviates from the ideal sinusoidal waveform, and can be described by harmonic and interharmonic currents. Many of these new devices are more sensitive to the voltage quality than conventional linear loads.

The phrase “Power Quality” has been widely used during the last decade and includes all aspects of events in the system that deviates from normal operation. It is however more correct to distinguish between voltage and current quality, rather than power quality.

Power quality is part of the wider concept, EMC (Electro Magnetic Compatibility).

## Aim of the research

Research, in general, on harmonic distortion aims at characterizing the distortion, the behaviour of the loads and the power system. Also the effects the distortion has on loads, the system and the environment are studied.

The research presented in this thesis concerns the sources of distortion (loads) and the interaction between those and the propagation of the distortion in the power system. Effects on the power system are also studied, e.g. additional losses, harmonic resonance and related financial costs. Further, mechanisms affecting the harmonic active power flow, in a certain point, are shown. A new mechanism concerning harmonic current interaction in high voltage transmission systems, due to a difference in the fundamental voltage phase angle between two nodes, is addressed.

## Outline of the thesis

### Chapter 1: **Introduction**

Gives an overview of the subject and the contents of the chapters in the thesis.

### Chapter 2: **Definitions and terminology**

Presents the most commonly used and related theory of harmonics.

### Chapter 3: **Sources of harmonic distortion**

Mainly based on field measurements with some simulations of the sources of distortion.

Parts of this chapter is published and presented in: J. Lundquist, “Field measurements of harmonic distortion and the role of the DC-Link inductor”, ICHQP ‘98, Athens, Greece, 1998.

### Chapter 4: **Distortion at different voltage levels**

Based on field measurements at 0.4 kV, 130 kV and 400 kV level. Shows typical variation of the distortion and effects due to interaction between loads and the power system. The behaviour is analyzed.

### Chapter 5: **Harmonic active power flow**

Describes the mechanisms of harmonic active power flow, in a certain point in the power system. Also the total power flow, affected by harmonic filters, is shown and the total losses and financial costs related to this are studied.

Parts of this chapter is published and presented in: J. Lundquist, M.H.J. Bollen, "Harmonic active power flow in low and medium voltage distribution systems", IEEE Power Engineering Society, Winter Meeting, January 2000, Singapore.

### Chapter 6: **Conclusions**

General and specific conclusions, from the field measurements, are presented. Also the linearity of the source and load impedance is discussed.

### Chapter 7: **Future work**

Gives the most important subjects that are to be studied to access the consequences of harmonic distortion and for the modeling of the whole system.

### Chapter 8: **References**

Lists the references.

### Appendix: **A**

Frequency spectra of the voltage and currents at nighttime, morning time, daytime and evening time for the high voltage measurements (130 and 400 kV), in chapter 4.

# 2 Definitions and Terminology

This chapter gives an overview of methods for the analysis of distortion in power system and some related, commonly used, indexes that gives information of the waveform deviation in condensed form.

## 2.1 General definitions

Any periodic signal (waveform) can be described by a series of sine and cosine functions, also called Fourier series.

$$u(t) = U_{\mathrm{dc}} + \sum_{n=1}^{\infty}\left(U_{(n)\mathrm{s}}\sin(n\omega t) + U_{(n)\mathrm{c}}\cos(n\omega t)\right) \qquad (2.1)$$

The coefficients are obtained as follows:

$$U_{(n)\mathrm{s}} = \frac{1}{\pi}\int_{0}^{2\pi} u(t)\sin(n\omega t)d\omega t \qquad (2.2)$$

$$U_{(n)\mathrm{c}} = \frac{1}{\pi}\int_{0}^{2\pi} u(t)\cos(n\omega t)d\omega t \qquad (2.3)$$

where $n$ is an integer and $\omega = 2\pi/\mathrm{T}$. T is the fundamental period time.

**The Discrete Fourier Transform (DFT)**

For a discrete/sampled signal, the frequency spectrum can be obtained as follows:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-\mathrm{j}2\pi\frac{k}{N}n} \qquad (2.4)$$

where $N$ is the number of samples over the period T, $x(n)$ is the amplitude at each sample and $k$ = 0, 1, 2, ..., N-1.

Each frequency is also here separated by 1/T, with the highest frequency component at k = N/2.

The highest frequency becomes: $\frac{N}{2T}$

### Sampling frequency to avoid aliasing (Nyquist frequency)

$$f_s > 2\, f_{(n)} \tag{2.5}$$

### Signal energy in time and frequency domain (Parceval’s relation)

$$\int_{-\infty}^{\infty} v^2(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left|V(\omega)\right|^2 d\omega \tag{2.6}$$

### Waveform distortion

- Odd harmonics give half wave symmetric distortion.

- Even harmonics give half wave unsymmetrical distortion.
  Note: DC-components give the same result.

- Interharmonics give unsymmetrical distortion between periods.

See also chapter 3.

### Window size of the analyzed signal

Different window sizes give different frequency spectra for a fluctuating distorted signal, i.e. the signal is not periodic or the window size is not chosen to cover the whole period.

If the window size is 20 ms (one cycle at 50 Hz) the resolution in the frequency domain is 50 Hz. Thus, no frequency components can be found between multiples of 50 Hz. If the window size is 10 cycles the resolution is 5 Hz.

See also chapter 3.

## Total harmonic distortion

$$THD_U = \frac{\sqrt{\sum_{n=2}^{\infty} U_{(n)}^2}}{U_{(1)}} \tag{2.7}$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_{(n)}^2}}{I_{(1)}} \tag{2.8}$$

## Total demand distortion, only for the current

$$TDD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_{(n)}^2}}{I_{(1)\text{rated}}} \tag{2.9}$$

## Effective value

$$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u(t)^2\,dt} = U_{(1)}\sqrt{1+THD_U^2} \tag{2.10}$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i(t)^2\,dt} = I_{(1)}\sqrt{1+THD_I^2} \tag{2.11}$$

Example:

$THD_U = 10\ \%$ ➔ $U_{RMS} = 1.005U_{(1)}$
$THD_U = 25\ \%$ ➔ $U_{RMS} = 1.031U_{(1)}$
$THD_U = 50\ \%$ ➔ $U_{RMS} = 1.118U_{(1)}$
$THD_U = 100\ \%$ ➔ $U_{RMS} = 1.414U_{(1)}$

For low distortion levels, as for the voltage, $U_{RMS} \approx U_{(1)}$. This applies not for higher distortion levels, as for the current.

**Active power, mean instantaneous power (total active power)**

$$P = \frac{1}{T}\int_0^T u(t)i(t)dt = P_{\mathrm{dc}} + \sum_{n=1}^{\infty} P_{(n)} \quad \text{where } P_{(n)} = U_{(n)} I_{(n)} \cos(\varphi_{(n)}) \tag{2.12}$$

**Reactive power**

$$Q = Q_{(1)} + \sum_{n=2}^{\infty} Q_{(n)} \quad \text{where } Q_{(n)} = U_{(n)} I_{(n)} \sin(\varphi_{(n)}) \tag{2.13}$$

**Apparent power**

$$S = U_{RMS} \cdot I_{RMS} \tag{2.14}$$

**Distortion power**

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{2.15}$$

**Power factor (total power factor)**

$$pf = \frac{P}{S} \tag{2.16}$$

**Fundamental displacement factor**

$$\cos(\varphi_{(1)}) = \frac{P_{(1)}}{U_{(1)} \cdot I_{(1)}} \tag{2.17}$$

**Crest factor**

$$C_r = \frac{\hat{u}}{U_{RMS}} \tag{2.18}$$

## 2.2 Harmonics in three phase systems

### Balanced conditions, system and loads

Fundamental voltages and currents in a balanced three phase system are shifted one-third of a cycle compared to each other

$$\begin{aligned} i_{\mathrm{R}}(t) &= i(t) \\ i_{\mathrm{S}}(t) &= i(t - T/3) \\ i_{\mathrm{T}}(t) &= i(t + T/3) \end{aligned} \tag{2.19}$$

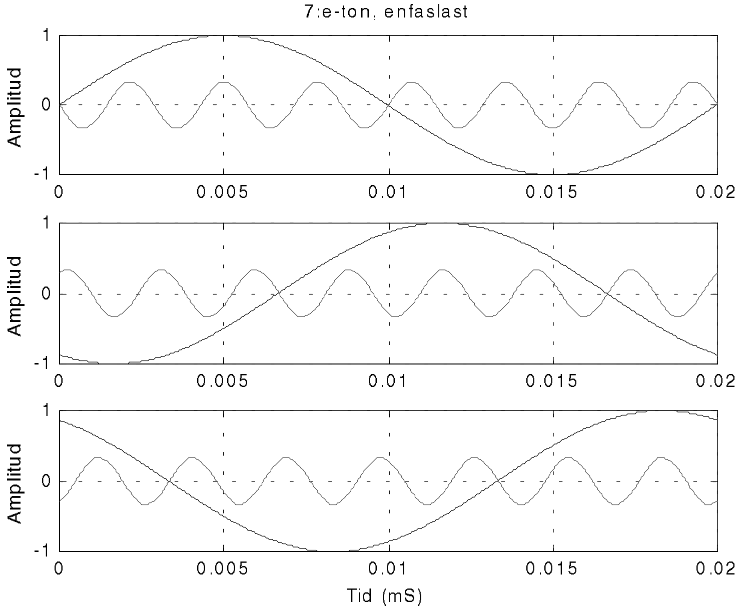
This results in a shift for the harmonics

$$\begin{aligned} i_{\mathrm{R}(n)}(t) &= \sqrt{2} I_{(n)} \cos\left(n 2\pi f_0 t + \phi_{(n)}\right) \\ i_{\mathrm{S}(n)}(t) &= \sqrt{2} I_{(n)} \cos\left(n 2\pi f_0 t + \phi_{(n)} - n\frac{2\pi}{3}\right) \\ i_{\mathrm{T}(n)}(t) &= \sqrt{2} I_{(n)} \cos\left(n 2\pi f_0 t + \phi_{(n)} + n\frac{2\pi}{3}\right) \end{aligned} \tag{2.20}$$

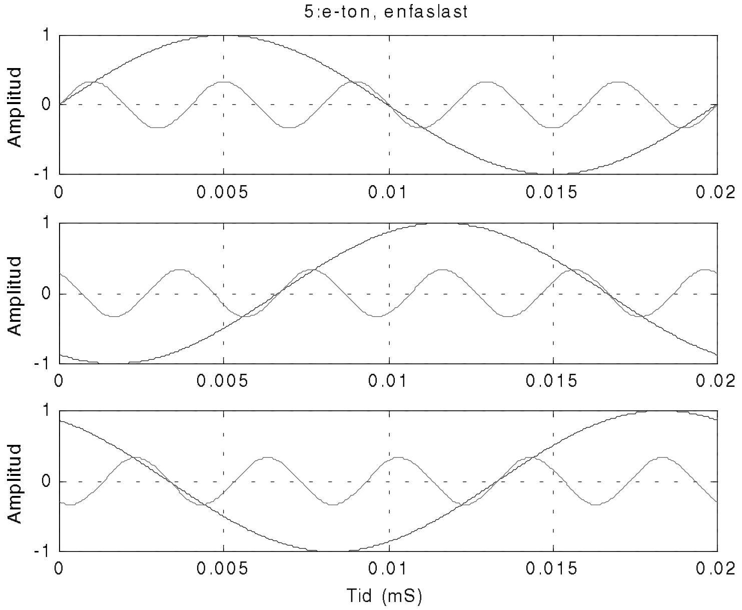
For the 7:th harmonic the current becomes, see also figure 2.2.1:

$$\begin{aligned} i_{\mathrm{R}(7)}(t) &= \sqrt{2} I_{(7)} \cos\left(7 \times 2\pi f_0 t + \phi_{(7)}\right) \\ i_{\mathrm{S}(7)}(t) &= \sqrt{2} I_{(7)} \cos\left(7 \times 2\pi f_0 t + \phi_{(7)} + \frac{2\pi}{3}\right) \\ i_{T(7)}(t) &= \sqrt{2} I_{(7)} \cos\left(7 \times 2\pi f_0 t + \phi_{(7)} - \frac{2\pi}{3}\right) \end{aligned} \tag{2.21}$$

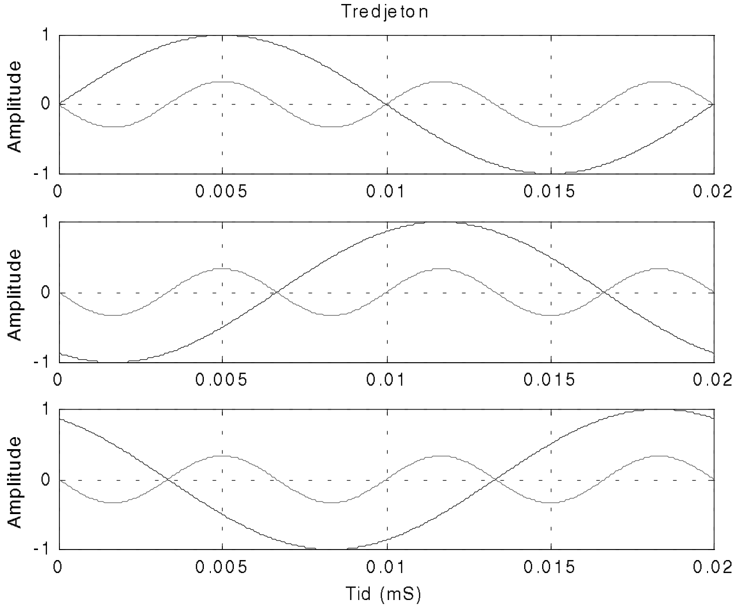
In figure 2.2.1 and 2.2.2 the 5:th and 7:th harmonic currents are plotted with a phase angle as for a single phase non-linear load. For a three phase non-linear load, the phase angles are phase shifted 180 degrees, both for the 5:th and the 7:th harmonic currents. The sequence systems do however not change.



2.2.1. Positive sequence 7:th current harmonic, single phase non-linear loads. Phase R (top), S (middle) and phase T (bottom).



2.2.2. Negative sequence 5:th current harmonic, single phase non-linear loads. Phase R (top), S (middle) and phase T (bottom).



2.2.3. Zero sequence 3:th current harmonic, single phase non-linear loads. Phase R (top), S (middle) and phase T (bottom).

Zero sequence third harmonic currents, figure 2.2.3, exist only for single phase non-linear loads, during balanced conditions.

Harmonics of different order form the following sequence set:

| | |
|---|---|
| Positive sequence: | 1, 4, 7, 10, 13, … |
| Negative sequence: | 2, 5, 8, 11, 14, … |
| Zero sequence: | 3, 6, 9, 12, 15, … (called triplen) |

The positive sequence system has phase order R, S, T (a, b, c) and negative sequence system has phase order R, T, S (a, c, b). In the zero sequence system the three phases have an equal phase angle.

## Unbalanced conditions, Symmetrical components

During load unbalance or unbalance of the power system all harmonics and the fundamental can consist of any sequence component.

$$\begin{bmatrix} U_{1(n)} \\ U_{2(n)} \\ U_{0(n)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} U_{\mathrm{R}(n)} \\ U_{\mathrm{S}(n)} \\ U_{\mathrm{T}(n)} \end{bmatrix} \qquad a = e^{j120^\circ} \qquad (2.22)$$

In most cases the “natural” sequence component is dominating for each harmonic with small contribution from the other sequences, but for the triplen harmonics there can during some conditions be only positive- and/or negative components.

See also chapter 3 and 4.

## 2.3 Circuit analysis methods

The most important aspects for the study of harmonic distortion propagation in power system are given below.

- The power system, i.e. generators, transformers, lines, cables is assumed to be linear.

- Loads can be either linear or non-linear.

- Assume there is no cross coupling between harmonics with different frequencies. In reality there is a cross coupling between harmonics with different frequencies. A strong coupling is present between the fundamental voltage component and the current harmonics from a non-linear load.

- Frequency domain: Easy method. Consider each component and use superposition. Iterate to reach steady state.

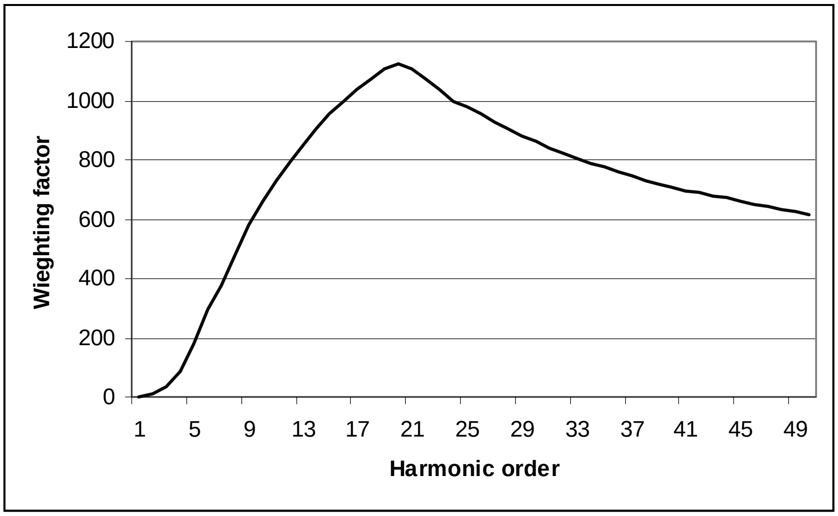
- Time domain: More difficult equations but faster and more accurate when simulating.

- Always study the power system as a three phase system.

- A study in the dq-frame (Park transformation) does not simplify the analysis or the understanding of the behaviour of the distortion.

## 2.4 Telephone psophometric current

Harmonic currents, mainly zero sequence, in distribution and transmission lines cause a magnetic field that can induce voltages in a nearby located telephone line. Each harmonic frequency, including the fundamental, is weighted with a factor [64], figure 2.4.1, taking into account the audio response of the human ear and a microphone. A similar curve exists in the USA, called TIF (Telephone Interference Weighting Factor), see [59].



2.4.1. Psophometric current weighting factors, $P_\mathrm{f}$.

The so-called psophometric current is calculated as

$$I_\mathrm{p} = \frac{1}{P_{800\,Hz}} \sqrt{\sum_{n=1}^{\infty} \left(P_\mathrm{f} \cdot I_n\right)^2} \quad \text{where } P_{800\mathrm{Hz}} = 1000. \qquad (2.23)$$

In chapter 4 the values are calculated from the high voltage measurements.

# 3 Sources of harmonic distortion

Non-linear equipment or components in the power system cause distortion of the current and to a lesser extent of the voltage. These sources of distortion can be divided in three groups:

- loads
- the power system it self (HVDC, SVC, transformers, etc)
- the generation stage (synchronous generators)

Subdivision can also be made regarding the connection at different voltage levels. In general, loads can be considered connected at lower voltage levels, the power system exists at all voltage levels and the generation stage at low and medium voltage levels.

The dominating distortion-producing group, globally, are the loads. At some locations HVDC-links, SVC's, arc furnaces and wind turbines contributes more than the other sources. The generation stage can, during some special conditions, contribute to some voltage distortion at high voltage transmission level.

The characteristic behavior of non-linear loads is that they draw a distorted current waveform even though the supply voltage is sinusoidal. Most equipment only produces odd harmonics but some devices have a fluctuating power consumption, from half cycle to half cycle or shorter, which then generates odd, even and interharmonic currents. The current distortion, for each device, changes due to the consumption of active power, background voltage distortion and changes in the source impedance.

In this chapter an overview will be given of the most common types of current waveforms from single and three phase non-linear loads for residential and industrial use. Most of the waveforms are obtained from field measurements. Influences on the current distortion of the supply voltage background distortion and fundamental voltage unbalance are also addressed.

## 3.1 Single phase loads

Electronic equipment, supplied from the low voltage power system, rectifies the ac power to dc power for internal use at different dc voltage levels. This is done, either with or without an ac step down transformer, and a diode rectifier. The dc voltage is smoothed by a dc capacitor, see figure 3.1.1. The power range for each device is small, from a few W up to some kW. The total harmonic distortion, THD, of the line current is often over 100 % and consists of all odd multiples of the fundamental component. In some case the THD can be nearly 150 %, mainly depending on the design of the DC-link and the crest factor of the supply voltage.

This group is used both by households and by industry. It consists of:

- TV’s
- Video recorders
- Computers
- Printers
- Micro wave ovens
- Adjustable speed drives (low power)
- H.F. fluorescent lighting
- Small UPS’s
- etc

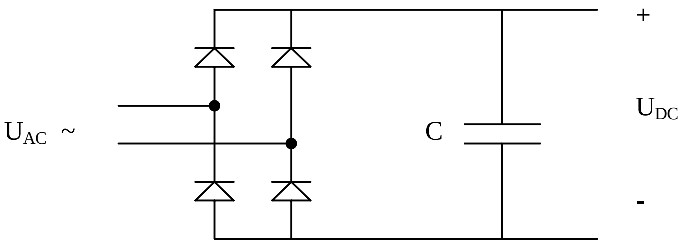


Figure 3.1.1. Single phase, two-pulse diode rectifier with capacitive DC-link.

The line current becomes pulsed, figure 3.1.2. The current starts to flow when the supply voltage is higher than the voltage over the DC capacitor, in figure 3.1.1, and stops when the voltage difference is zero. The example, shown in figure 3.1.2, is from a television receiver with a diode rectifier.

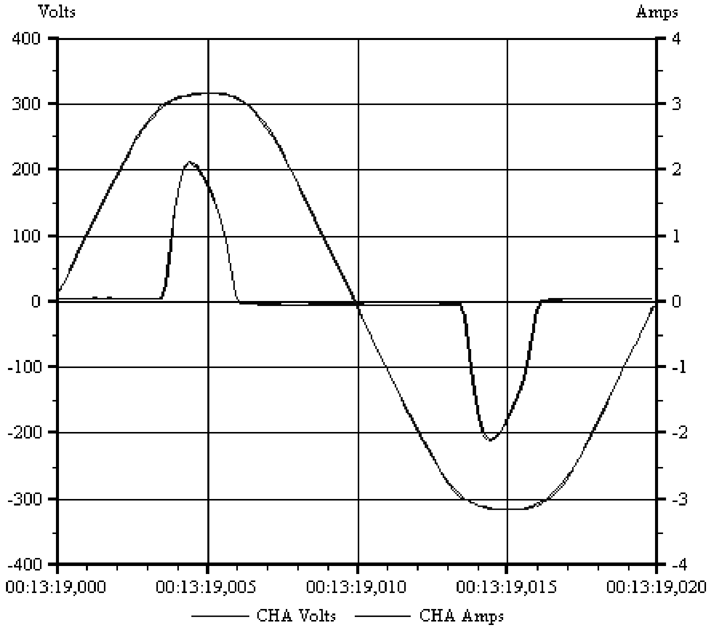


Figure 3.1.2. Phase voltage (continuous) and phase current (pulsed) to a television receiver.

For diode rectifiers the current pulses are almost in phase with the voltage. The power factor (cos $\varphi$) is nearly 1.

With thyristors, instead of the diodes, the firing angle delays the start of the conducting of the current. This will affect the active and reactive power taken from the supply, i.e. the power factor.

The waveform of the current in figure 3.1.2 has the harmonic content shown in figure 3.1.3, with a THD at 120 %. The phase angle of each harmonic is likewise the amplitude, important. All odd harmonics are present with, in general, decaying amplitude at higher order.

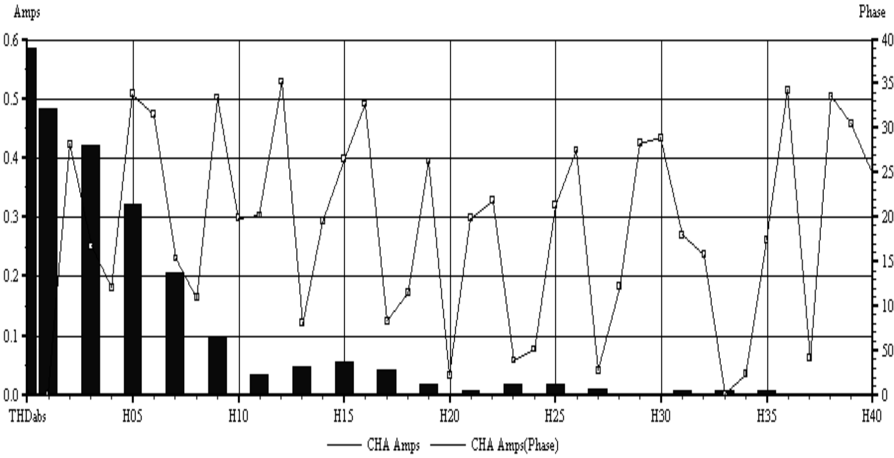


Figure 3.1.3. Frequency spectra with phase angles of the phase current. Current THD is 120 %. (Amplitudes in RMS)

In the ideal case (with sinusoidal voltage, resistive source impedance and constant DC-link voltage) the phase angle of the 3:rd, 7:th, 11:th and so forth is negative (180 degrees). The phase angle of the 5:th, 9:th, 13:th and so forth is positive, likewise the fundamental component (0 degrees). In reality there is a small deviation from this due to the design of the DC-link, background voltage distortion and the source impedance.

A thyristor rectifier will shift the fundamental current component a certain angle $\alpha$ and all the harmonics an angle *n* time $\alpha$. Where *n* is the harmonic order. The amplitude of the fundamental component and of each harmonic changes depending on the design of the DC-link and the type of load.

Some device uses a small line side inductor and transistors, instead of diodes, which are switched with a high frequency, around 30 kHz. Several different rectifier configurations exist, also with different switching frequencies. The advantage is that the line current becomes more sinusoidal but contains a high frequency ripple, see figure 3.1.4, sometimes up to 100 kHz.

The design of the control system, for the switching of the transistors, is of great importance for the resulting shape of the current waveform.

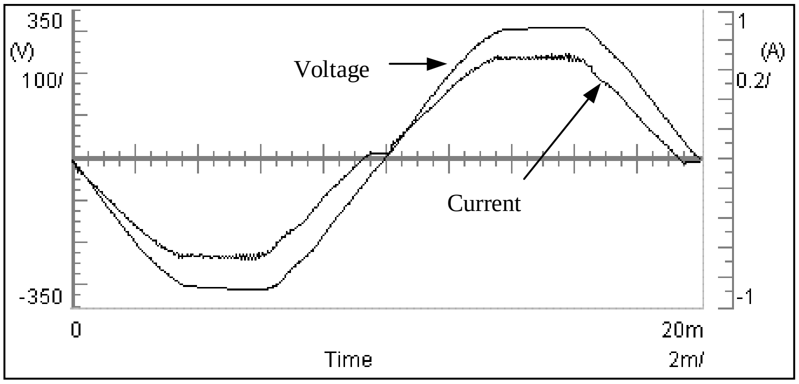


Figure 3.1.4. Phase current to a single phase HF-switched rectifier for fluorescent lighting. The active power taken is the same as for the TV in figure 3.1.2.

In this example the harmonic background voltage distortion affects the current distortion, which therefore also includes the low order harmonics (3, 5 and 7), but with low amplitudes. This is due to the type of control of the transistor switching.

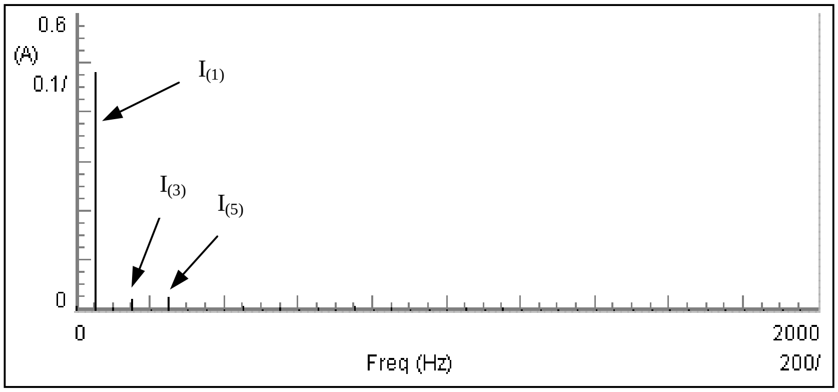


Figure 3.1.5 Frequency spectra for the HF-switched current. (Amplitudes in RMS)

Compared with the diode rectifier in figure 3.1.2, the current distortion is low, 7 % THD.

### 3.1.1 Background voltage distortion

Voltage distortion, caused by the current distortion from other similar loads or by the load itself, tends to reduce the current distortion for diode and thyristor rectifiers, figure 3.1.1.1, see also [11][65]. The current pulse becomes flatter but wider, compared to figure 3.1.2.

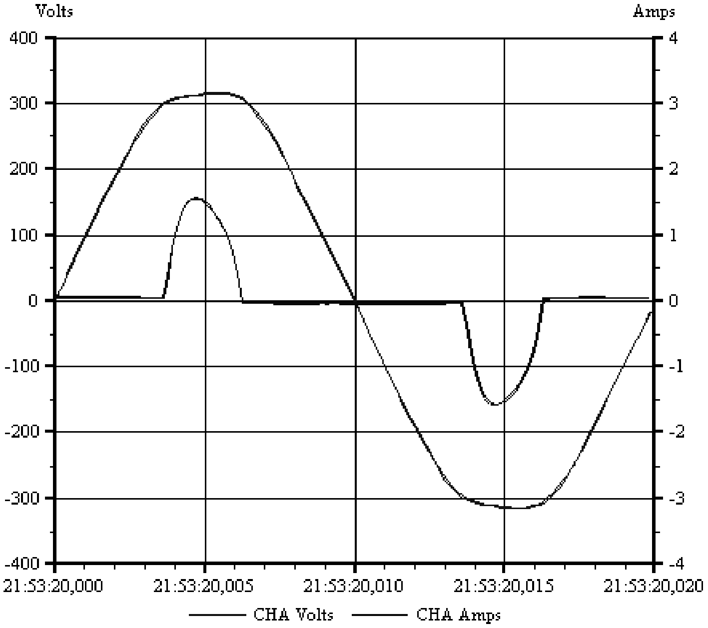


Figure 3.1.1.1. Phase voltage (continuous) and phase current (pulsed) to the same television receiver as in figure 3.1.2, but with 2 % background voltage distortion.

For controlled high frequency switching rectifiers, as in figure 3.1.4, the current distortion can increase depending on the control system for the switching of the transistors. The current distortion will however remain much lower than for non-controlled rectifiers.

The current harmonics are reduced due to the lower but wider current pulse, figure 3.1.1.2.

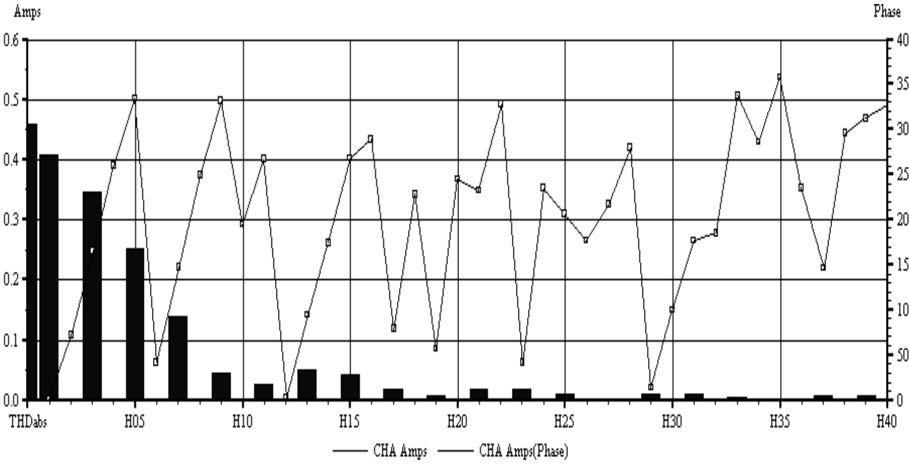


Figure 3.1.1.2. Frequency spectra with phase angles of the phase current. Current THD is 112 %. (Amplitudes in RMS)

See also chapter 4 on the effects of voltage background distortion.

## 3.2 Three phase loads

Three phase rectifiers are used for higher power applications, up to several MW. The rectifying topology is similar to single phase rectifiers but with a front end for connection of three phases, see figure 3.2.1. The rectifier can either be controlled or non-controlled and can consist of diodes, thyristors or transistors. The switching frequency for controlled transistor rectifiers is normally not above 7 to 8 kHz. The DC-link consists, in most cases, of a capacitor for the lower power applications. For larger rectifiers a smoothing inductor and a capacitor are used. For controlled transistor rectifiers the DC-link consists of a capacitor and on the line side an inductor is used.

The three-phase group is used mainly in industry applications and in the power system. Some examples are:

- Adjustable speed drives
- Large UPS's
- Arc furnaces
- HVDC-links
- SVC's
- Traction, vehicles

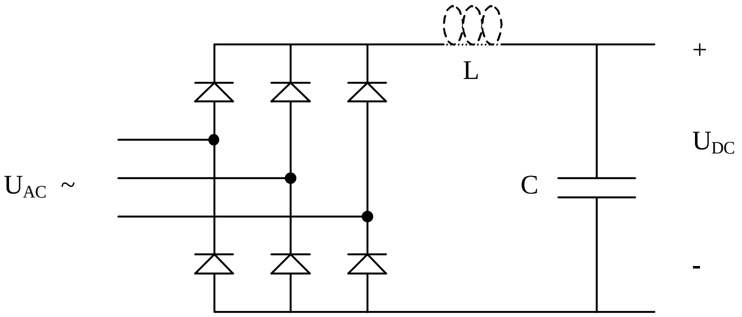


Figure 3.2.1. Three phase, six-pulse, diode rectifier with inductive/capacitive or capacitive DC-link.

The current spectrum consists of odd multiples, in pairs of 6 ± 1 (no multiples of three), with decaying amplitude for increasing order. The amplitudes of the harmonics are similar to those for a single phase rectifier, but the phase angles are different, e.g. the phase angle for the 5:th and 7:th harmonics have opposite sign (180 degrees phase angle difference) compared to those of a single phase rectifier.

Without the smoothing inductor in the DC-link the current consists of two pulses per half cycle and the total harmonic distortion, THD, of the line current can be as high as 200 %. With a large inductor, the current becomes more squared and the distortion is around 25 %. The use of a line side inductor reduces also the harmonic content, but prolongs the commutation of the current from one diode to another.

Examples of different distortion of the line current will be shown from field measurements including high-order harmonics, non-symmetrical distortion and the distortion during regenerative braking. The influence of the DC-link inductor on the harmonic distortion will be discussed. Also the effects on the voltage distortion are addressed.

The measurements are performed at the terminals of the rectifiers and are obtained from different types of ac converters with six pulse diode or thyristor rectifiers in an industrial plant. The internal power system of the plant is a 400 V ac network with distribution transformers, 20.5/0.4 kV, 1000 kVA, $u_k = 6.2$ %, Dyn11.

The rated powers of the converters are between 1 kW and 75 kW.

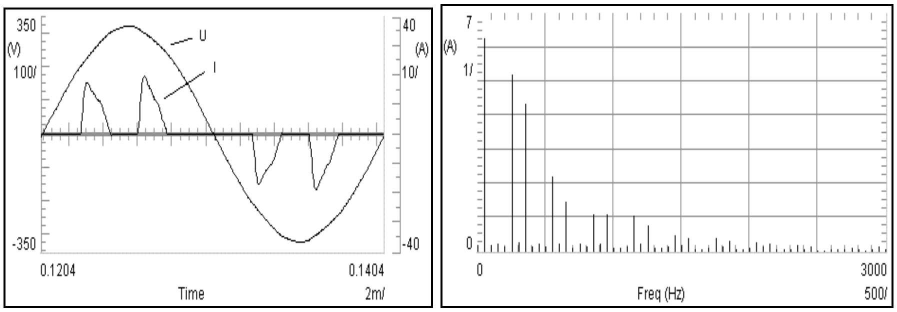
The DC-link inductor and capacitor sizes varies between different rectifiers, the values are:

L = 0 to 80 μH / kW and
C = 40 to 1100 μF / kW.

In the text the size of the inductor and the capacitor are named small, medium and large, which refers to the ranges above.

### 3.2.1 Size of the smoothing inductor

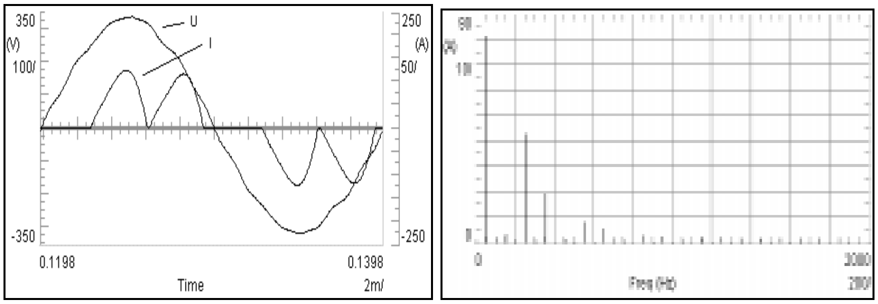
Figure 3.2.1.1 shows the line current to a 2.2 kW converter with a six-pulse diode rectifier, used in an industrial washing machine. The current is discontinuous and has two pulses per half cycle with steep positive flanks, due to the absence of a smoothing inductor. The line voltage has no noticeable change in the voltage wave shape due to the relatively small load (0.2 %), compared to the rated transformer size.



(a) (b)

Fig. 3.2.1.1. (a) Discontinuous current with two pulses per half cycle. (b) Frequency spectrum of the current, $I_{THD}$ = 121 % ($U_{THD}$ = 1.1 %).

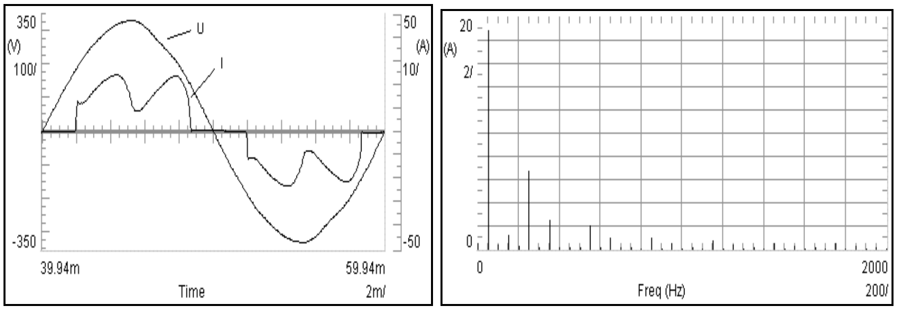
Figure 3.2.1.2 shows the current from a 75 kW converter with a thyristor rectifier used in a grinding machine. The current is continuous with two pulses per half cycle. A small smoothing inductor is present. The much larger load size (7.5 %), compared to Fig. 3.2.1.1, causes some noticeable voltage distortion.



(a) (b)

Fig. 3.2.1.2. (a) Continuous current with two pulses per half cycle. (b) Frequency spectrum of the current, $I_{THD}$ = 59 % ($U_{THD}$ = 2.5 %).

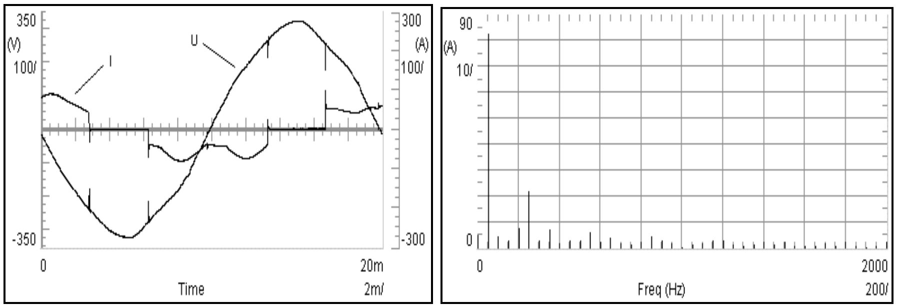
In figure 3.2.1.3 the current to a 22 kW converter with a diode rectifier, used in a milling machine, is shown (2.2 % load size). The current is continuous and somewhat smoothed with a medium size smoothing inductor, but still it has two dominating pulses. The steep flanks are due to the inductor that makes the current stiff.



(a) (b)

Fig. 3.2.1.3. (a) Continuous current with two pulses per half cycle with steep positive flanks. (b) Frequency spectrum of the current, $I_{THD}$ = 41 % ($U_{THD}$ = 1.6 %).

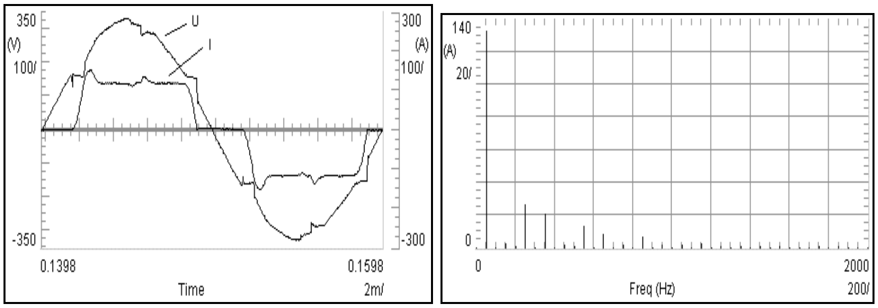
Figure 3.2.1.4 shows the current for a 40 kW thyristor rectifier with a large inductor, (4 % load size). The current is phase shifted around 90 degrees to change the active power flow to the load. The wave shape remains the same, so that each harmonic $n$ is phase shifted $n*90$ degrees. The current is continuous with steep positive and negative flanks with a transient. The current transients cause commutation notches in the line voltage due to capacitive source impedance and that the commutation takes place at non-zero voltage. The relative notch depth, $\delta u$, is defined as $U_{\text{notch}} / U_{(1)}$.



(a) (b)

Figure 3.2.1.4. (a) Continuous smoothed current with two small pulses per half cycle. Commutation notches due to the steep flanks of the current in combination with a capacitve source impedance. (b) Frequency spectrum of the current, $I_{THD}$ = 33 % ($U_{THD}$ = 2.0 %, $\delta u$ = 23 %).

In figure 3.2.1.5 the current from a converter (80 kW, 8 % load size) with a thyristor rectifier is shown, used for hardening of steel pieces. The current is continuous and smoothed with a large inductor and has steep positive and negative flanks (two small pulses, about 15 Amps, each half cycle on the top of the waveform, like figure 3.2.1.4, are truncated due to the measuring equipment). The current is stiff due to the presence of the large inductor. The commutation notches are caused by six identical converters (48 % total load size), fed from the same transformer (1000 kVA), which seriously affect the line voltage.



(a) (b)

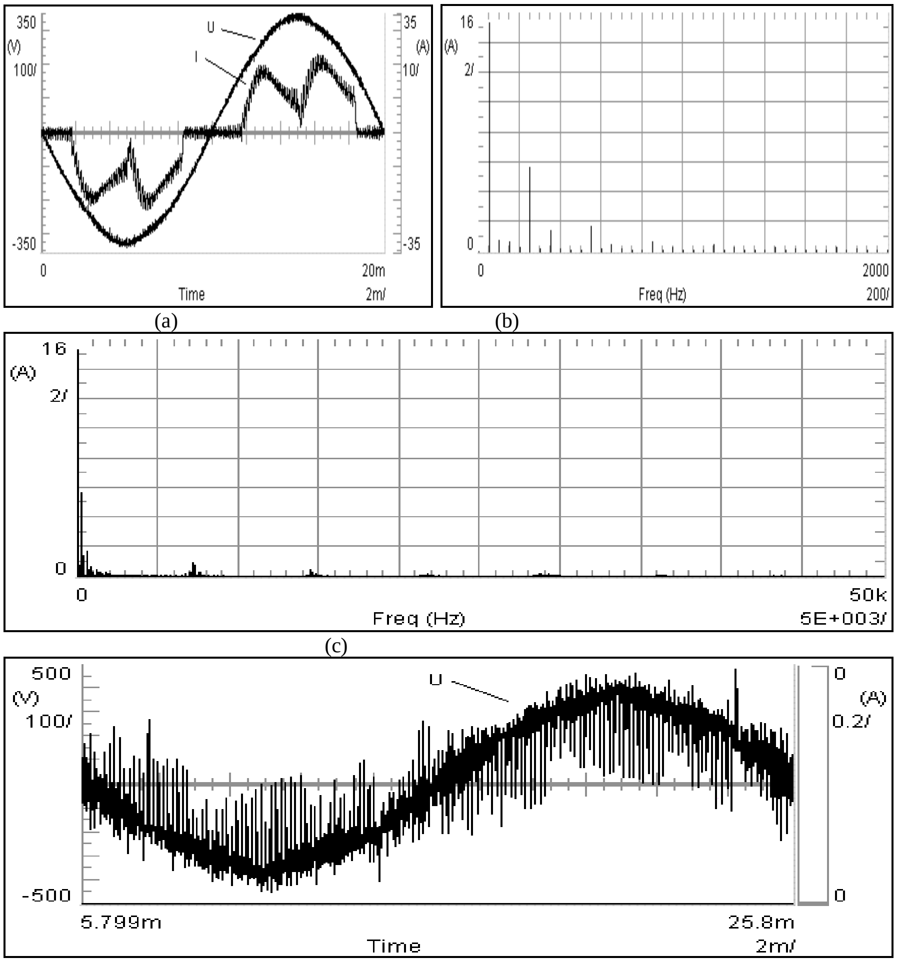
Fig. 3.2.1.5. (a) Continuous smoothed current with steep positive and negative flanks. Commutation notches due to the steep flanks of the current from six identical converters. (b) Frequency spectrum of the current, $I_{THD}$ = 28 % ($U_{THD}$ = 6.3 %, $\delta u$ = 10 %).

Comparing figure 3.2.1.1 through 3.2.1.5 shows that a DC-link smoothing inductor is able to considerably reduces the current harmonics, but it can lead to serious voltage distortion instead due to commutation notches.

The current distortion can, for a specific rectifier, also vary with changes of the amount of active power flow.

### 3.2.2 High frequency (HF) ripple

Figure 3.2.2.1 shows a 36 kW converter with a diode rectifier with a small DC capacitor and no inductor, used in a drilling machine. Additional line inductances (0.4 mH/phase) were installed before the diode rectifier to reduce some of the high frequency ripple. The HF-ripple, around 7 kHz, in the current is caused by the switching in the inverter bridge. The line voltage also shows the HF-ripple.



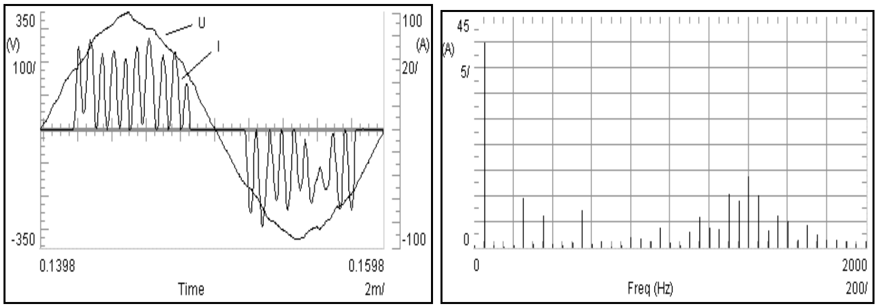
(a) (b)

(c)

(d)

Fig. 3.2.2.1. (a) Continuous current with two pulses per half cycle, with high frequency ripple, somewhat smoothed with a smoothing inductor. (b) Frequency spectrum of the current, $I_{THD}$ = 41 % ($U_{THD}$ = 1.4 %, before the line inductance). (c) Main ripple at 7 kHz and higher multiples. (d) Line voltage between the line inductance and the converter (rectifier).

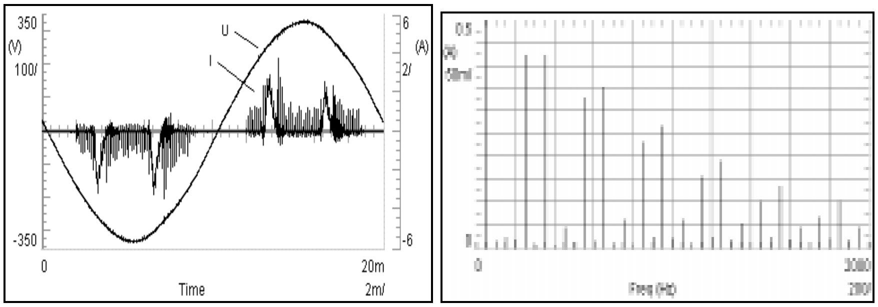
Figure 3.2.2.2 is obtained from a 19 kW converter with a variable DC voltage. The DC voltage is varied by switching a transistor (chopper) placed after the diode rectifier to pulsate the right amount of current to the DC-link capacitor via an inductor. A lot of even harmonics are present in the current. A serious amount of harmonics is visible between 1 and 2 kHz. This is due to the switching of the transistor (chopper). These high frequencies cause also noticeable voltage distortion.



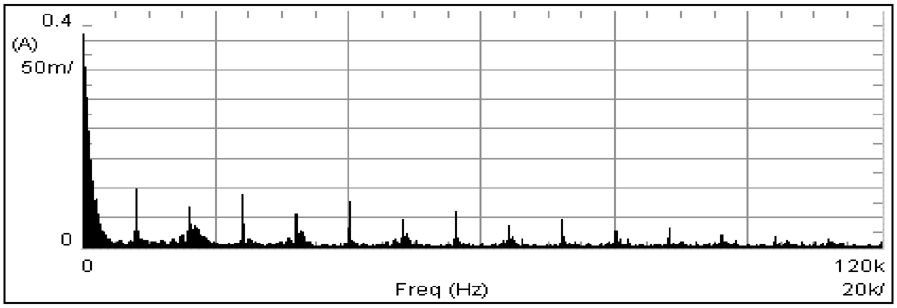
(a) (b)

Figure 3.2.2.2. (a) Discontinuous oscillating current with steep flanks. (b) Frequency spectrum of the current, $I_{THD}$ = 73 % ($U_{THD}$ = 3.2 %).

In figure 3.2.2.3 the current to a 2.2 kW diode rectifier is shown, used in an industrial washing machine. The current is discontinuous with two main pulses per half cycle and with a HF-ripple. There is no smoothing inductor present and the capacitor is small. The line voltage is affected by the HF-ripple.



(a) (b)

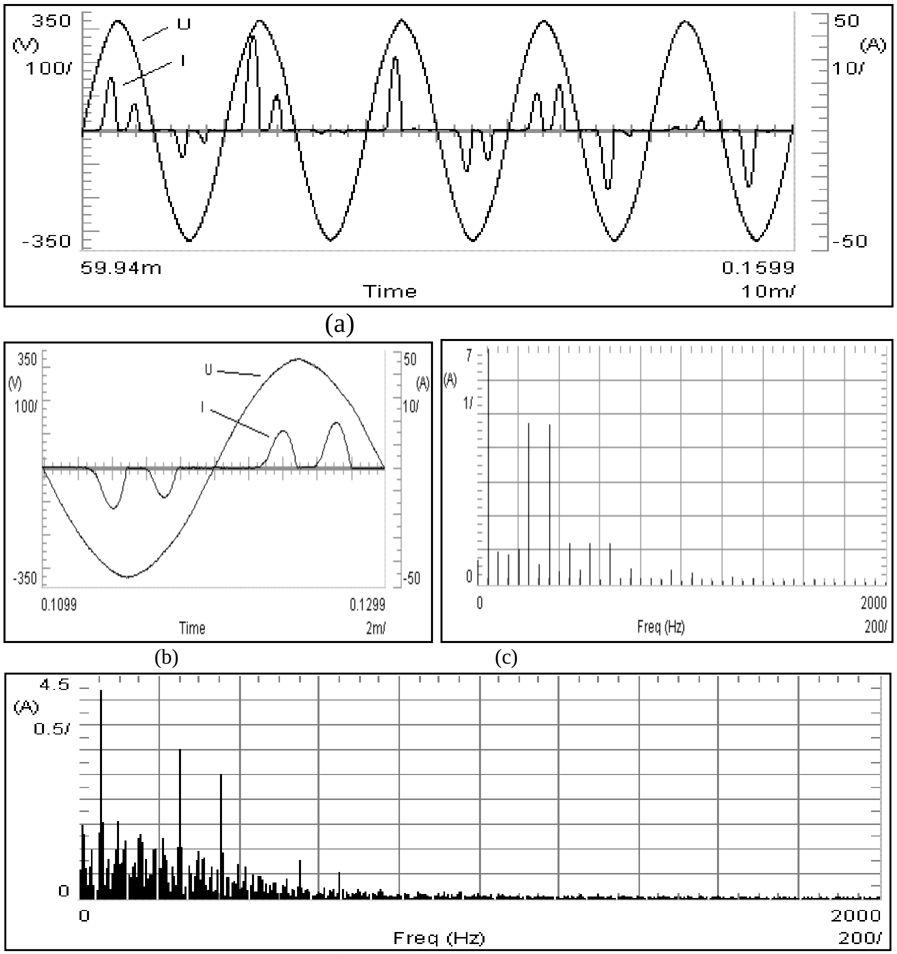


(c)

Figure 3.2.2.3. (a) Discontinuous current with two main pulses per half cycle with high frequency ripple. (b) Frequency spectrum of the current, $I_{THD}$ = 186 % ($U_{THD}$ = 1.2 %). (c) Multiple ripple at higher frequencies.

### 3.2.3 Non symmetrical current waveforms

Figure 3.2.3.1 shows the current to a 34 kW diode rectifier, used for several servos in a milling machine. The current is discontinuous and non-symmetrical, the smoothing inductor is absent. It includes both even and inter-harmonics and a DC-offset. The irregular behavior of the current is due to the intermittent power consumption of the servo load. The line voltage is not affected.



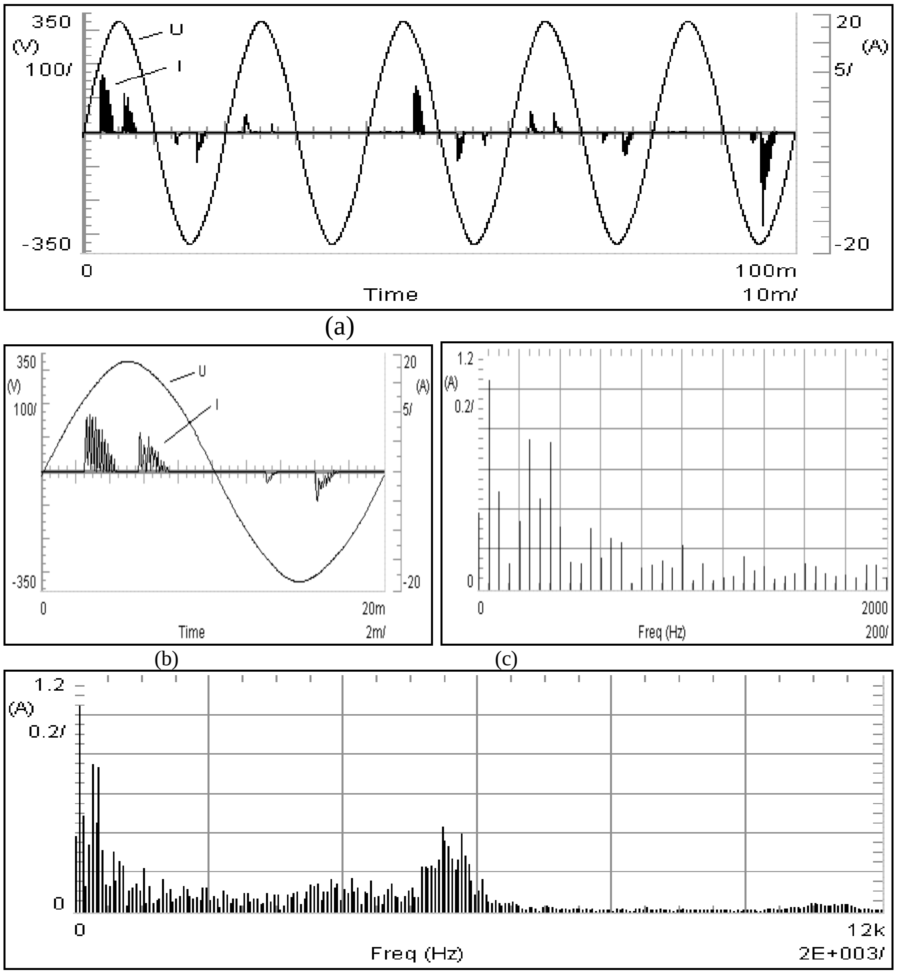
(a)

(b) (c)

(d)

Figure 3.2.3.1. (a) Discontinuous non-symmetrical current. (b) Analyzed period, which is not representative for the frequency spectrum of any other period. (c) Frequency spectrum of the current (one cycle), $I_{THD}$ = 105 % ($U_{THD}$ = 1.1 %). (d) Frequency spectrum taken over 10 cycles.

In figure 3.2.3.2 the current to a 40 kW diode rectifier is shown, used for several servos in a milling machine. The current is discontinuous and non-symmetrical, the smoothing inductor is absent and the capacitor is small. The current includes even harmonics and interharmonics, high frequency ripple and a DC-offset. Severe harmonic distortion in the current is present around 6 kHz. The frequency spectrum shown is only valid for the analyzed period. The voltage is not affected.



(a)

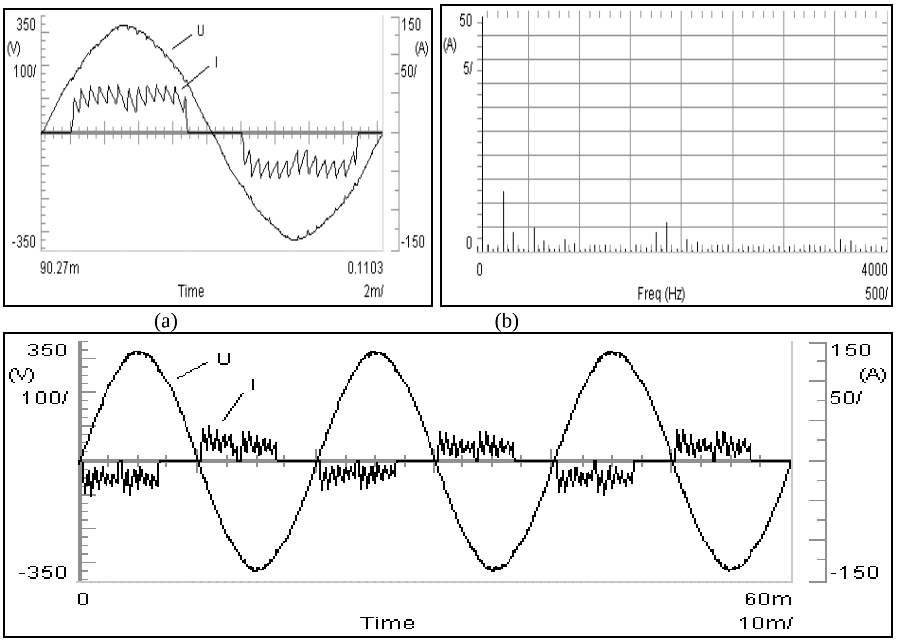
(b) (c)

(d)

Figure 3.2.3.2. (a) Discontinuous non-symmetrical current with high frequency ripple. (b) Analyzed period, which not is representative for the frequency spectrum for any other period. (c) Frequency spectrum of the current (one cycle), $I_{THD}$ = 147 % ($U_{THD}$ = 1.4 %). (d) Same as (c) but with more frequency components.

### 3.2.4 Regeneration, braking the load

Figure 3.2.4.1 shows the current to a 45 kW thyristor rectifier, used in a milling machine. Power is fed back to the supply network during braking the load. The converter is fed by a secondary transformer, which increases the source impedance (no data is available on the transformer). The current is continuous but has a large ripple of high harmonic order due to the small capacitor. A smoothing inductor is present. The secondary side voltage of the transformer is clearly affected by the ripple.

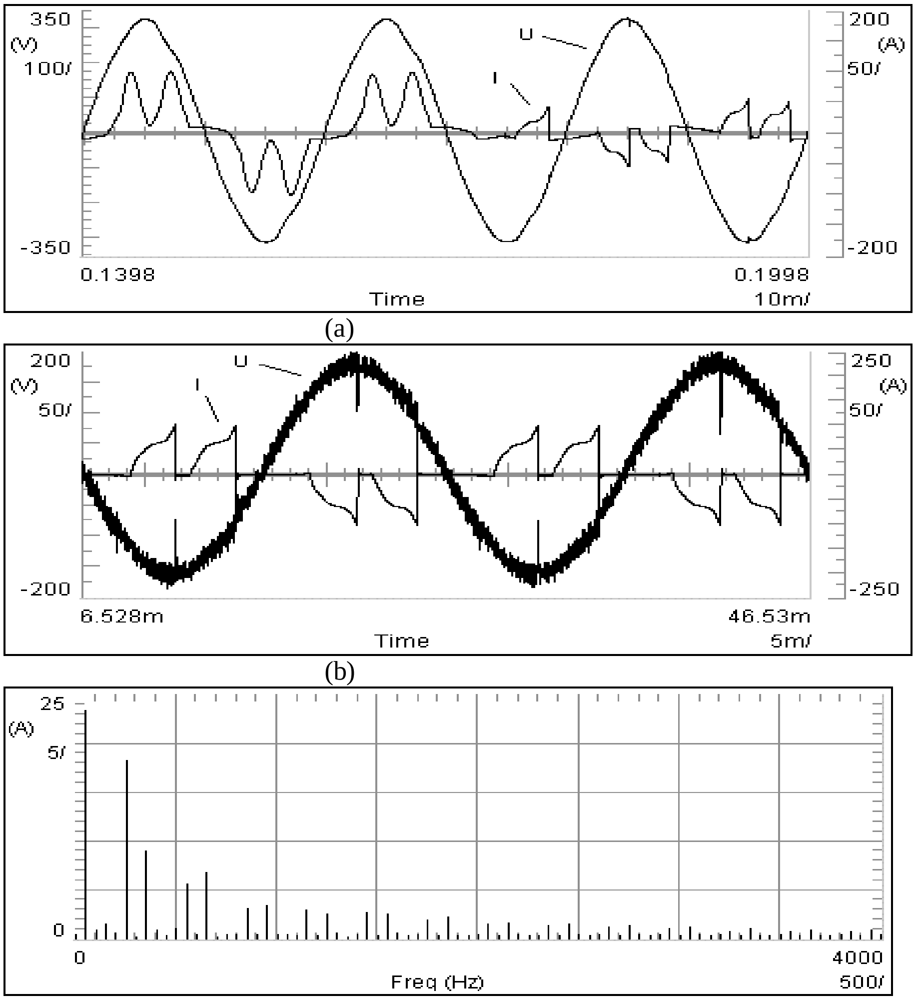


(a) (b)

(c)

Figure 3.2.4.1. (a) Continuous current with high ripple during normal operation, caused by a small capacitor and a smoothing inductor present. (b) Frequency spectrum of the current, $I_{THD}$ = 34 % ($U_{THD}$ = 2.1 %). (c) Power feeding back (P = - 3.1 kW).

Figure 3.2.4.2 is from a 15 kW converter with a thyristor-/transistor rectifier, used in a grinding machine. The topology of the rectifier is not known, but there is a difference between the two operation modes. It is fed from a secondary transformer and has a line filter before the rectifier. The current is continuous when power is taken from the net and discontinuous, with steep negative flanks, when power is fed back (during braking of the load). The voltage is affected by lower harmonics due to the pulsating current at positive power and by notches due to the steep flanks at negative power. The line filter introduces HF-ripple and notches in the voltage feeding the rectifier due to its internal series inductance (no data of the filter is available). Note that the size of the DC-link inductor and capacitor is different during the braking of the load, compared with normal loading.



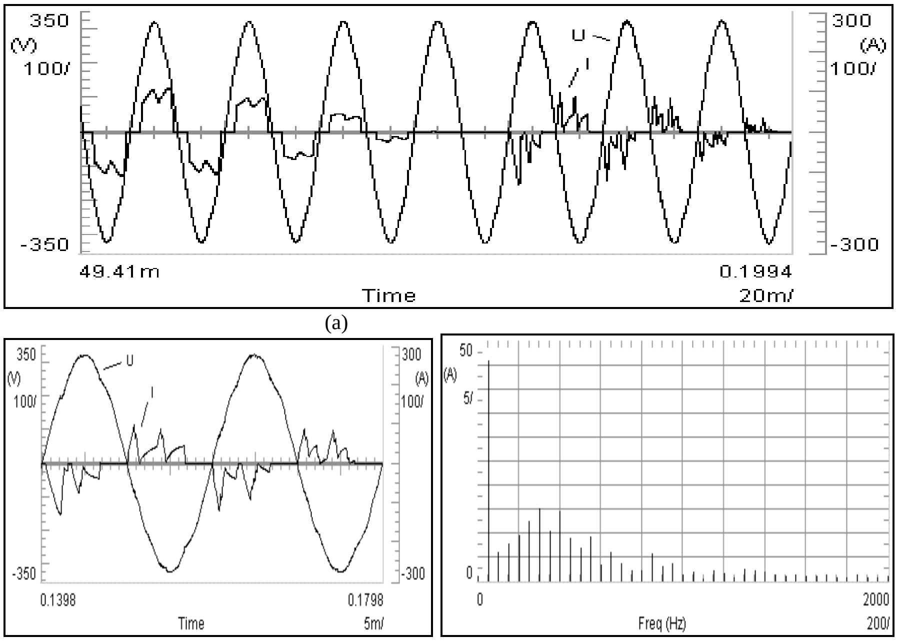
(a)

(b)

(c)

Figure 3.2.4.2. (a) Changing from continuous to discontinuous current, two pulses per half cycle, when braking the load. (b) Power feeding back, voltage after the line filter with HF-ripple, feeding the rectifier (P = -3.6 kW). (c) Frequency spectrum of the current when power is fed back (one cycle), $I_{THD}$ = 104 %.

Figure 3.2.4.3 shows the current to a 75 kW thyristor rectifier that is fed from a secondary transformer. The current is continuous and smoothed when power is taken from the net and discontinuous and has steep positive and negative flanks when power is fed back. Also here the DC-link has a different size during regeneration. The current does almost not affect the line voltage, but the voltage after the transformer shows some small commutation notches.



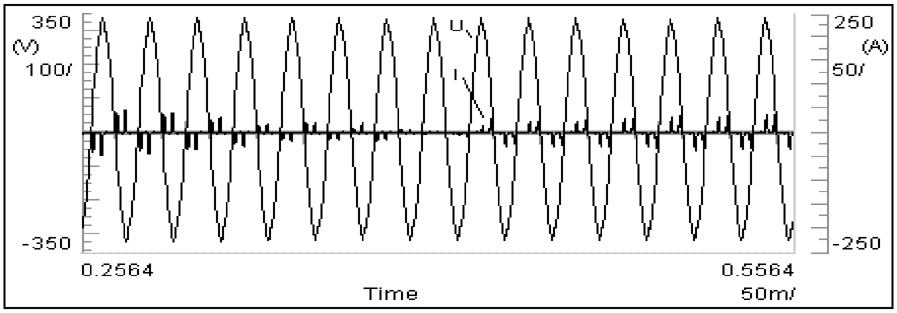
(a)

(c)

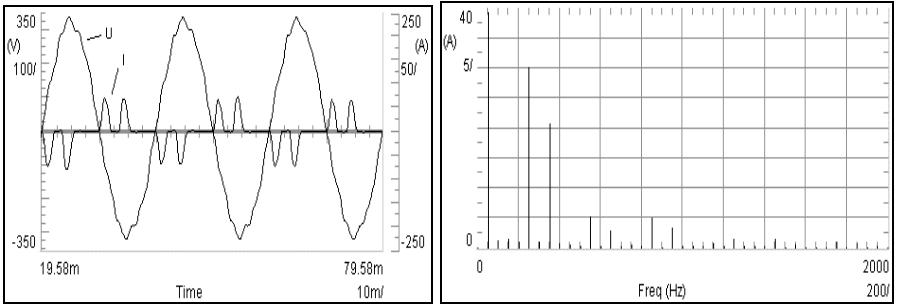
(b)

Figure 3.2.4.3. (a) Changing from continuous smoothed current to discontinuous pulsating current, when braking the load. (b) Power feeding back, voltage after the transformer, feeding the rectifier (P = -6.0 kW). (c) Frequency spectrum of the current when power is fed back (one cycle), $I_{THD}$ = 76 %.

In figure 3.2.4.4 the current waveform from a 75 kW converter, with a thyristor rectifier, is shown when power is taken and fed back. The current is discontinuous with two pulses per half cycle due to a small smoothing inductor and the shape is the same for positive and negative power. The line voltage is somewhat more affected during braking due to steeper flanks of the current.



(d)



(a)(b)

Figure 3.2.4.4. (a) Changing from braking to loading. (b) Power feeding back. The current is discontinuous with two pulses per half cycle (P = -5.0 kW). (c) Frequency spectrum of the current when power is fed back (one cycle), $I_{THD}$ = 96 %.

It is shown that a large variety of harmonic current distortion exists due to three-phase rectifiers in low voltage networks. The type of distortion is strongly related to the DC-link: the size of the capacitor and the presence and size of the smoothing inductor. The amount of active power flow on the dc-side, of a rectifier with a smoothing inductor, can also affect the current distortion. A large power flow reduces the current THD and a small power flow increases the THD, but the current harmonics in ampere follows of course the power flow. Sometimes the switching pattern in the VSI can contribute to the distortion of the line current.

A small, or no, smoothing inductor leads to large current distortion with two current pulses per half cycle. When the inductor is absent the positive current flanks can be steep depending on the size of the DC capacitor and the crest factor of the line voltage. A small capacitor can cause a high frequency ripple.

A large inductance smoothes the top of the current waveform but introduces instead steep flanks, which are stiff. If the relative load size is large, above 40 % of the transformer rating, and the rectifier is current stiff it could cause serious commutation notches in the voltage. The commutation time can be reduced with a thyristor rectifier, due to a higher commutation voltage when the firing of the thyristor is delayed. This increases the derivative of the current flanks. The momentary voltage drop is proportional to the derivative of the current.

Line side inductors reduce the current and voltage distortion in the supply network, but can introduce large voltage distortion feeding the rectifier. For thyristor and transistor rectifiers there can be a risk for disturbing it self, e.g. the voltage zero crossing can be affected.

## 3.3 Fundamental voltage unbalance of the supply

When a six-pulse diode- or thyristor rectifier with a small smoothing inductor is connected to an unbalanced fundamental line voltage, the rectifier takes triplen non-zero sequence harmonic currents. These triplen harmonics, mainly third and ninth, are not zero sequence components because they are phase-shifted +/- 90 degrees in each phase (180 degrees between the phases). They have different amplitudes in the three phases depending on the type of unbalance of the voltage, see table 3.3.1. The currents can be significant in industrial systems with three-phase rectifier load. Also on transmission level the positive and negative sequence components can represent a large part of the third harmonic, see chapter 4. Because of the non-zero sequence nature of this current, it will pass through distribution transformers and delta connected capacitor banks.

A voltage dip, due to a single-phase or phase-to-phase fault, is a severe unbalance. Therefore the third harmonic current can be very large if the total number of connected rectifiers is big. Large rectifiers used in the power system, like HVDC, can also generate significant third harmonics during a voltage dip. The smoothing inductor in the DC-link inductor reduces however the triplen harmonics.

| | $U_R < U_S < U_T$ | $U_R < U_S = U_T$ | $U_R = U_S < U_T$ |
|---|---|---|---|
| Phase R | $I_{(3)}$ @ - 90° | 0 | $2 * I_{(3)}$ @ - 90° |
| Phase S | $2 * I_{(3)}$ @ 90° | $2 * I_{(3)}$ @ 90° | $2 * I_{(3)}$ @ 90° |
| Phase T | $I_{(3)}$ @ - 90° | $2 * I_{(3)}$ @ - 90° | 0 |

Table 3.3.1. Typical amplitude and phase angle for the third harmonic current in each phase for three different voltage amplitude unbalances.

In figure 3.3.1 to 3.3.3 different current waveforms to a 75 kW diode rectifier, with no inductor and a 1100 μF/kW capacitor, are simulated.

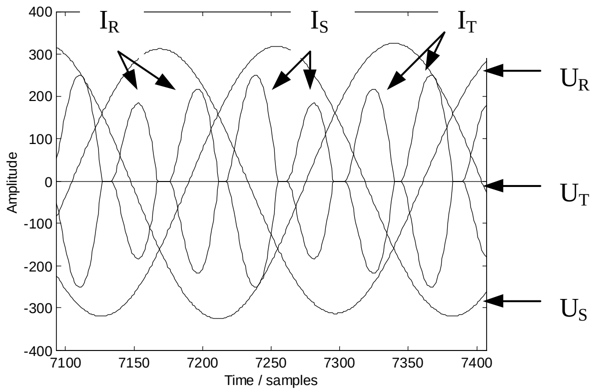


Figure 3.3.1. Phase currents due to voltage unbalance 0.96*$U_R$, 0.98*$U_S$, 1*$U_T$.

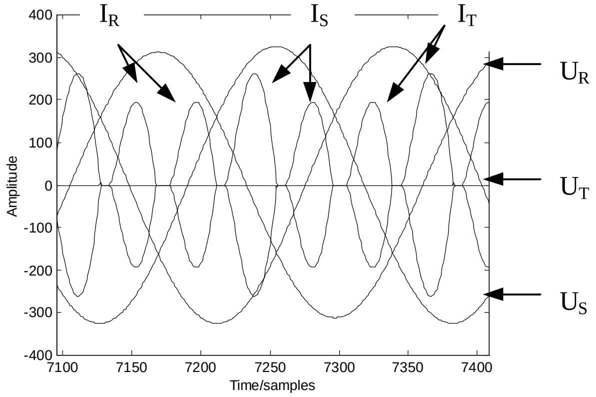


Figure 3.3.2. Phase currents due to voltage unbalance 0.96*$U_R$, 1*$U_S$, 1*$U_T$.

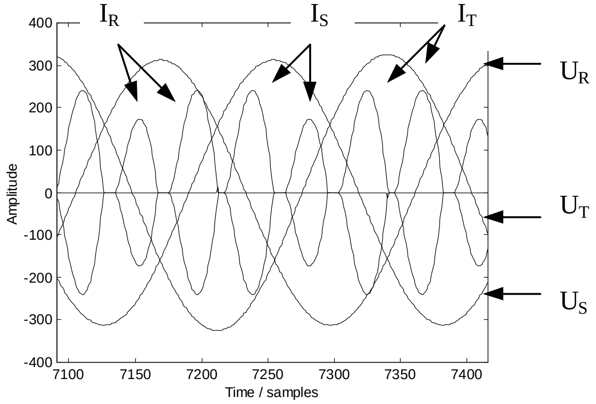


Figure 3.3.3. Phase currents due to voltage unbalance 0.96*$U_R$, 0.96*$U_S$, 1*$U_T$.

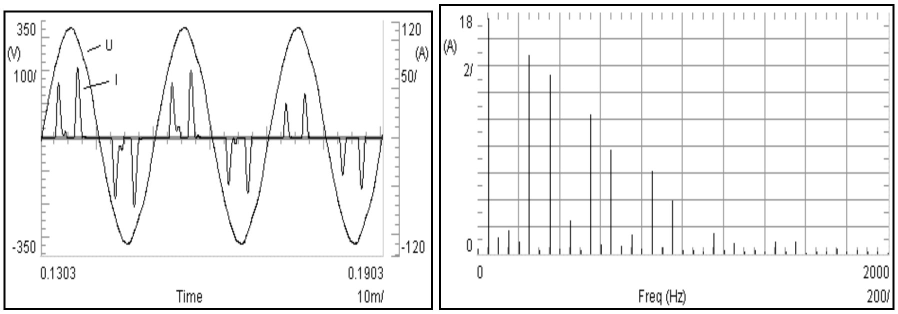
Expressed in sequence components the fundamental voltage and the 3:rd harmonic current become as in table 3.3.2.

| **FND Voltage** | **0.96$U_R$, 0.98$U_S$, 1$U_T$** | **0.96$U_R$, 1$U_S$, 1$U_T$** | **0.96$U_R$, 0.96$U_S$, 1$U_T$** |
|---|---|---|---|
| Positive Sequence | **0.9800 @ 0°** | **0.9867 @ 0°** | **0.9733 @ 0°** |
| Negative Sequence | **0.0115 @ -150°** | **0.0133 @ 180°** | **0.0133 @ -120°** |
| Zero Sequence | **0.0115 @ 150°** | **0.0133 @ 180°** | **0.0133 @ 120°** |
| | | | |
| **3:rd harm. Current** | | | |
| Positive Sequence | **1 @ -150°** | **1.1547 @ 180°** | **1.1547 @ -120°** |
| Negative Sequence | **1 @ -30°** | **1.1547 @ 0°** | **1.1547 @ -60°** |
| Zero Sequence | **0 @ 0°** | **0 @ 0°** | **0 @ 0°** |

Table 3.3.2. Sequence components for the fundamental voltage and the 3:rd harmonic current, for three typical fundamental voltage unbalances.

The fundamental voltage zero sequence component does not affect the rectifier due to its delta connection.

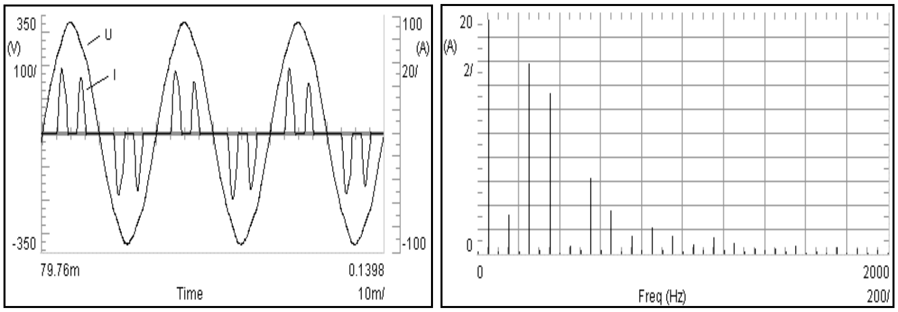
Figure 3.3.4 is monitored at a 15 kW converter with a six-pulse diode rectifier that was fed with an unbalanced voltage. The magnitude of the voltage was about 1 % lower in one phase than in the other two phases (1/3 % negative sequence voltage). The DC-link only consists of a small capacitor and with no smoothing inductor present. Even such a small unbalance in the voltage already causes noticeable triple harmonics, about 10 % third and 14 % ninth harmonics in the current.



(a) (b)

Figure 3.3.4. (a) Current with two pulses per half cycle, different in amplitude, when the line voltage is unbalanced. (c) Frequency spectrum of the current, $I_{(3)}$ = 10 %, $I_{(9)}$ = 14 %, $I_{(15)}$ = 8 %, $I_{THD}$ = 144 %.

Figure 3.3.5 shows the current for a 22 kW converter with a six-pulse diode rectifier that was fed with an unbalanced voltage, like the one in figure 3.3.4. A different size of the DC capacitor gives a difference in the frequency spectrum of the current.



(a) (b)

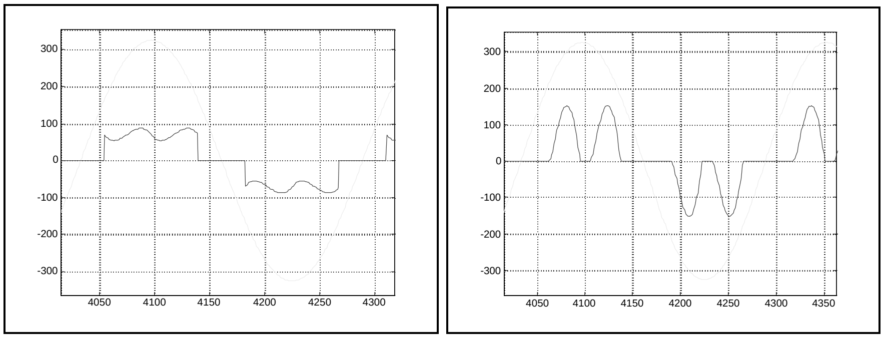
Figure 3.3.5. (a) Current with two pulses per half cycle, different in amplitude, when the line voltage is unbalanced. (c) Frequency spectrum of the current, $I_{(3)}$ = 16 %, $I_{(15)}$ = 8 %, $I_{THD}$ = 115 %.

The difference in highest and lowest pulse, between figure 3.3.4 and 3.3.5, is due to different type of voltage unbalance.

## 3.4 Simulations of the current distortion and the influence of the size of the smoothing inductor

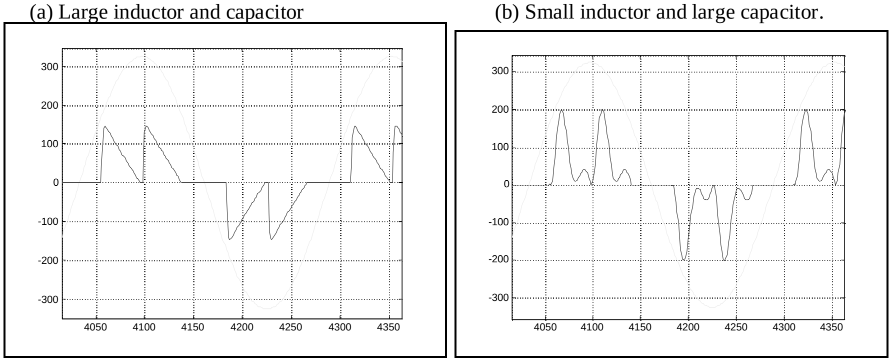
Simulations have been performed of a three phase, six pulse, diode rectifier with balanced and unbalanced fundamental voltage. Some simplifications have been made: the source impedance is zero, the rectifier has ideal commutation and the load is resistive, 22 kW.

In figure 3.4.1 the line current is shown for different sizes of the smoothing inductor and for the capacitor. The sizes are as referred in chapter 3.2. The feeding line voltage is balanced.



(a) Large inductor and capacitor

(b) Small inductor and large capacitor.



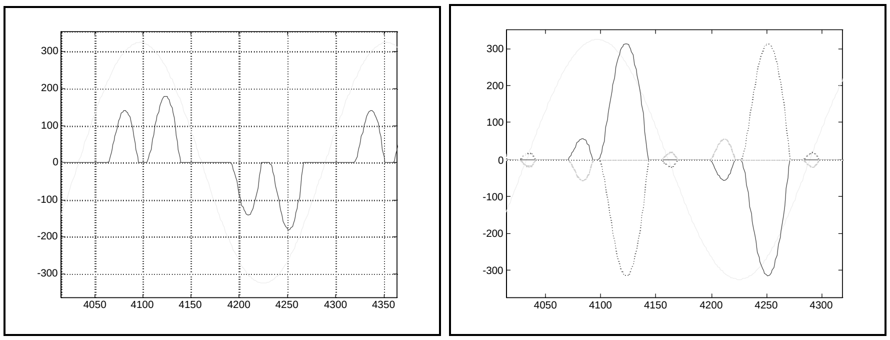
(c) Medium inductor and small capacitor.

(d) Both small L and C.

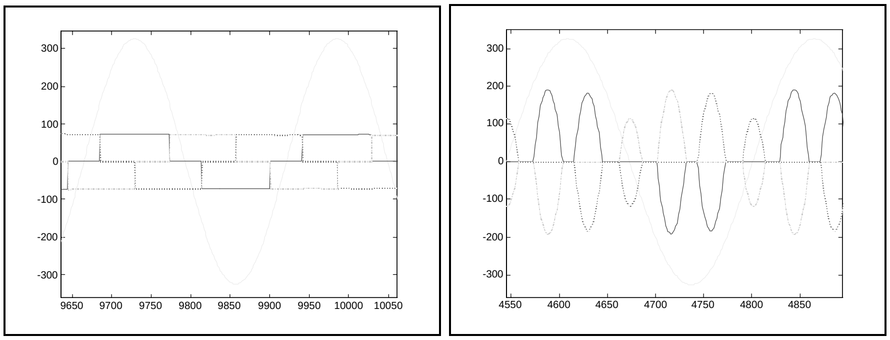
Figure 3.4.1. Current distortion with balanced voltage for different sizes of smoothing inductor and capacitor.

In (a) the current distortion, THD, is around 30 % and has in (d) increased to 180 % due to the smaller size of the smoothing inductor.

Figure 3.4.2 shows the line current for the same rectifier above, with different sizes of the smoothing inductor and when the feeding line voltage is unbalanced. The DC-link capacitor was at large size in all the cases.



(a) 3% voltage drop in one phase, small L. (b) 20% voltage drop in one phase, small L.



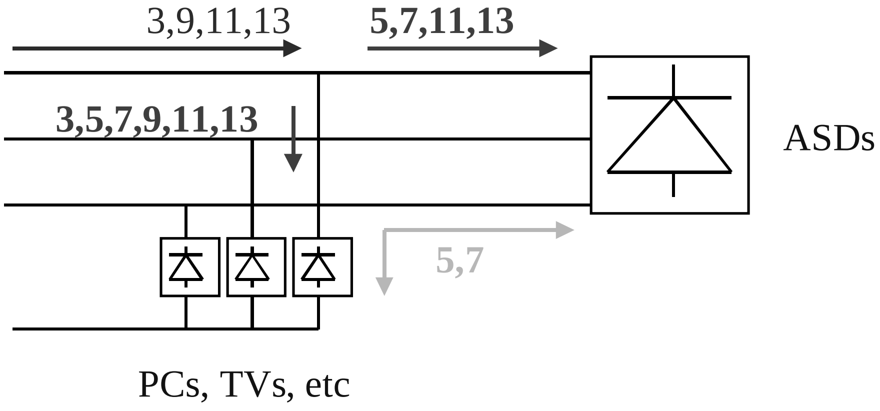
(c) 5% lower voltage in phase b and c, large L. (d) 5% lower voltage in phase b and c, small L.

Figure 3.4.2 Current distortion with unbalanced voltage for different sizes of smoothing inductor.

The size of the smoothing inductor in the DC-link has a big influence on the non-zero triplen harmonics. In figure 3.4.2 (a) only a small voltage unbalance causes around 15 % third harmonic current when the inductor is small. With a larger voltage drop, as in (b), the three phase rectifier acts almost as a single phase rectifier with a 30 degrees phase shift of the current (90 degrees for the 3:rd harmonic). With a large smoothing inductor, figure (c), the current does not include any 3:rd harmonic at all (below 1 %). In (d) the 3:rd harmonic is around 10 % with a small inductor, for the same voltage drop as in (c).

## 3.5 Current interaction between single and three phase diode rectifiers

When single and three phase diode rectifiers are mixed, on the same voltage level, the total current distortion decreases. This is due to a cancellation of the 5:th and 7:th harmonic currents caused by the 180 degrees difference in the phase angles from these loads, see figure 3.5.1 and [15].



3.5.1. Cancellation of the 5:th and 7:th harmonic currents.

A cancellation can also be present between three phase thyristor rectifiers with different firing angles.

## 3.6 Transformer delta coupling

The propagation of harmonic current distortion, from non-linear loads at low voltage level, through transformers can change the waveform and reduce the THD. The most common type of transformer coupling for low voltage distribution, 0.4 kV, in Sweden and Europe is the Delta-wye. In Sweden the type Dyn11 is very common where the secondary voltage and current are phase shifted 30 degrees before the primary.

Positive harmonic current components on the secondary side will be phase shifted –n*30 degrees to the primary side, negative harmonic current components is phase shifted +n*30 degrees and zero sequence components are not transferred to the primary side at all. They will only circulate in the delta winding. This means that single phase non-linear loads on the secondary side will cause a current distortion on the primary side like a three phase non-linear load. This assumes that the single phase loads are spread equally over the three phases.

# 4 Distortion at different voltage levels

This chapter presents the results of field measurements at low (0.4 kV) and high voltage (130 and 400 kV) levels and shows distortion levels and some typical characteristics of the distortion, at each voltage level. Further, the impact on the distortion caused by different sources of distortion, interaction between loads and the operation and configuration of the power system are studied.

## 4.1 Low voltage

Field measurements have been performed at a residential location on the terminals of a television receiver (98 W) to study the variation in harmonic active power flow and current distortion due to changes in the voltage background distortion. The monitoring was done over 12 hours in April 2000, from noon to midnight. Figure 4.1.1 shows the phase voltage and phase current at afternoon time. The voltage has a somewhat flattened top, mainly due the load current taken by the TV.

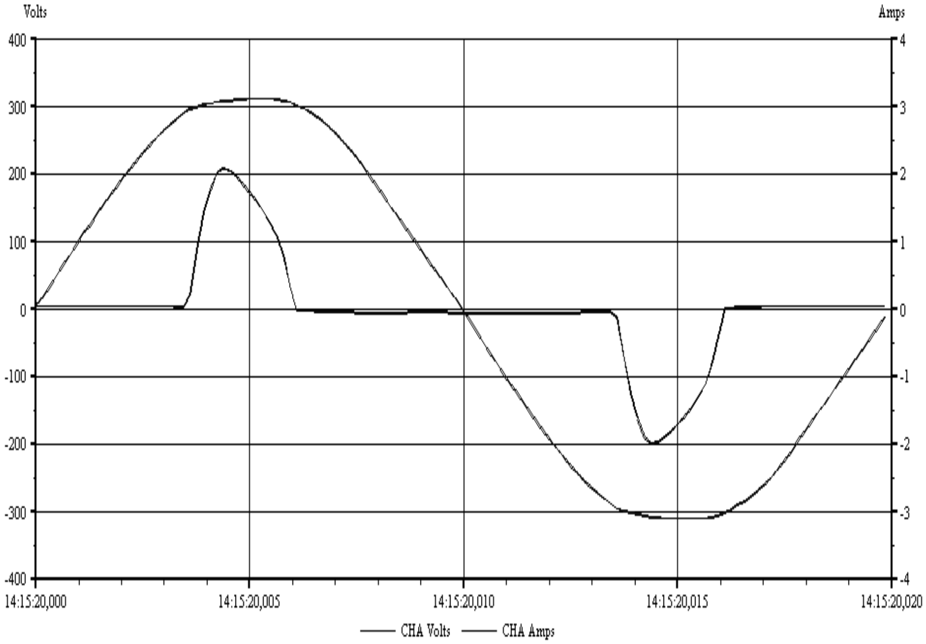
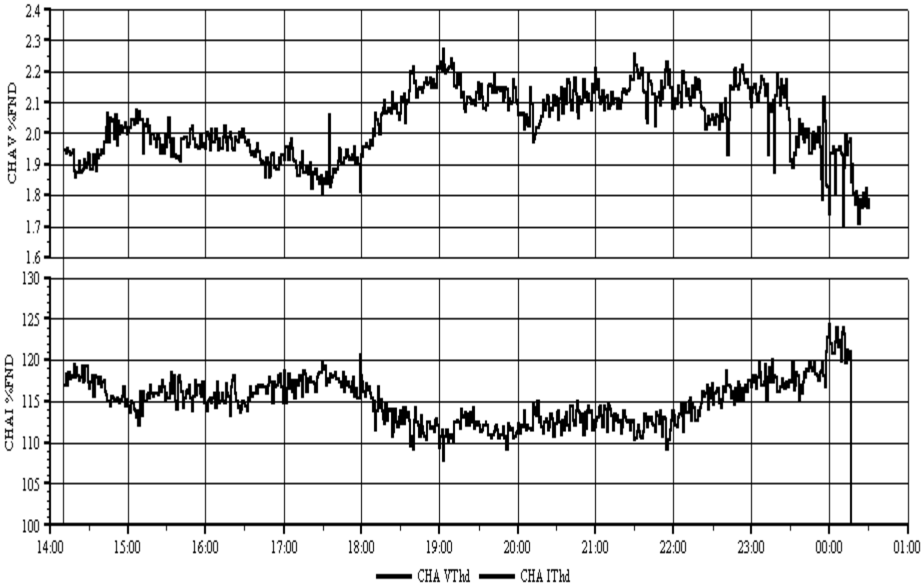
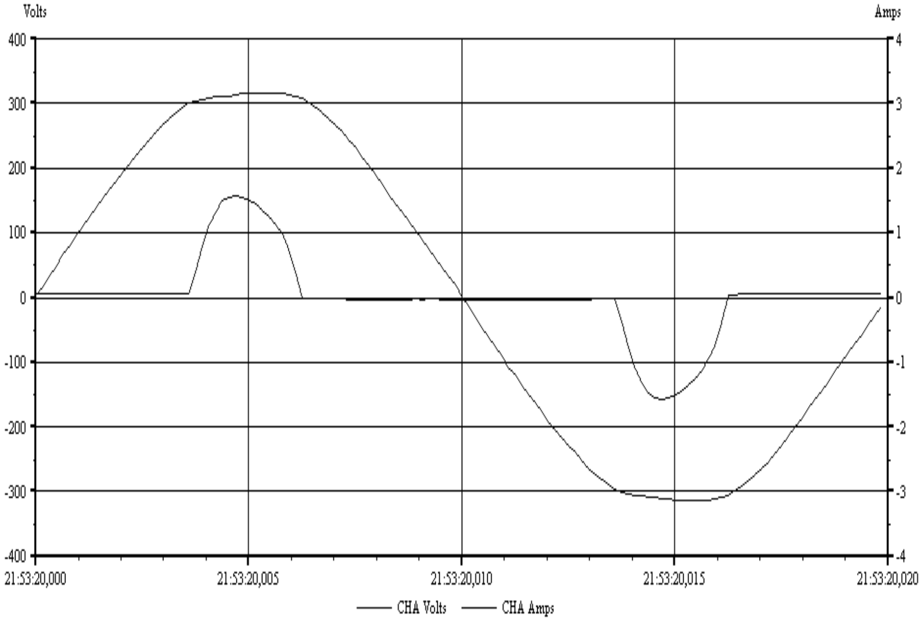


Figure 4.1.1. Voltage and current wave shapes, at afternoon time.

The voltage and current THD are seen in figure 4.1.2. The current distortion decreases when the voltage distortion increases, which is typical for non-linear single phase loads. The increase of the voltage distortion, at evening time, is caused by the use of television receivers in the nearby area. This results in a more flattened top of the voltage waveform, figure 4.1.3.



4.1.2. Voltage THD (top) and current THD (bottom), in percent of the fundamental component.



4.1.3. Voltage and current wave shapes, at evening time.

At evening time the current THD reduces to around 110 %, compared to around 120 % at daytime, figure 4.1.2.

The fundamental voltage and current components are seen in figure 4.1.4. The current varies about 20 % but independent of the variations of the voltage, which varies 3 % from the lowest to the highest value. The voltage steps are due to switching of capacitor banks and transformer tap changers at higher voltage levels.

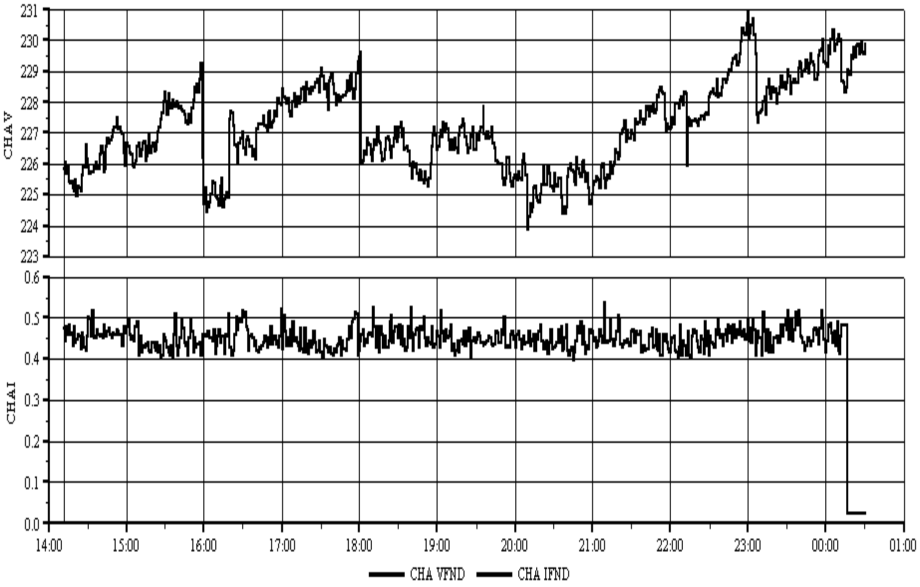


Figure 4.1.4. Fundamental phase voltage (top) and phase current (bottom).

The total active power, fundamental plus harmonic power, taken by the TV is shown in figure 4.1.5. The total active power is around 98.3 % of the fundamental active power, which is normalized to 100 %. This is due to the negative active power generated by the current harmonics taken by the TV. The negative harmonic active power flow can be seen as additional losses in the rest of the power system.

The fundamental power varied between 92 and 120 W and the total active power was 1.7 % lower.

See also chapter 5 about harmonic active power flow.

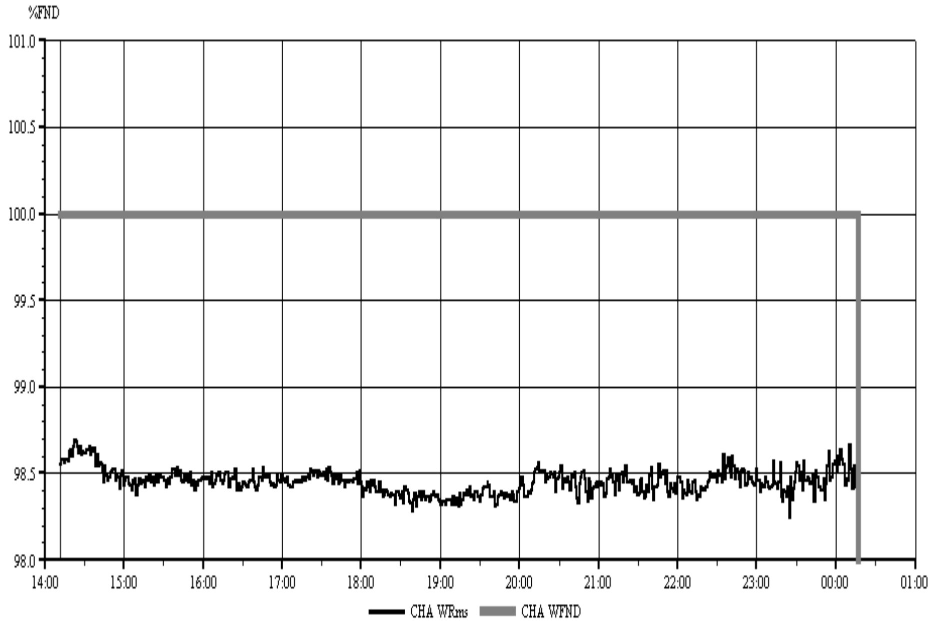


Figure 4.1.5. Total active power (bottom) in percent of the fundamental (top).

If, for example in Sweden, 2 million TV receivers each generate the same amount of negative harmonic active power flow and they are used 6 hours per day, 365 days per year, the total financial cost for the additional losses is 4.4 million SEK/year.

If 4 million computers (which have the same type of current distortion) are used 10 hours per day, the total financial cost for the additional losses is 14.6 million SEK/year.

Totally this is around 20 million SEK/year, about 0.6 % of the total fundamental component transmission losses in Sweden.

### Conclusion 0.4 kV

- The current distortion is affected by the voltage distortion and reduces 10 % when the voltage distortion increases 0.25 %.

- The total active power is lower than the fundamental power due to negative harmonic power flow, around 1.7 % of the fundamental.

- The total financial cost for the additional losses for 6 million TV's and computers in Sweden is around 0.6 % of the total fundamental losses.

- The following values show the most common distortion levels, taken from measurements partly presented in chapter 3:

**Industrial distribution:**

| | |
|---|---|
| Single devices (converters) | $I_{THD}$: 25 – 200 % |
| Totally for a low voltage transformer | $I_{THD}$: 15 – 25 % |
| | $U_{THD}$: 3 – 6 % |

- The following values are from "Elforsk rapport 97:3" [14]:

**Public distribution:**

| | |
|---|---|
| Residences, low voltage | $I_{THD}$: 5 – 30 % |
| Single larger customer, low voltage | $I_{THD}$: 2 – 20 % |
| Totally for a low voltage transformer | $I_{THD}$: 2 – 15 % |
| | $U_{THD}$: 1 – 6 % |

## 4.2 Medium voltage

The following values are from "Elforsk rapport 97:3" [14]:

| | |
|---|---|
| Single customer, medium voltage | $I_{THD}$: 2 – 20 % |
| | $U_{THD}$: 1 – 5 % |

## 4.3 High voltage

The measurements from the 130 and 400 kV levels have been performed over one week to catch the daily variations, with 10 minutes intervals. The measurements where not made at the same period, the 130 kV measurements where taken during June and the ones at 400 kV during September 1999. The monitoring was done on existing voltage and current transformers. All values presented is rms phase to ground quantities. The frequency response for the measuring transformers is not known but the error in amplitude can probably be considered acceptable (below 10 % up to 1 kHz). For some manufactures there can be a significant error (12 p.u. or more) in amplitude at a certain harmonic [12][13], especially for capacitive voltage transformers. Despite the uncertainty in the harmonic amplitudes it is interesting to study the variation over time and due to the switching of capacitor banks. The accuracy for all the measuring transformers, at 50 Hz, was 0.2 % according to the grid owner. The monitoring equipment had a maximum error of 0.5 %.

The error in phase angle of the transformers is also not known, neither is it mentioned or tested in [14].

Both the 130 and 400 kV system are meshed, figure 4.3.0. The area fed by the northern part of the 130 kV system has a population of about 200 thousands and includes several large industries.

The 130 kV system was in normal operation during the monitoring period. The operating status of the 400 kV system was not known.

The actual operating voltage is higher than the denoted 130 kV and 400 kV.

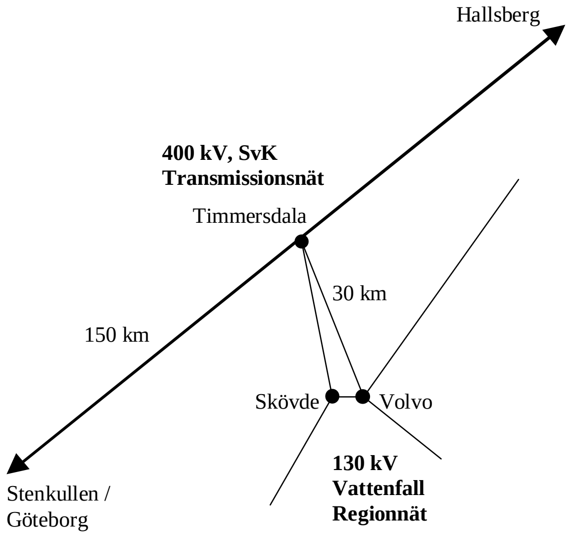


Figure 4.3.0 The part of interest of the meshed 130 kV and 400 kV system.

Two important phenomena of the voltage and current distortion in high voltage transmission systems have to be considered both for analysis of measurement data and for load modeling. They are valid both for radial and meshed systems.

- The first phenomenon is local resonance in a certain point of the line, with possible high peaks of a voltage or a current harmonic. This is due to the relationship between the wavelength at the harmonic frequency and the length of the line. This is published and described by several authors e.g. in [2].

  At 50 Hz the wavelength is about 6000 km for overhead lines. For higher frequencies the wavelength becomes proportionally shorter. At the 5:the harmonic, for example, the wavelength is 1200 km and at the 19:th harmonic only 315 km. Wave effects become apparent for line length above one eight of a wavelength, thus for 750 km at 50 Hz, for 150 km at the 5:th harmonic and already for 40 km at the 19 harmonic.

Both the amplitude and the phase angle, for the voltage and current components, are affected by the wave effect and can thus be different along the line. This can be of importance concerning increased stress on the system and for increased telephone interference.

- The second phenomenon to be considered is interaction in the current distortion between cities, large industries or HVDC-links (not devices). The interaction can increase or decrease the current distortion in a certain point (node) or at a generator. This is due to the difference in phase angle of the fundamental voltage in two different nodes. The phase angle between the voltages depends mainly on the active power flow between these nodes. If the line resistance is neglected the angle become

$$\O_{AB} = \arcsin\left(\frac{P_{AB} \cdot X_{AB}}{U_A \cdot U_B}\right)$$

The phase angle of the current harmonics is related to the fundamental current that in turn is related to the fundamental voltage phase angle.

Increasing the current distortion to a city, e.g. adding non-linear loads, does not necessary lead to an increased voltage distortion. The same effect can be seen between loads (devices) when three phase and single phase non-linear loads are mixed at low voltage level (0.4 kV), see [15].

No published documentation has been found describing this phenomenon.

## 130 kV sub-transmission (feeding point of a 50 MVA industry)

The transformer station feeds a large modern mechanical industry, divided in two parts fed by separate transformers. The phase voltage and phase current were monitored to the 20 MVA part of the industry on the 130 kV side of the 75 MVA transformer, see figure 4.3.1. The measurements were performed in early June 1999. Both parts of the industry have a highly automated production and the 30 MVA part contain a number of large diode and thyristor rectifiers (a few MVA). The production was operating 24 hours a day, except Saturday and Sunday, with a small reduction over the night, figure 4.3.2 and 4.3.3. The current distortion (THD) at the low voltage level, on the transformer secondary side (0.4 kV), is about 25 %.

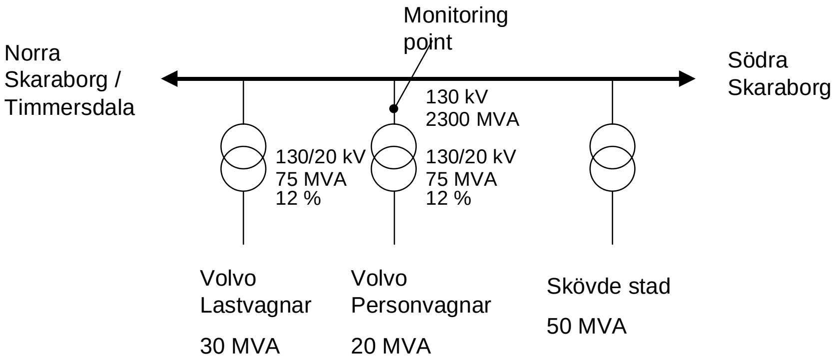


Figure 4.3.1. Scheme of the 130 / 20 kV transformer station.

At the 130 kV level, at the 400/130 kV transformer station in Timmersdala (at 30 km distance), a 60 Mvar shunt capacitor bank is located which is connected and disconnected daily and also on demand to control the voltage on the 400 kV level. The capacitor bank has synchronized circuit breakers. Some years ago there were disturbances in the industry when the bank was switched, without the synchronized circuit breakers. In the area at medium voltage levels, connected to 130 kV system, a large number of capacitor banks is connected, some of them are switched daily.

The 30 MVA part of the industry has fixed capacitor banks. The 20 MVA part has about 5 Mvar with a mix of fixed banks and harmonic filters (harmonic 5 and 7), all at the 0.4 kV level. Of the 20 MVA load there is about 30 % induction motors, 60 % drives and other rectifiers and 10 % is office equipment and lighting.

### Time variation of the fundamentals over one week

Figure 4.3.2 shows the fundamental phase voltage and current from Wednesday noon, June 2, to Wednesday noon, June 9, 1999. The large steps in the voltage are due to the switching of capacitor banks, mainly the 60 Mvar bank in Timmersdala. The increase of the voltage during the weekend, up to 142 kV line to line voltage, is mainly due to the load reduction in the industry.

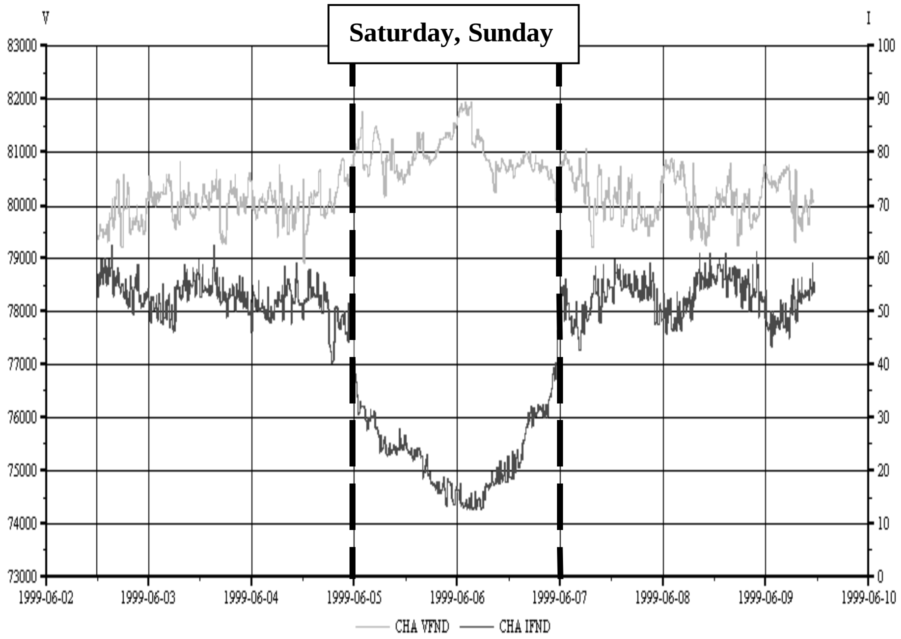


Figure 4.3.2 Fundamental phase voltage (top) and phase current (bottom).

The phase current has a daily variation that follows the production, it varies between 15 and 60 A.

Figure 4.3.3 shows the fundamental active and reactive power per phase. During the weekend both the active and reactive power consumption are lower. The internal low voltage capacitor / filter banks remain connected, which cause the reactive power become negative (capacitive) during the weekend.

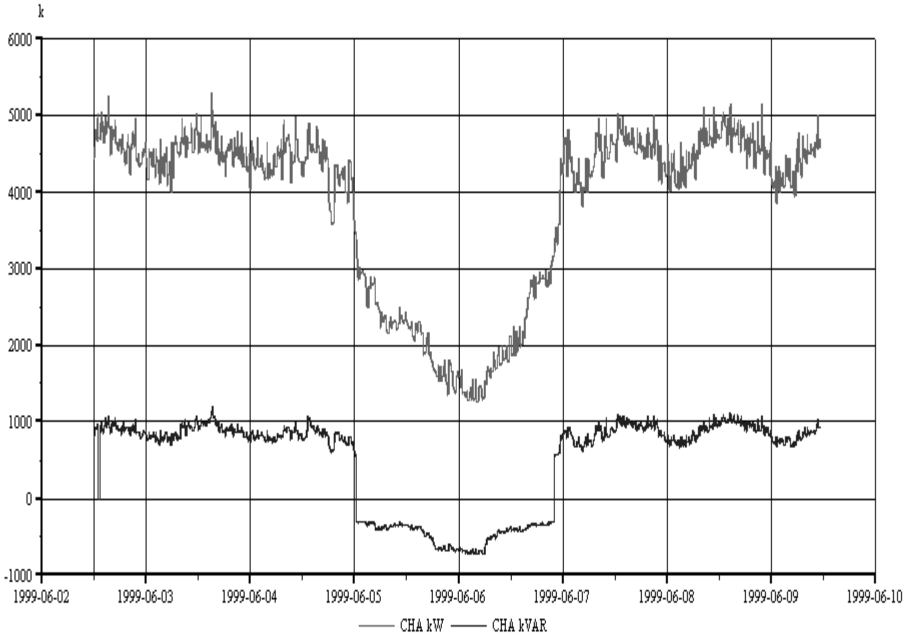


Figure 4.3.3 Fundamental P (top) and Q (bottom), per phase.

An important factor, from many points of view, is the fundamental voltage unbalance, figure 4.3.4. For different loads, different aspects of the unbalance are important. Motors are affected by negative sequence voltage and other types of loads can be affected by the difference between the phases in amplitude or phase angle. The fundamental voltage unbalance causes increased unbalanced harmonic currents, mainly non-zero sequence triplen harmonic distortion, see chapter 3 and later in this chapter. The negative sequence component, around 0.75 %, has a daily variation during the weekdays and the zero sequence component, around 0.65 %, shows no daily variation but a step change before, during and after the weekend. There is no explanation for these steps in the zero sequence.

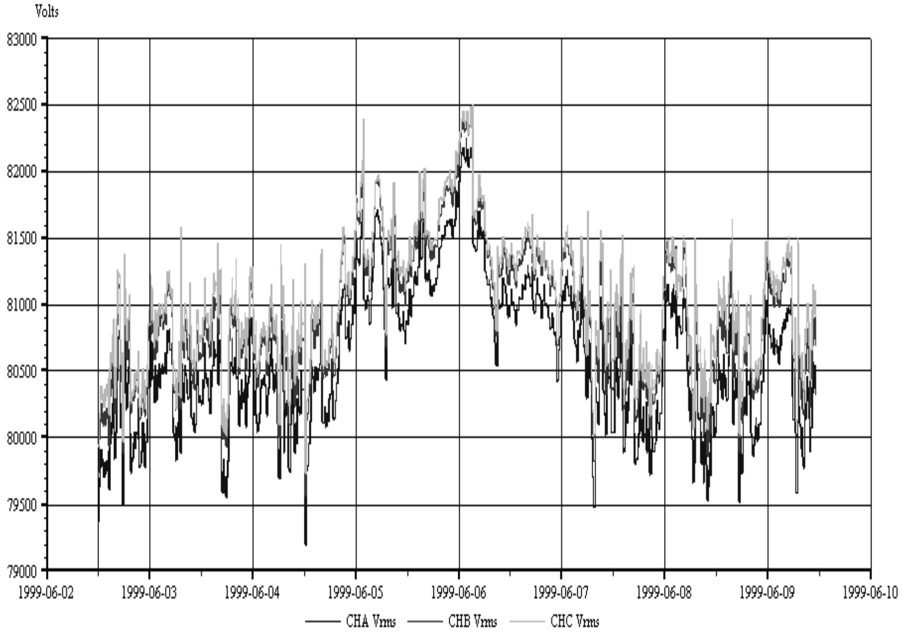


Figure 4.3.4. Fundamental voltage amplitude in phase R (dark), S (light dark) and T (light). The lowest amplitude is in phase R during the whole week.

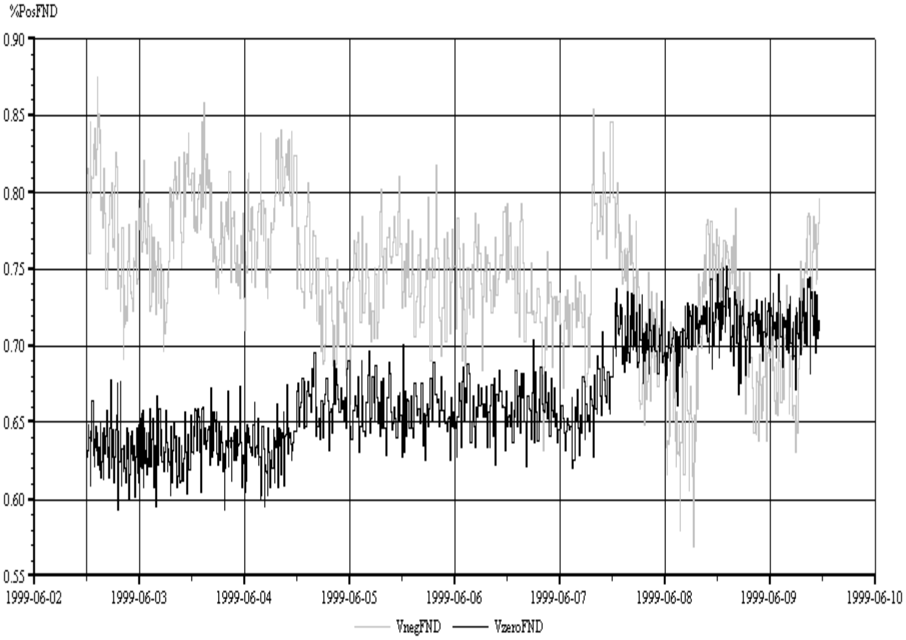


Figure 4.3.5. Negative (light) and zero (dark) sequence component relative to the fundamental voltage amplitude.

## Time variation of the harmonic distortion over one week

### Harmonic 5, 7

For both the 5:th and 7:th voltage harmonics there is a large increase of the amplitude at evening time and during the weekend, figure 4.3.6. This is due to the "Television peak" caused by the use of television and computers at residential low voltage level. The relative value of the 5:th harmonic is 0.2 % at daytime and up to 0.45 % at evening time. The 7:th harmonic reaches a maximum value of 0.3 %.

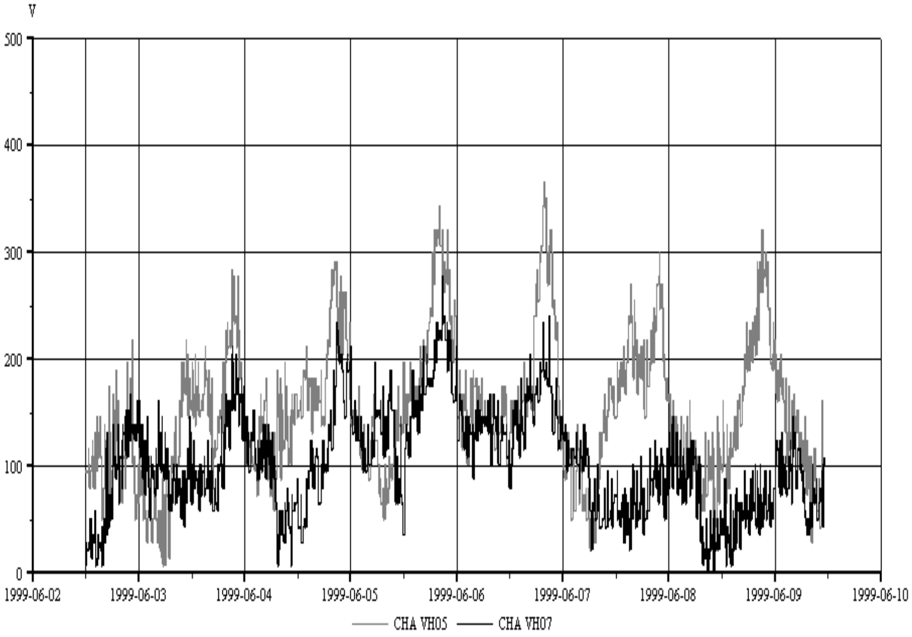


Figure 4.3.6. Voltage harmonic 5 (light) and 7 (dark).

A reduction of the 7:th harmonic can be seen at morning time during the weekdays, compared to nighttime. This is mainly due to interaction between single phase and three phase loads external to the industry.

The increase of the 5:th harmonic during morning time, weekdays, is mainly due to the use of single phase loads, e.g. computers and fluorescent lighting, at external low voltage levels.

The long line wave effects also play a role, both for the 5:th and the 7:th harmonic, but this is not investigated here.

The interaction between single phase and three phase loads is strongest for the 5:th and 7:th harmonic currents because they are generated with opposite phase angle. This can cause a total cancellation of these harmonics if the amplitudes are equal for the different types of loads. See chapter 3.

When single phase non-linear loads are connected at morning time, weekdays, an interaction with three phase non-linear loads is most obvious for the 7:th harmonic.

Variations can also be seen in the current harmonics 5 and 7, figure 4.3.7, but here the largest variation is in the 7:th harmonic. Contrary to lower voltage levels the 7:th harmonic is larger than the 5:th at the feeding point, except for daytime during the weekend. This is due to low impedance for the 7:th harmonic voltage, seen from 130 kV level towards the industry. The 7:th harmonic current follows the same variation as the harmonic voltage.

The low voltage capacitor banks and the harmonic filters (7:th) cause low 7:th harmonic impedance (series resonance) in the industry, figure 4.3.6. The reduction of the 7:th harmonic current amplitude at morning time follows the reasoning for 7:th harmonic voltage above, except for the Sunday morning when it appears to be affected only by the internal interaction when some small loads start (see also figure 4.3.2 and 4.3.3).

Without the small loads the current distortion is expected to be similar, or somewhat higher, to the one at Saturday which is related to the 7:th harmonic voltage.

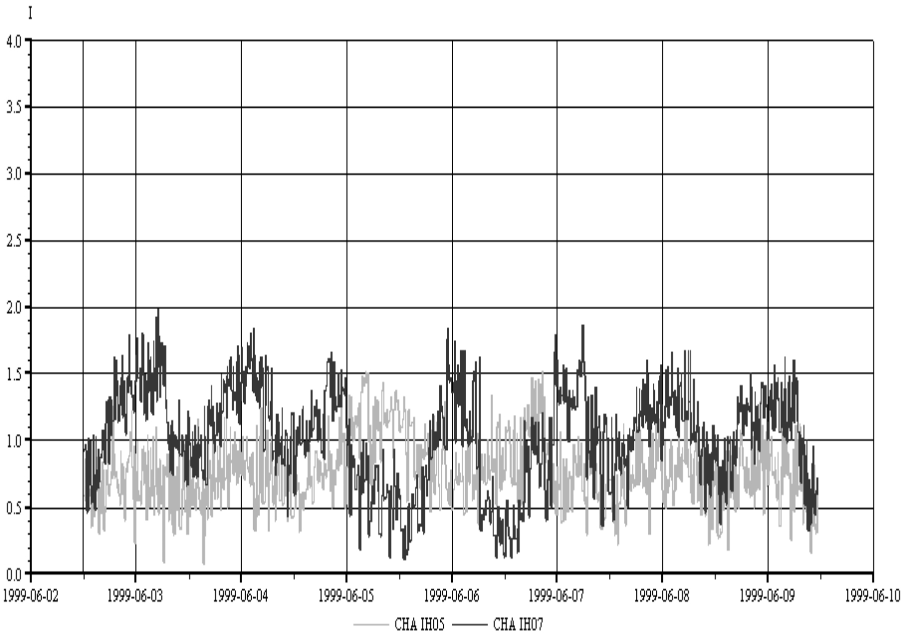


Figure 4.3.7. Current harmonic 5 (light) and 7 (dark).

The 5:th harmonic current follows somewhat the increase of the 5:th harmonic voltage during evening time and the weekend, but the increase is small. There is no significant resonance in the industry seen from the 130 kV side for the 5:th harmonic, but there is some reduction of the 5:th harmonic impedance caused by the internal low voltage 5:th harmonic filters.

The impedance seen from 130 kV side for the 7:th harmonic is affected by a series resonance mainly between the 20/0.4 kV transformers impedance and the fixed capacitor banks, see figure 4.3.8. Also the 7:th harmonic filters located at some of the 20/0.4 kV transformers, instead of fixed capacitor banks, contribute to the 7:th harmonic impedance, but the resonance frequency is shifted somewhat lower, to order 6.4, due to the inductance of the intermediate transformers.

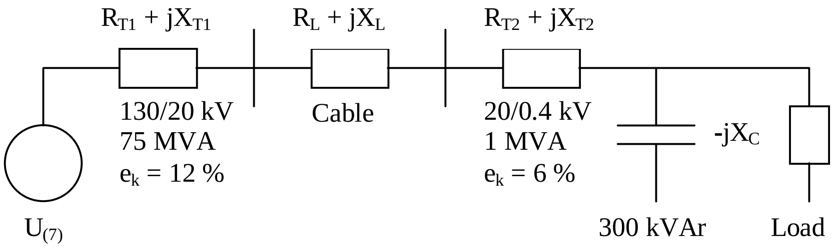
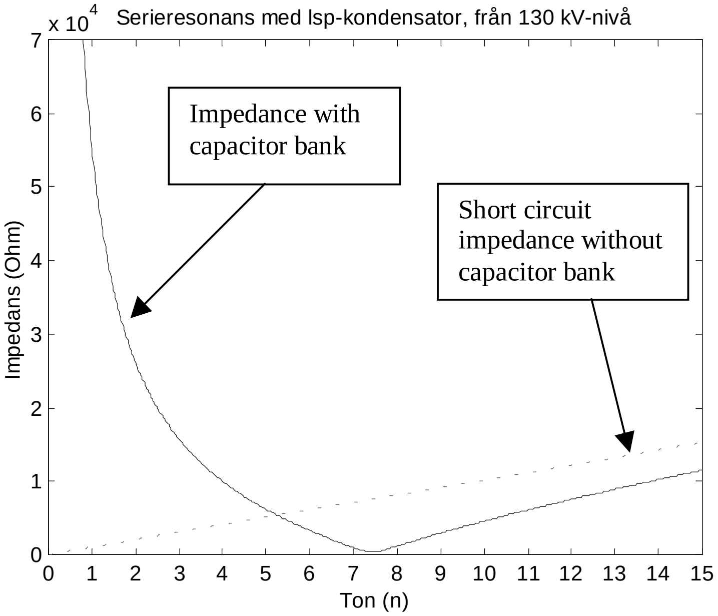


Figure 4.3.8. Series resonance from 130 kV to 0.4 kV level.

Resonance occurs at harmonic order, n, $X_{T2} >> X_L$ and $X_{T1}$:

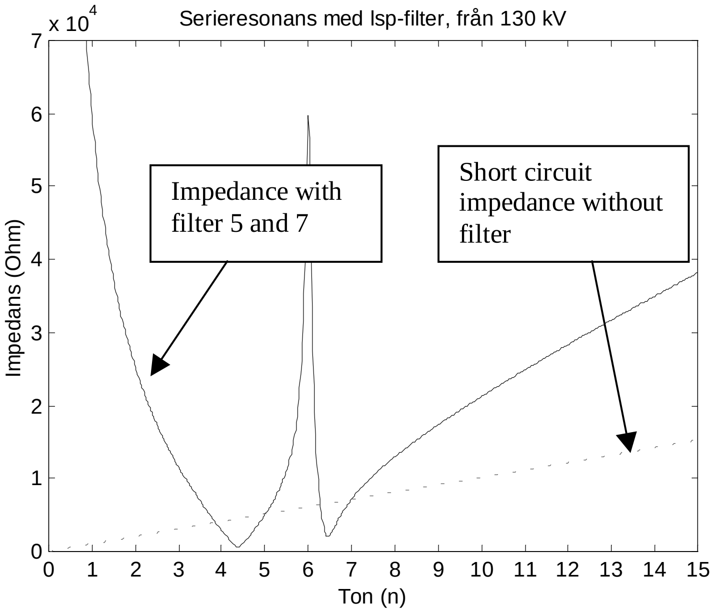
$$n = \sqrt{\frac{X_C}{X_{T2} + X_L + X_{T1}}} \approx \sqrt{\frac{X_C}{X_{T2}}} = 7.45$$

The impedance curve for the 130/20 kV transformer and only one 20/0.4 kV transformer with a fixed capacitor bank, is seen in figure 4.3.9. All loads are neglected.



4.3.9. Series resonance from 130 kV with one low voltage capacitor bank.

The impedance curve for the 130/20 kV transformer and only one 20/0.4 kV transformer with a 5:th and a 7:th harmonic filter becomes as in figure 4.3.10. All loads are neglected.



4.3.10. Series resonance from 130 kV with one 5:th and one 7:th harmonic tuned low voltage filter.

The resonance frequency of the harmonic filters, tuned for the 5:th and 7:th harmonic, are shifted about 8 % lower in frequency to order 4.3 and 6.4 respectively due to the transformer inductance. For the detuned filters resonance occurs near the 4:th and 6:th harmonic.

The 7:th harmonic impedance is most affected by the series resonance caused by the low voltage capacitor banks. An equivalent scheme is obtained if a short circuit is made between the cable and the 1 MVA transformer in figure 4.3.8. Thus it is only the total impedance of the 130/20 kV transformer, the cable and the equivalent resistance of the low voltage transformers and capacitor banks (totally about 20 transformers/banks) that is seen for the 7:th harmonic voltage from the 130 kV level.

The calculated impedance for the 130/20 kV transformer and the cable is 210 Ω. The measured impedance is in the range of 100 to 300 Ω.

The resonance gives an increased 7:th harmonic voltage on the transformers and capacitors. If it is assumed that 50 % of the 7:th harmonic current at the 130 kV level is passing the capacitor banks, the other 50 % is through passive loads and all other harmonic interaction is neglected, the 7:th harmonic voltage will be about 45 V over each capacitor. In practice the voltage is much lower due to damping and harmonic interaction caused by loads.

A correlation was found between the variation of the 5:th and the 7:th harmonic voltage and the variation of the total active power flow, including the harmonic power, to the industry. In figure 4.3.11 the total active power $P_{(\mathrm{tot})}$ relative the fundamental power $P_{(1)}$ in phase S and the dominating symmetrical sequence components of the 5:th (negative) and the 7:th (positive) harmonic voltage are plotted. The increase of the harmonic voltage amplitudes cause an increase of the total active power flow, somewhat less than one tenth of a percent, with peaks at evening time and especially at Saturday night.

The total active power $P_{(\mathrm{tot})}$ is calculated as the sum of the active power of all harmonics, with sign, including the fundamental. A positive increase means that the harmonic power is towards the industry (load), the harmonic current is more or less in phase with its corresponding voltage.

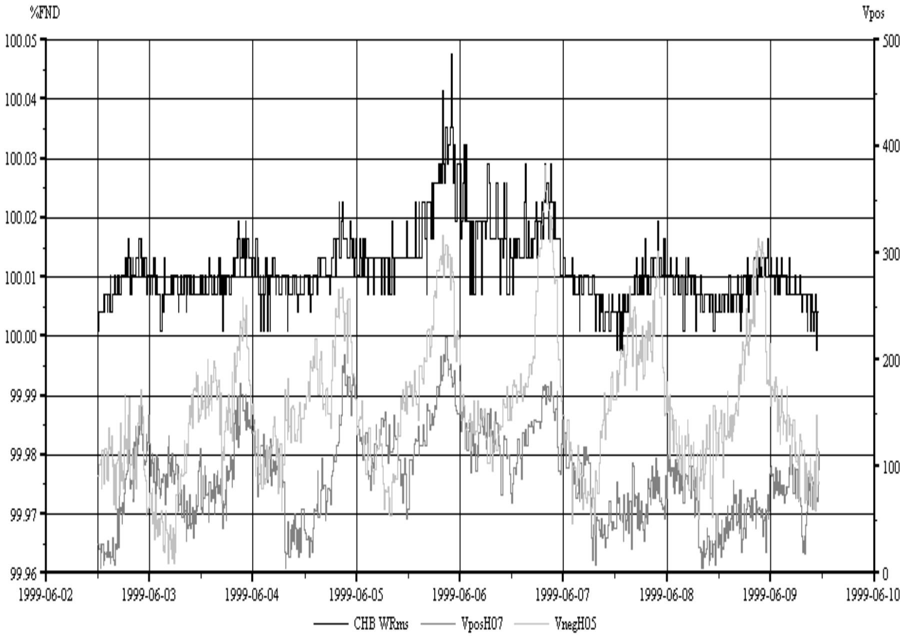


Figure 4.3.11. Active power $P_{(tot)}$ (dark) and the negative 5:th (light) and positive 7:th (light dark) sequence harmonic voltage.

By the above reasoning it can be concluded that the industry does not contribute to the 5:th and 7:th voltage harmonics on the 130 kV level. There is instead a decrease of the voltage distortion due to the internal capacitor banks. The industry is filtering the feeding 130 kV network.

A similar filtering effect may also be present at the feeding point to larger cities and industries, with capacitor banks at lower voltage levels.

## Harmonic 11, 13

The amplitudes of the 11:th and 13:th voltage harmonics, figure 4.3.12, decrease somewhat during daytime and there is no increase during evening time, like the 5:th and 7:th. The reduction of the amplitudes is most probably due to the reduction of the 400 kV 11:th and 13:th harmonics caused by the daily connection of the 60 Mvar capacitor bank at Timmersdala. The load current, figure 4.3.13, to the industry does not cause the 11:th and 13:th harmonic voltage because there is no relation between the changes in the voltage and current harmonics.

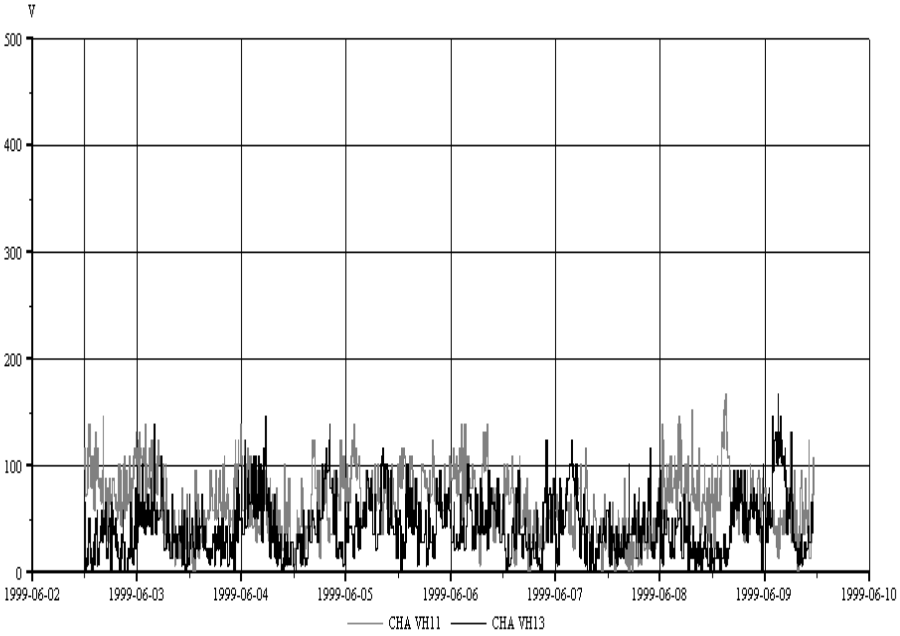


Figure 4.3.12. Voltage harmonic 11 (light) and 13 (dark).

The 11:th and 13:th current harmonics are small, about 1 %, figure 4.3.13. There is a tendency to a reduction of the 11:th harmonic during the weekend.

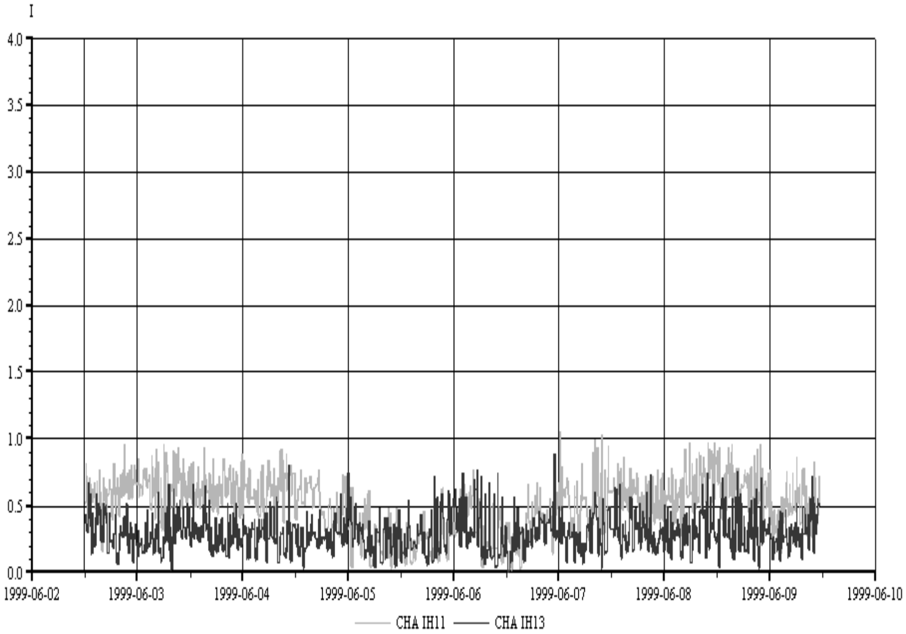


Figure 4.3.13. Current harmonic 11 (light) and 13 (dark).

## Harmonic 3

A major difference between the 3:rd (and 9:th, see figure 4.3.20) harmonic and the 5:th, 7:th, 11:th and 13:th harmonics is that the triplen harmonics are not equal in amplitude in the three phases, see figure 4.3.14 and 4.3.15. This means that they are not only zero sequence, as they are in a normal balanced case.

Only a small increase can be seen in the 3:rd harmonic voltage during daytime in phase R and T, figure 4.3.14, which not only is related to the production in the industry but also in the area. The distortion of the 3:rd harmonic voltage in phase S is higher than in the two other phases and the variation follows more the daily consumption in the area, with peaks at day and evening time and low amplitudes at the morning. It is not related to the load current to the industry.

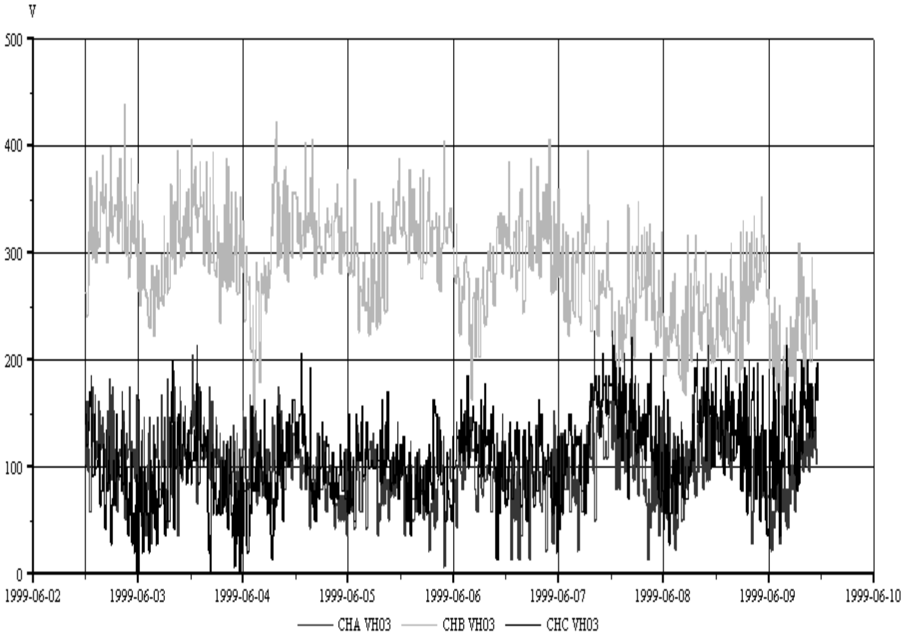


Figure 4.3.14. Voltage harmonic 3 in phase R (light dark), S (light) and T (dark).

The current distortion in each phase, figure 4.3.15, shows a variation similar to the variation of the voltage distortion in the same phase during the weekdays but with a total different relationship between the phases with the highest amplitude. During the weekend the 3:rd harmonic current in phase R shows a large increase and phase S and T shows a decrease. The change of the distortion in all the phases follows the reduction of the production in the industry.

The 3:rd harmonic current does not cause the 3:rd harmonic voltage distortion due to the lack of correlation between them. Instead there is a small influence on the current distortion related to the 3:rd harmonic background voltage distortion, in each phase, following the daily variations. This may be due to the low voltage capacitor banks and harmonic filters causing reduced impedance, similar as for the 5:th and 7:th voltage harmonics.

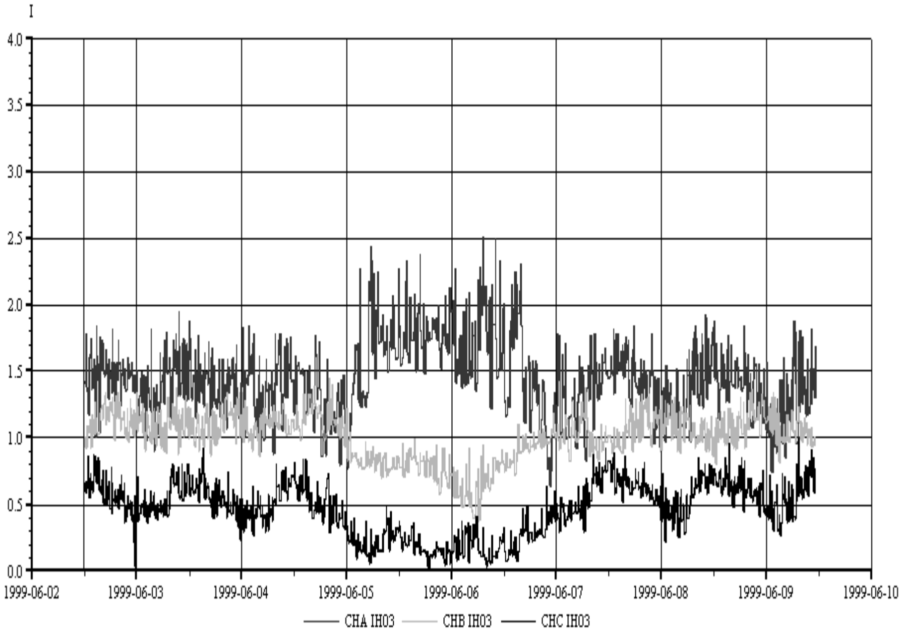


Figure 4.3.15 Current harmonic 3 in phase R (light dark), S (light) and T (dark).

The difference in the amplitude, between the three phases, of the 3:rd harmonic voltages and the currents is due to two reasons. One reason is load unbalance caused by single phase loads. The other reason is positive and negative sequence 3:rd harmonics generated by three phase rectifiers supplied by an unbalanced fundamental three phase voltage. The 3:rd harmonic positive and negative sequence currents are shifted either +90 or –90 degrees and can be different in amplitude in each phase depending on the type of unbalance.

For a six pulse diode rectifier fed by an amplitude unbalanced fundamental voltage, with phase R as the lowest, phase S as the middle and phase T as the highest one, the 3:rd harmonic current becomes:

$I_{(3)}$@-90° in phase R,
$2I_{(3)}$@90° in phase S,
$I_{(3)}$@-90° in phase T.

Depending on the relative sizes of the smoothing inductor and the capacitor in the DC-link, connected after the rectifier, there can also be large 9:th and sometimes also 15:th harmonic currents. All of them contain no zero sequence components.

The transformer type and coupling will change the 3:rd harmonic current between the phases and also the propagation of the symmetrical components from the secondary side to the primary side. The most commonly used transformer type at low voltage level in Sweden is the Dyn11.

Some part of the 3:rd harmonic current in each phase (zero sequence component), figure 4.3.16, is probably due to transformer saturation (in the 75 MVA 130/20 kV transformer) caused by the fundamental voltage positive sequence component. The 75 MVA transformer is Wye-wye connected and grounded and all loads are connected to secondary side of the Delta-wye low voltage 1 MVA transformers.

### Time variation of the 3:rd harmonic symmetrical components

The zero sequence component of the 3:rd harmonic voltage increases during the weekend due to the increase in the fundamental voltage, see also figure 4.3.2. The 3:rd harmonic voltage distortion is of course the resulting voltage for the whole 130 kV system and loads.

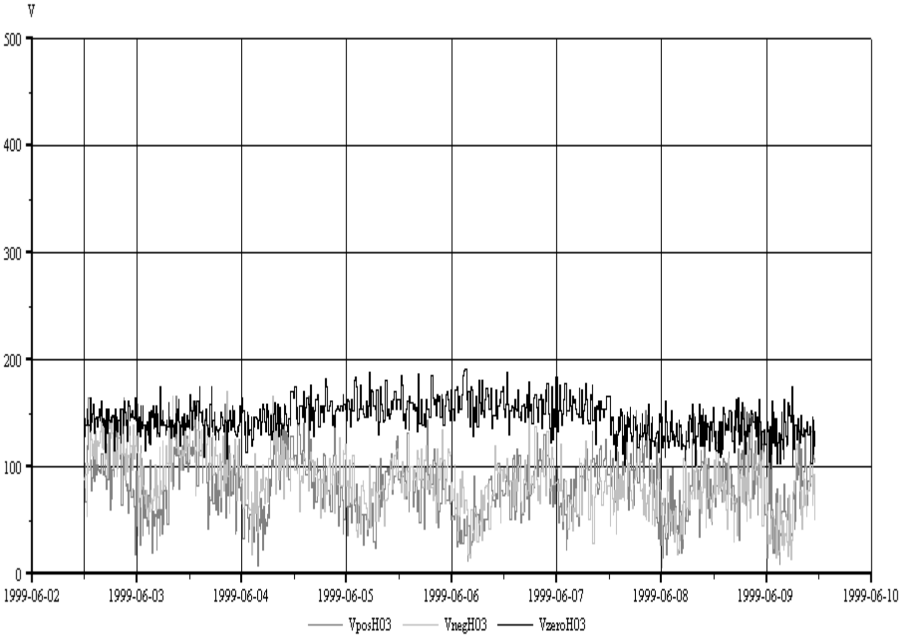


Figure 4.3.16. Third harmonic positive (light dark), negative (light) and zero (dark) sequence voltage.

The zero sequence 3:rd harmonic current is almost constant with a small daily variation, which also is seen in the positive and negative sequence components, see figure 4.3.17.

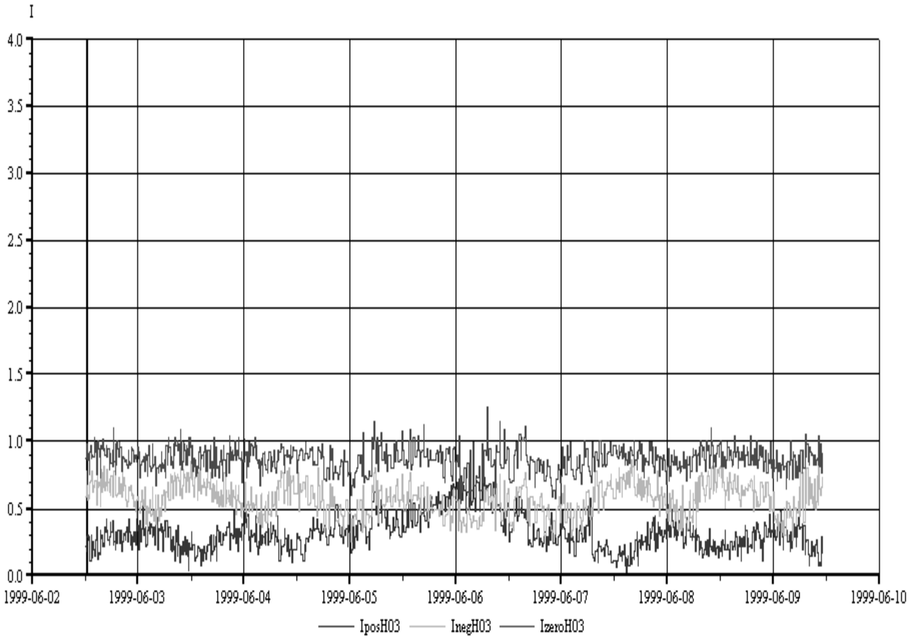


Figure 4.3.17. Third harmonic positive (bottom), negative (middle) and zero (top) sequence current.

A very interesting correlation was found in the variation of the unbalances of the 3:rd harmonic current and the fundamental voltage during the week. The positive sequence component of the 3:rd harmonic current follows the variation in the positive sequence fundamental voltage component, see figure 4.3.18. Also the correlation for the negative sequence components of the 3:rd harmonic current and fundamental voltage is good, see figure 4.3.19. These relationships confirm that the non-zero sequence components of the 3:rd harmonic current on higher voltage levels are related to fundamental voltage unbalance supplying three phase non-linear loads at low voltage level. No correlation for other harmonic sequence components were found.

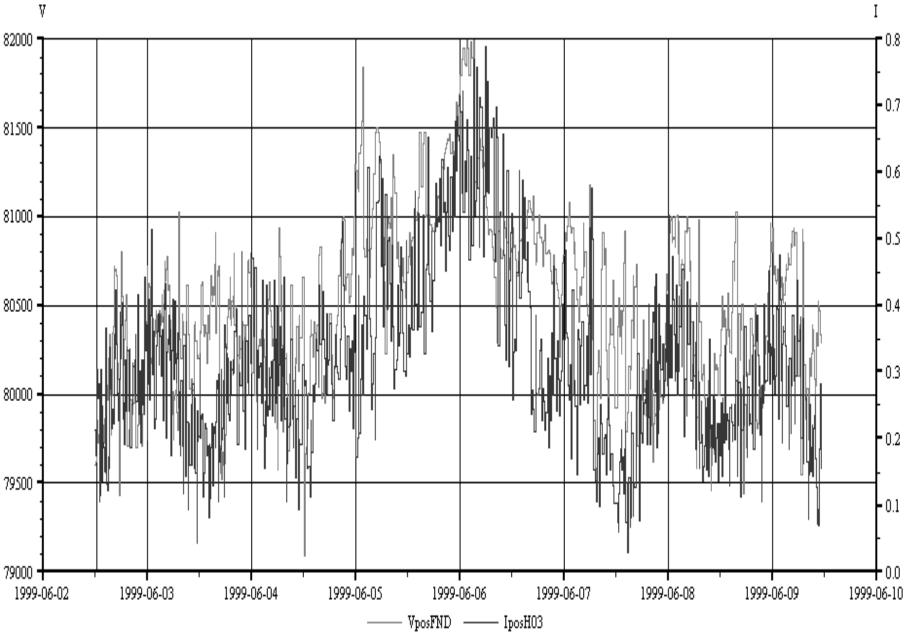


Figure 4.3.18. Positive sequence components of the 3:rd harmonic current (dark) and the fundamental voltage (light).

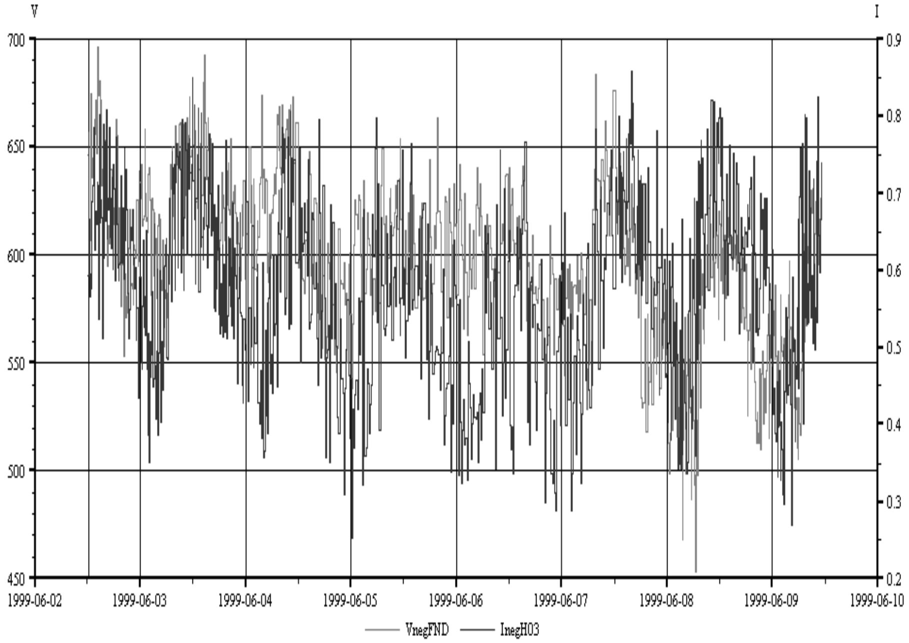


Figure 4.3.19. Negative sequence components of the 3:rd harmonic current (dark) and the fundamental voltage (light).

### Harmonic 9

The 9:th harmonic voltage distortion, figure 4.3.20, is small and has like the 3:rd harmonic voltage different amplitudes in each phase, again with phase S showing the highest amplitude. A small increase of the zero sequence component was noticed during the weekend due to the increased fundamental voltage. There is no daily variation. The uncertainty of the monitored values is big due to the low amplitudes.

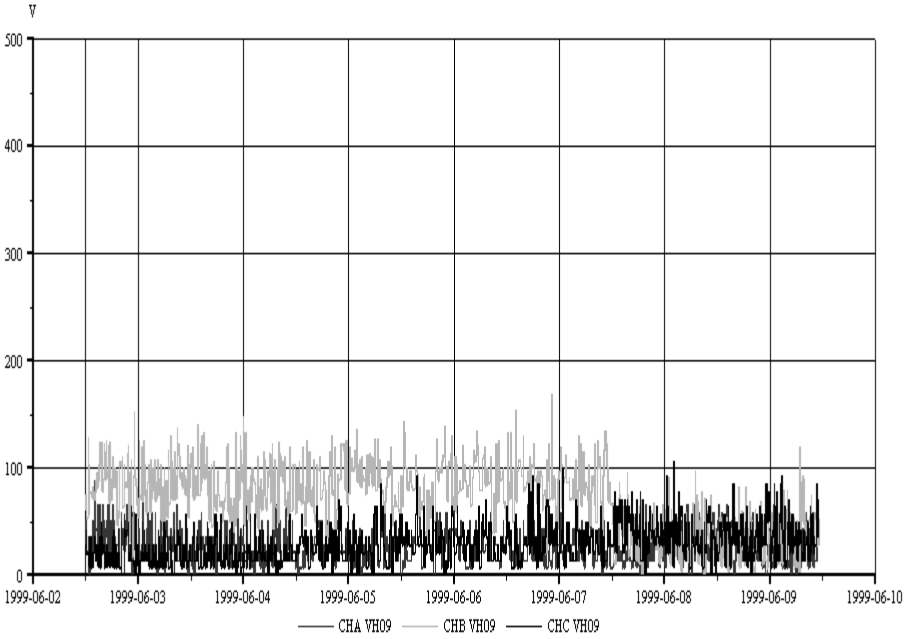


Figure 4.3.20. Voltage harmonic 9 in phase R (light dark), S (light) and T (dark).

The 9:th harmonic current, figure 4.3.21, shows also different amplitudes in each phase, and also here the highest phase is R like the 3:rd harmonic current but with a decrease instead of an increase during the weekend.

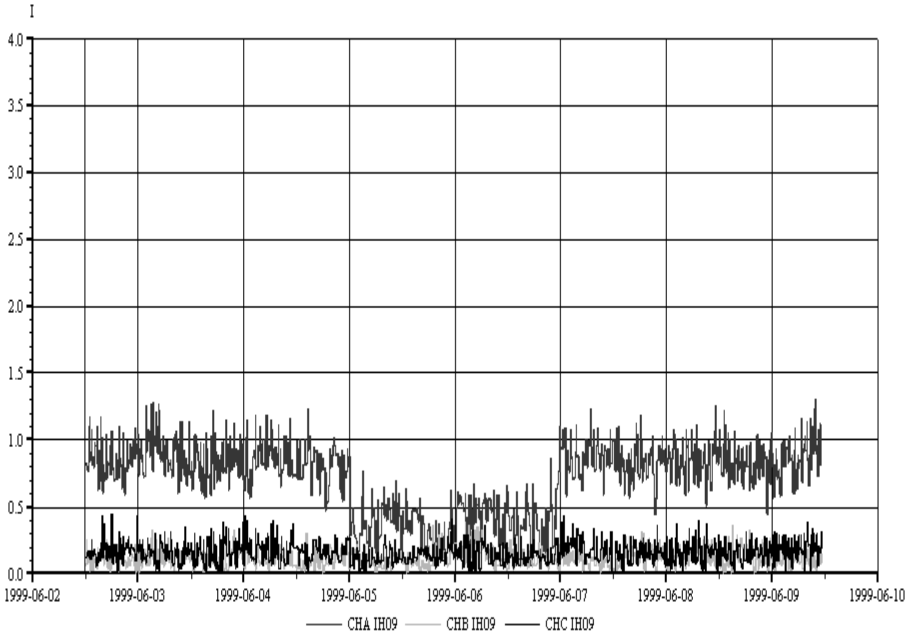


Figure 4.3.21. Current harmonic 9 in phase R (light dark), S (light) and T (dark).

## Conclusions 130 kV

The most important conclusions can be summarized as follows:

- The voltage distortion does not follow the power consumption in the industry. Residential and commercial loads at external low voltage levels mainly cause it, with "television peaks" at evening time. The industry does not contribute to the voltage distortion. The voltage THD varies between 0.2 and 0.7 %.

- Switching in the 60 Mvar capacitor bank in Timmersdala reduces somewhat the 11:th and 13:th voltage harmonics.

- The current distortion is mainly caused by the 130 kV voltage distortion. Low impedance is present at the 7:th harmonic due to the internal low voltage capacitor banks causing a series resonance with the low voltage transformers. The current distortion follows the changes in the 130 kV voltage distortion. The current THD varies between 2 and 13 %.

- The relationship between the harmonic current distortion and the harmonic voltage distortion is sometimes inductive, capacitive or resistive and not fully linear. Neither from the 130 kV level point of view (load impedance for the voltage distortion) nor from the non-linear load point of view (source impedance for the distorted load current). This means that a certain current harmonic does not give a proportional voltage harmonic, or the other way around.

- The harmonic active power flow is positive (towards the industry) which increases the total active power. The increase is small, below one tenth of a percent. The additional internal losses caused by the current distortion at the low voltage level are not seen in the monitoring point, as harmonic active power flow. The harmonic losses are included in the fundamental active power flow to the industry. It is not investigated how big these internal losses are but they can be estimated by measurements, not shown here, to be below 10 % in average of the fundamental losses.

- Fundamental voltage unbalance, around 0.8 % negative sequence on the 130 kV level, in combination with nonlinear low voltage loads, mainly three phase six pulse rectifiers, cause non-zero sequence triplen harmonic currents on the 130 kV level.

- Zero sequence third harmonic voltage and current shows a more or less constant level during the week. This is most probably due to transformer saturation caused by the fundamental voltage amplitude. An increase in the third harmonic voltage was seen during weekend when the fundamental voltage amplitude also increased.

- Additional effects in the industry of the harmonic distortion, originating from 130 kV level, are possible component overloading, derating, reduction of lifetime and other disturbances affecting production equipment. These phenomena are not investigated here.

## 400 kV transmission (feeding point of 130 kV sub-transmission)

The transformer station in Timmersdala is one of six stations feeding the 130 kV system for Skaraborg and neighboring areas, at a distance of approximately 200 km. The transformer station also feeds some other smaller networks at local grid owners. The 400 kV system is part of the Swedish transmission system. The phase voltage and phase current were monitored on the 400 kV side of the 750 MVA transformer, see figure 4.3.22, in late September 1999. The 400/130 kV transformer is Wye-wye connected and grounded on both sides and has tap changers on the 130 kV side.

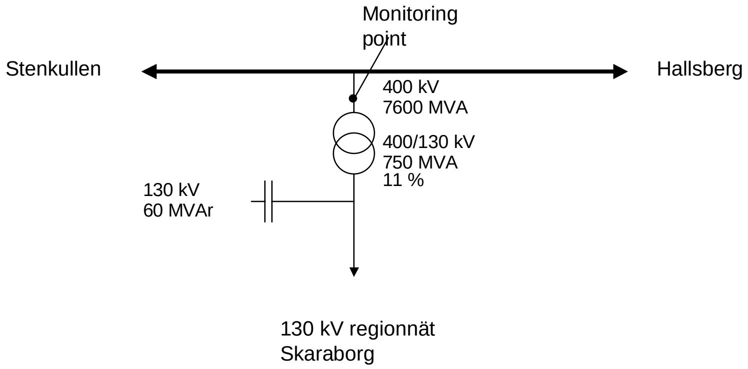


Figure 4.3.22. Part of the scheme for the 400/130 kV transformer station in Timmersdala.

On the 130 kV side of the transformer a 60 Mvar shunt capacitor bank is located which is connected and disconnected daily and also on demand to control the voltage on the 400 kV level. The capacitor bank has synchronized circuit breakers. At lower voltage levels, connected to the 130 kV system there are a large number of capacitor banks, in the range of 5 to 16 Mvar, that are daily switched.

At Stenkullen, about 150 km from Timmersdala, the HVDC-link to Denmark is located and connected to the 400 kV system via a 400/130 kV transformer. There is also a SVC located there. Some tenth of kilometers south of Stenkullen the HVDC-link Lindome is located, also connected to Denmark.

The active power flow through both HVDC-links is shown in figure 4.3.23 and the total active power, without sign, is shown in figure 4.3.32 during the actual week. Both HVDC-links are 12-pulse rectifiers. Their current has dominating 11:th and 13:th harmonic currents on the AC-side.

It is not the amount of power that is of interest here because of complexity of harmonic propagation in transmission systems that requires a much deeper study, instead it is when the links are in operation.

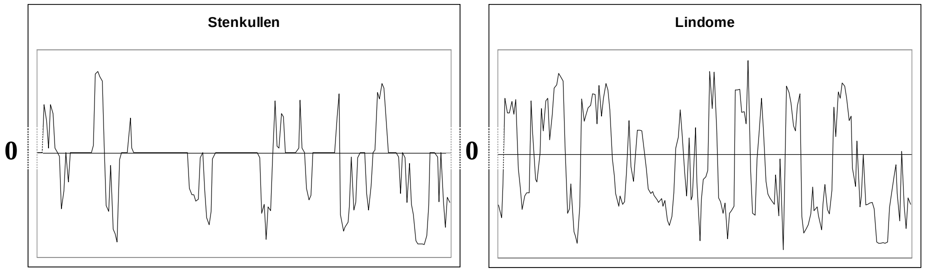


Figure 4.3.23. Active power flow at the HVDC-links at Stenkullen and Lindome.

Several parameters affect the distortion caused by the HVDC rectifiers on the 400 kV system and the propagation to Timmersdala. The most important ones are the direction and amount of active power flow on the DC-side, the 400 kV network layout, the fundamental voltage unbalance, current interaction with other loads/cities, long line resonance and the difference in the fundamental voltage phase angle at the three locations.

The distortion level for a specific harmonic in a certain point along the line can be totally different compared to another point of the line, also between the phases due to unbalance. It is valid both for harmonic voltages and currents. This is important to remember when analyzing monitored data from transmission systems.

## Time variation of the fundamentals over one week

Figure 4.3.24 shows the fundamental phase voltage and current from Thursday noon, September 23, to Thursday noon, October 2, 1999. The phase voltage has a rather constant level during the week with steps around 2 % in amplitude. The steps with steep flanks, 0.8 to 1.5 %, are due to the switching of the 60 Mvar capacitor bank (20 Mvar per phase), see also figure 4.3.25. The phase current shows a daily variation with a decrease during the weekend that is due to the reduction of the industrial loads. At evening time the residential "television peak" is obvious both in the current and the active power.

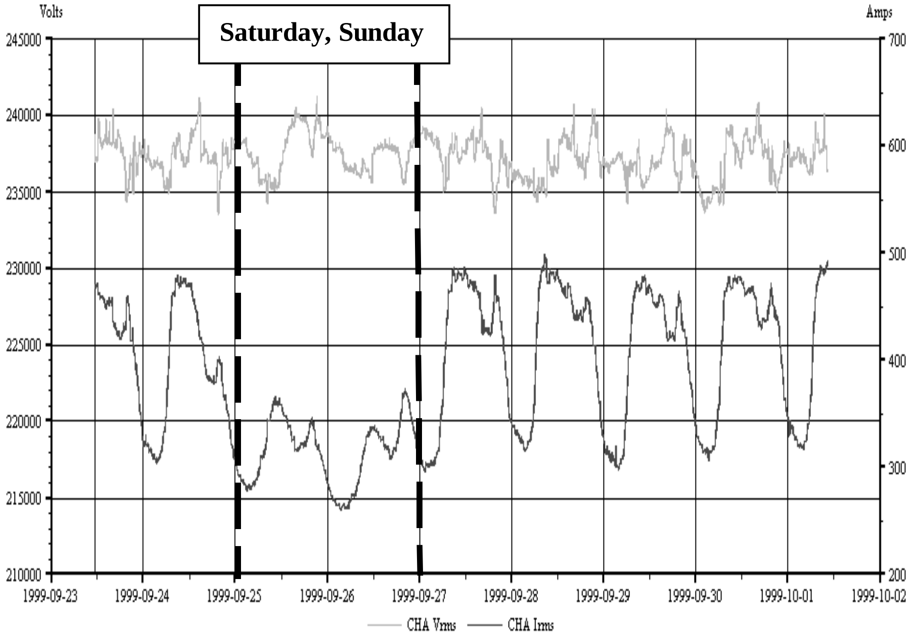


Figure 4.3.24. Fundamental phase voltage (top) and phase current (bottom).

The active power follows well the variation of the current.

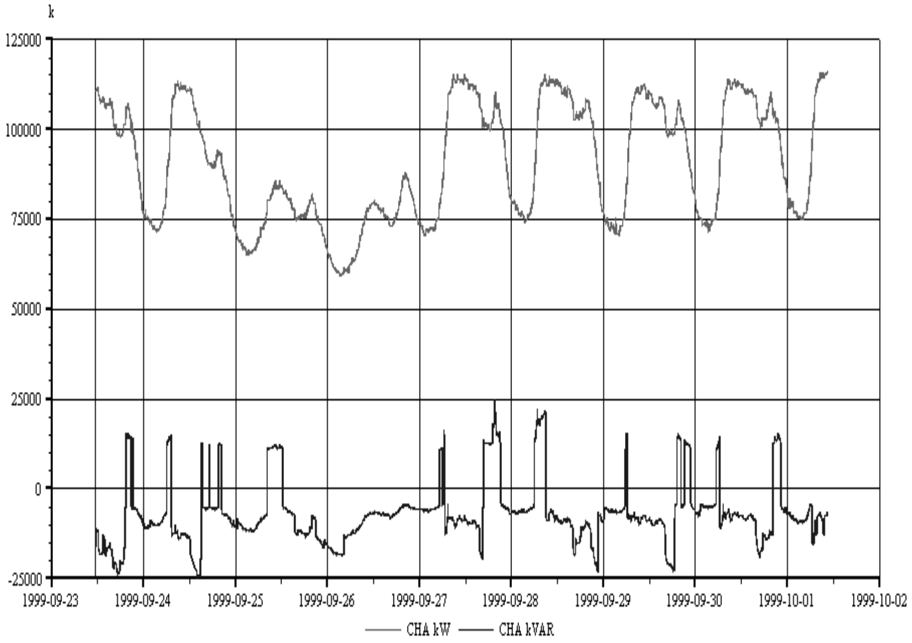


Figure 4.3.25. Fundamental P (top) and Q (bottom), per phase.

The voltage unbalance, figure 4.3.26, is of the same type as the unbalance in the 130 kV system, shown earlier in this chapter, with phase R as the lowest amplitude. The negative sequence component, figure 4.3.27, is around 0.75 % and the zero sequence component is around 0.65 % of the positive sequence component. Both show a daily variation during the week and follow the load current, especially for the negative sequence component that also has a small reduction during the weekend. The “television peak” is seen in both components. This confirms that the voltage unbalance is strongly affected by the power consumption of the loads.

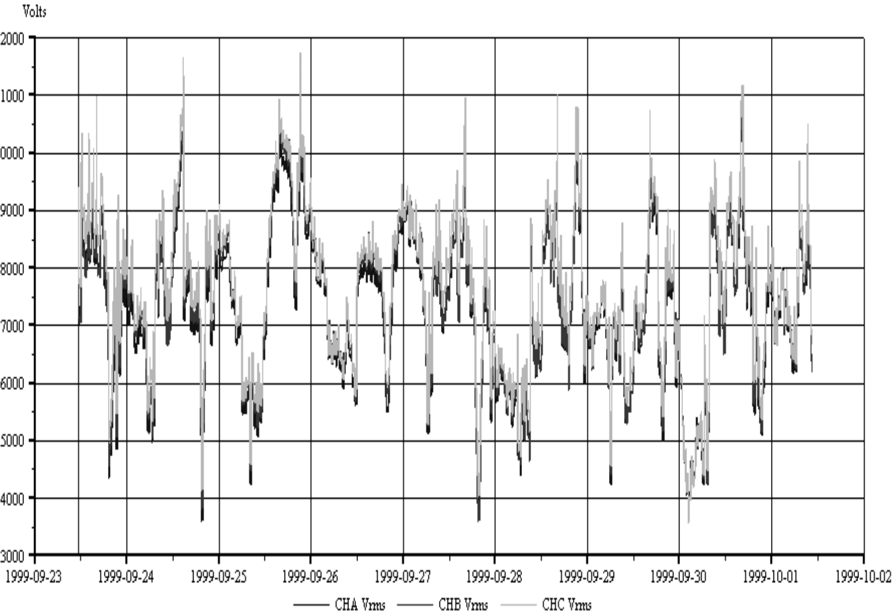


Figure 4.3.26. Fundamental voltage amplitude in phase R (dark), S (light dark) and T (light). The lowest amplitude is in phase R during the whole week.

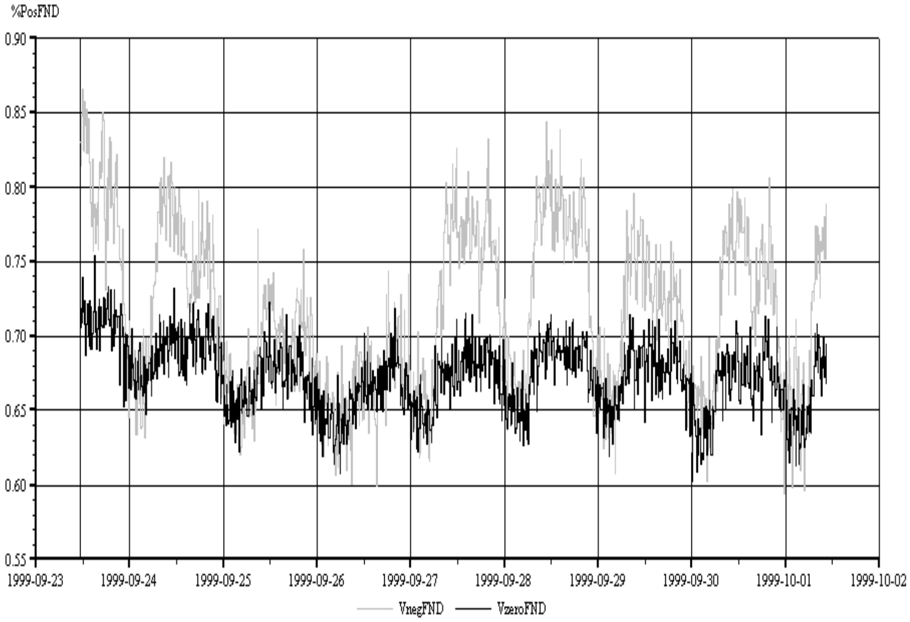


Figure 4.3.27. Negative (light) and zero (dark) sequence component relative to the fundamental voltage amplitude.

### Time variation of the harmonic distortion over one week

Harmonic 5, 7

Both the 5:th and 7:th voltage harmonics show daily variations with clear "television peaks" at evening time, figure 4.3.28. During the weekend the distortion is higher compared to the weekdays which probably is due to higher source impedance for the 5:th and 7:th harmonic currents, including the whole system and loads (many industrial loads are disconnected during weekend time). In general, over the whole week, the use of residential single phase non-linear loads (television and computers) causes a higher distortion of the 5:th and 7:th harmonics than industrial single and three phase non-linear loads.

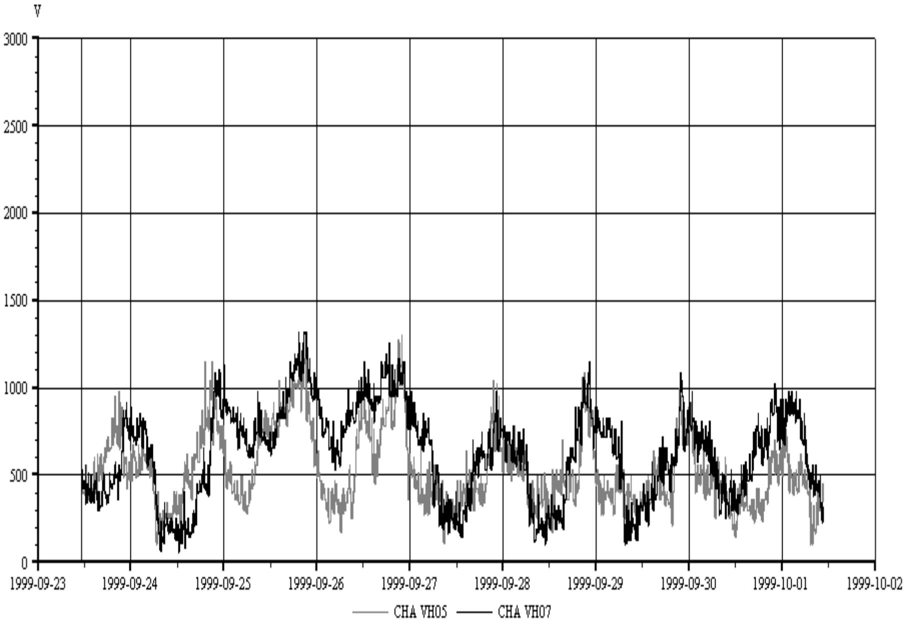


Figure 4.3.28. Voltage harmonic 5 (light) and 7 (dark).

The fact that the 5:th harmonic is lower than the 7:th can be due to a lower negative sequence impedance in electrical machines, for low order harmonics. Another explanation can be long line resonance causing a change in the amplitude along the line, compared to the source location. The line is about 45 electrical degrees long for the

5:th and 7:th harmonics from Stenkullen/Göteborg and 40 degrees from Hallsberg.

The current distortion, figure 4.3.29, shows a similar daily variation as the voltage with, main peaks at evening time and during the weekend. The cause is the use of television and computers at residential low voltage level, both in the 130 kV system and in other systems.

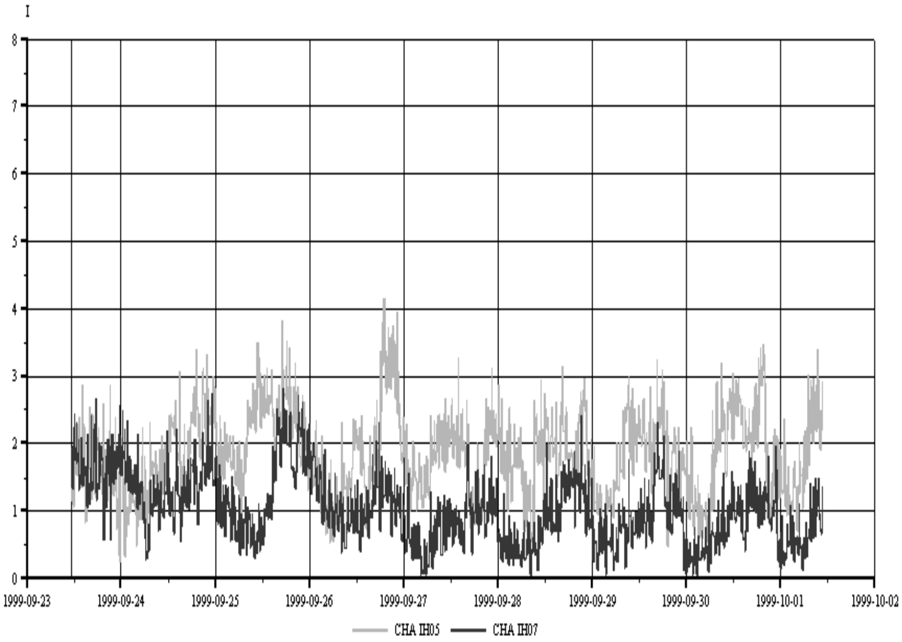


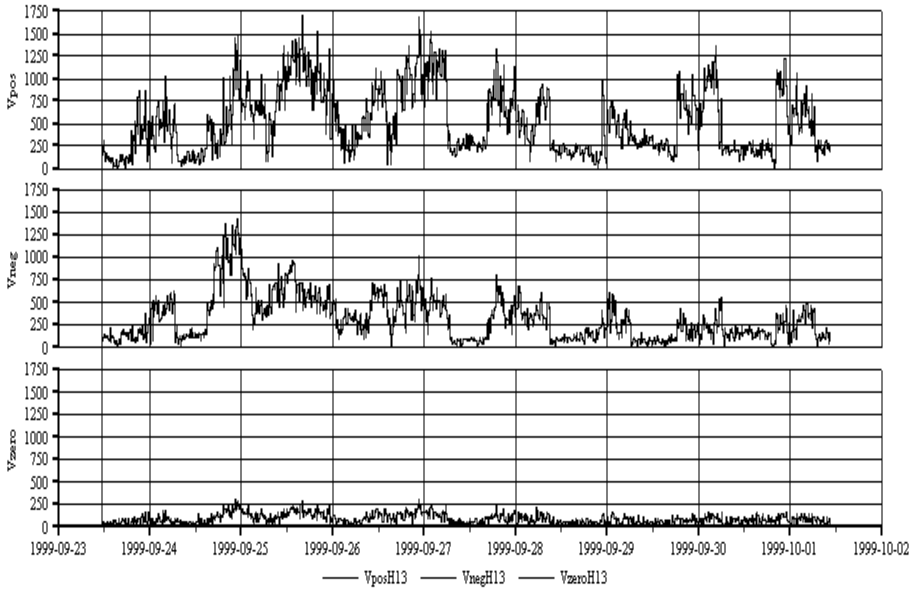
Figure 4.3.29. Current harmonic 5 (light) and 7 (dark).

There is no proportional correlation between the 5:th and 7:th harmonic voltage distortion and the current distortion, except for evening time weekdays and especially at Friday, Saturday and Sunday evening. The current harmonics are then driven towards the 130 kV system by the 5:th and 7:th harmonic voltage distortion. The corresponding voltage and current harmonic are almost in phase at that time. This is probably due to low impedance caused by series resonance at lower voltage levels.

The 5:th harmonic current shows some increase during the weekdays due to industrial and commercial loads. In general, during the week, the 5:th and 7:th harmonic currents do not by themselves cause the corresponding voltage harmonics.

Harmonic 11, 13

The distortion level is higher for the 11:th and 13:th harmonic voltage compared to the 5:th and 7:th ones. The 13:th harmonic has a maximum of 1.2 %. An unbalance was also found between the phases for the 13:th harmonic, figure 4.3.30. The negative sequence component varies between 40 and 90 % of the positive sequence and the zero sequence varies between 5 and 20 %. No significant unbalance was found for the 5:th, 7:th harmonics and only a small unbalance for the 11:th harmonic voltage.



4.3.30. Sequence components of the 13:th voltage harmonic.

A correlation was found between the variation of the amplitudes of the 11:th and 13:th voltage harmonics, figure 4.3.31, and the power flow at the HVDC-links at Stenkullen and Lindome outside Göteborg, figure 4.3.32. The distortion increases when the power flow increases, independent of the direction.

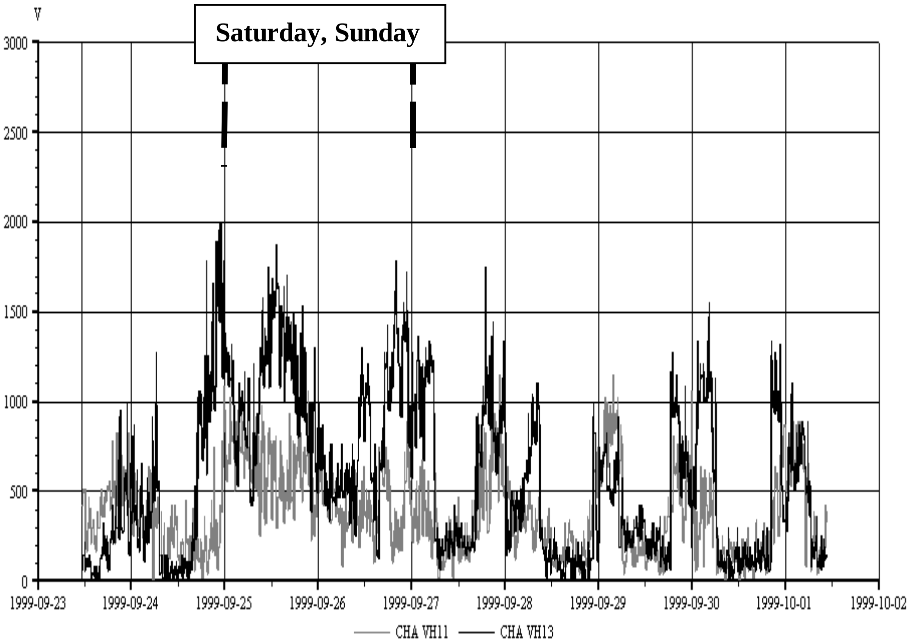


Figure 4.3.31. Voltage harmonic 11 (light) and 13 (dark).

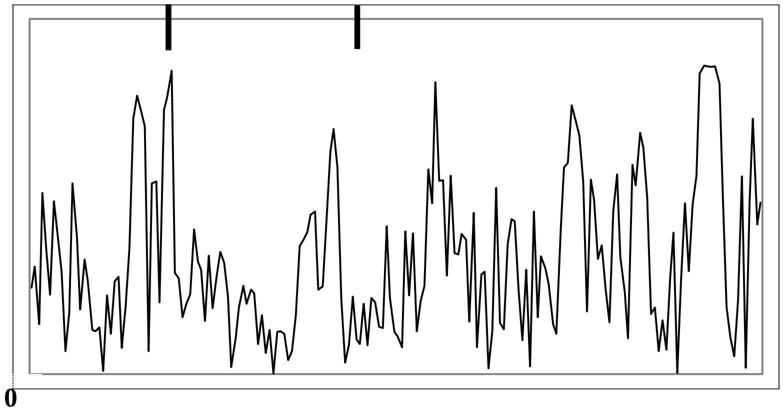


Figure 4.3.32. Total active power flow at both HVDC sites, without sign.

Another important observation is that the 11:th and 13:th voltage harmonics reduces almost to zero at daytime during the weekdays, independent of the power flow at the HVDC sites. This is due to a low impedance caused by a series resonance between the 750 MVA transformer and the 60 Mvar capacitor bank on the 130 kV side, see figure 4.3.33.

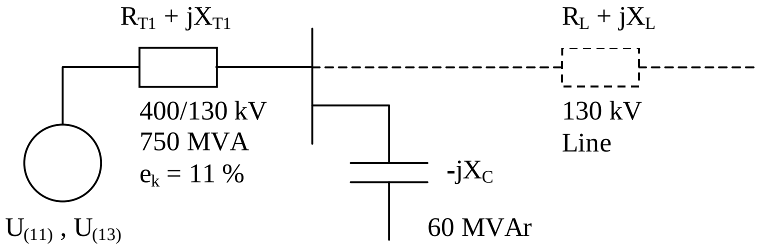


Figure 4.3.33. Series resonance from 400 kV to 130 kV level.

Resonance occurs at harmonic order n:

$$n = \sqrt{\frac{X_{\mathrm{C}}}{X_{\mathrm{T1}}}} = 10.7$$

The 130 kV line capacitance is neglected because it is much smaller than the 60 Mvar bank, $Q_C >> Q_{Line}/2$ ($X_C << X_{Line}/2$). The calculated resonance frequency is somewhat lower than order 11 and 13, but it appears to affect both harmonics. The exact resonance characteristic is not known and depends on the 400 kV long line parameters, R, L and C. The line is about 90 electrical degrees long for the 11:th and 13:th harmonics from Stenkullen/Göteborg and 80 degrees from Hallsberg.

A difference compared to lower voltage levels, found also for the 5:th and 7:th voltage harmonics, is that the 13:th harmonic is larger than the 11:th. The explanation can be the same as for those.

The accuracy and the frequency response for the 400 kV capacitive voltage dividers used for the monitoring need to be studied in more detail. But the two above described phenomena are still present.

The current 11:th and 13:th distortion is small, figure 4.3.34, below 0.5 % of the fundamental. No correlation was found with the 11:th and 13:th voltage distortion.

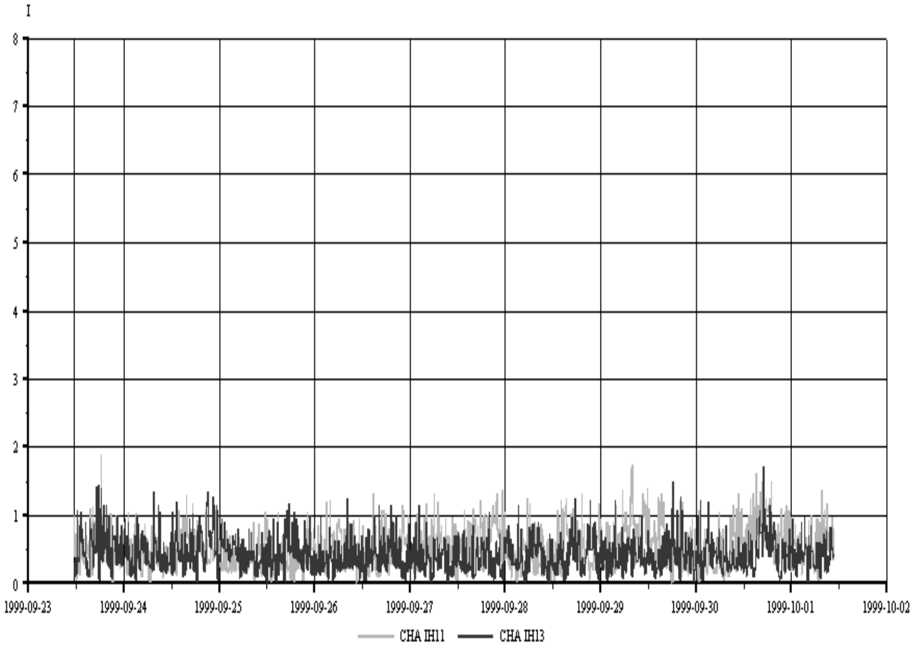


Figure 4.3.34. Current harmonic 11 (light) and 13 (dark).

## Harmonic 3, 9

The 3:rd and 9:th voltage harmonics, figure 4.3.35, are smaller than the 5:th, 7:th, 11:th and the 13:th voltage harmonics. They show a rather constant level during the week with no obvious load variations or "television peaks".

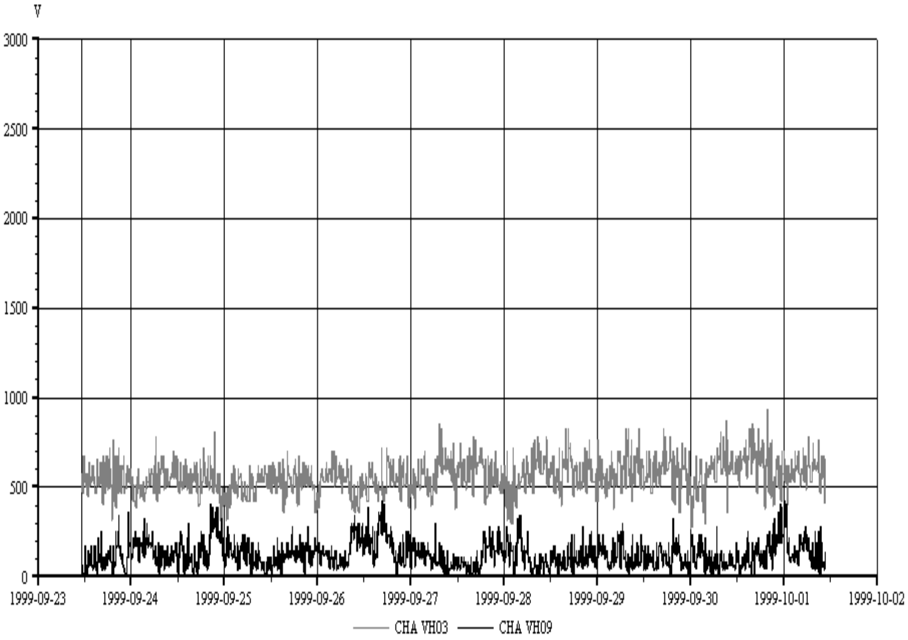


Figure 4.3.35. Voltage harmonic 3 (light) and 9 (dark).

For the 3:rd and 9:th harmonic currents almost a constant level appears during the week, figure 4.3.36, as for the corresponding harmonic voltages.

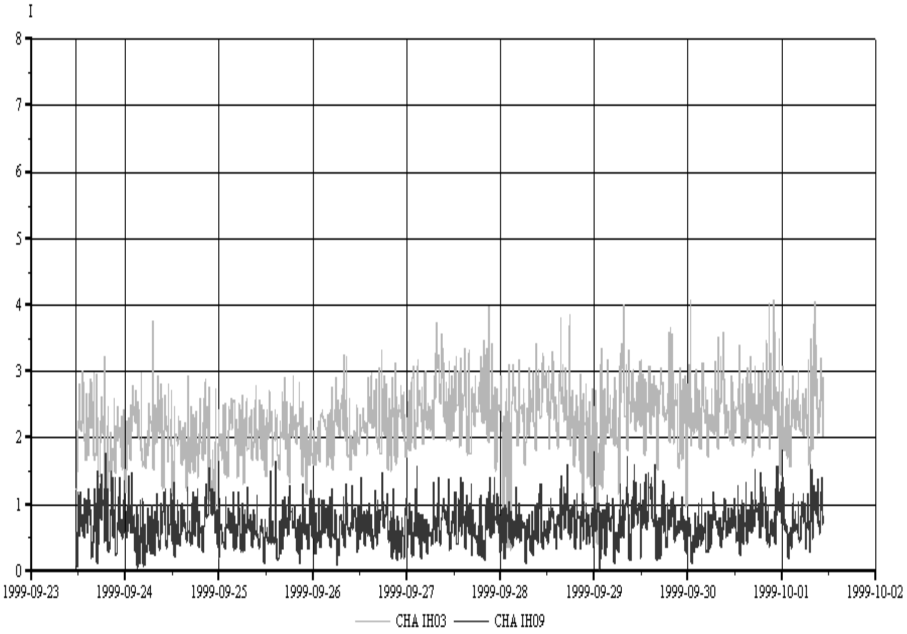


Figure 4.3.36. Current harmonic 3 (light) and 9 (dark).

There is a difference between the phases, both for the 3:rd harmonic voltage and current, figure 4.3.37 and 4.3.38, which means that they consist not only of zero sequence. Phase S shows the highest amplitude, especially during the weekend. For the 3:rd harmonic voltage this is the same phase as in the 130 kV system, but the measurements where not done at the same time. For the 3:rd harmonic current the phases are different.

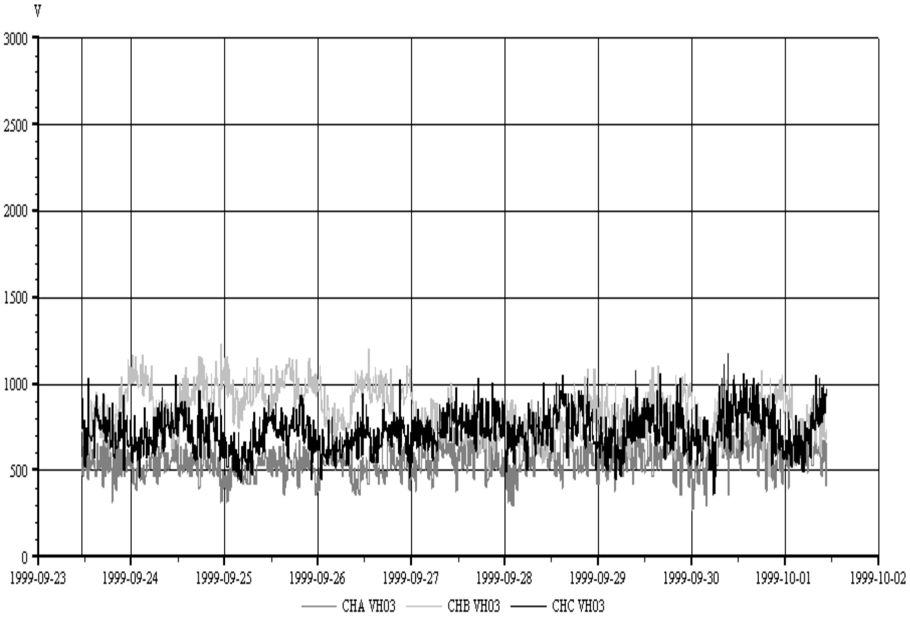


Figure 4.3.37. Voltage harmonic 3 in phase R (light dark), S (light) and T (dark).

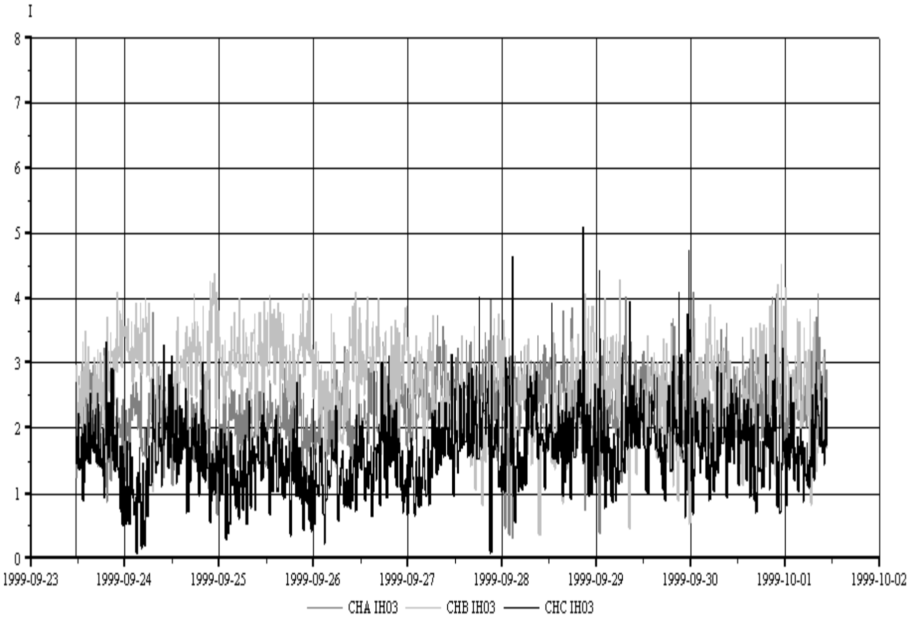


Figure 4.3.38. Current harmonic 3 in phase R (light dark), S (light) and T (dark).

### Time variation of the third harmonic symmetrical components

The largest part of both the 3:rd harmonic voltage and current is the zero sequence component, which shows a constant level during the week. The zero sequence component is due to transformer saturation caused by the fundamental voltage. The 3:rd harmonic voltage, figure 4.3.39, shows a daily variation in positive and negative sequence components that is mainly due to low voltage non-linear loads.

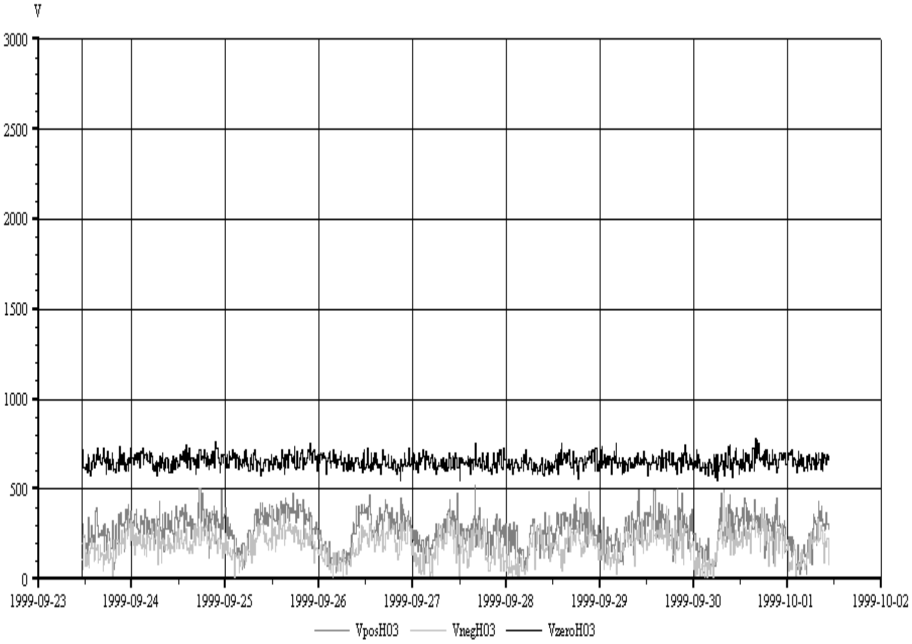


Figure 4.3.39. Third harmonic positive (light dark), negative (light) and zero (dark) sequence voltage.

The 3:rd harmonic current, figure 4.3.40, shows only a small variation in the zero sequence component during the weekend and no correlation was found to the variation in the fundamental voltage zero sequence component.

In figure 4.3.41 the psophometric current is shown, calculated from all the odd zero sequence harmonic currents up to order 19.

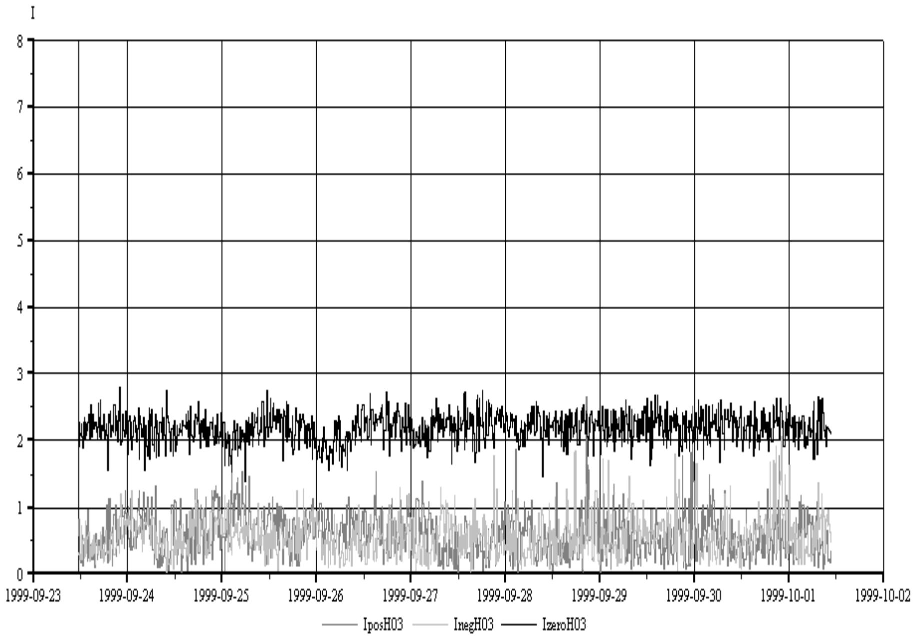


Figure 4.3.40. Third harmonic positive (light dark), negative (light) and zero (dark) sequence current.

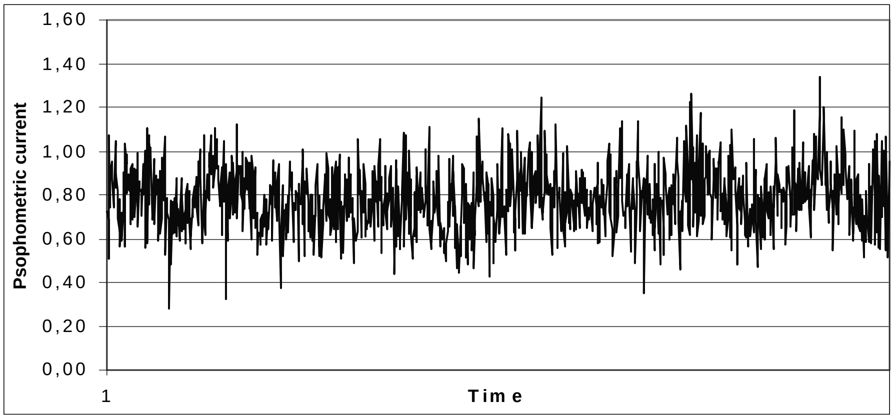


Figure 4.3.41. Psophometric current during the week, up to harmonic order 19.

The average value for the whole week is 0.72 A (weighted). If only harmonics up to order 15 are included, the value is 0.66 A (weighted), up to order 13 it is 0.52 and up to order 9 it is 0.42.

## Conclusions 400 kV

The most important conclusions can be summarized as follows:

- The voltage distortion is caused by two different sources. The largest contribution is from the HVDC-links located in Stenkullen and Lindome, outside Göteborg, with large 11:th and 13:th voltage harmonics. These harmonics follow the power flow at both sites. Residential loads at low voltage level, not only in the actual area, cause large 5:th and 7:th harmonics with "television peaks" at evening time. Changes in the harmonic source impedance (or load impedance, depending on what is defined as load and source, see also Chapter 5) cause a daily variation of the 5:th and 7:th harmonic voltages.

- The propagation of voltage harmonics in the transmission system from the HVDC-links to Timmersdala depends on several parameters. The most important ones are the direction and amount of active power flow on the DC-side, the 400 kV network layout, the fundamental voltage unbalance, current interaction with other loads/cities, long line resonance and the difference in the fundamental voltage phase angle at the three locations.

- Switching in the 130 kV 60 Mvar capacitor bank in Timmersdala reduces the 11:th and 13:th voltage harmonics to nearly zero due to a series resonance between the 750 MVA transformer and the capacitor bank.

- The current distortion, harmonics 5 and 7, has peaks at evening time and during the weekend. At the weekend they are mainly caused by the corresponding 400 kV voltage harmonics in combination with low impedance at lower voltage levels due to series resonance. During weekdays 5:th harmonic current has some increase caused by industrial and commercial loads. The 11:th and 13:th harmonic currents are small and show no variation.

- The relationship between the harmonic current distortion and the harmonic voltage distortion is sometimes inductive, capacitive or resistive and not fully linear. Neither from the 400 kV level point of view (load impedance for the voltage distortion) nor from the load point of view (source impedance for the distorted load current at 130 kV level). This means that a certain current harmonic does not give a proportional voltage harmonic, or the opposite.

- The harmonic active power flow is small, below one tenth of a percent. The additional internal losses caused by the current distortion at lower voltage levels are not seen in the monitoring point, as harmonic active power flow. The harmonic losses are included in the fundamental active power flow.

- Fundamental voltage unbalance is around 0.75 % negative sequence and is of the same type as the unbalance on the 130 kV level, with the lowest amplitude in phase R.

- Non-zero sequence triplen harmonic currents are present.

- Zero sequence third harmonic voltage and current show a constant level during the week. This is most probably due to transformer saturation caused by the fundamental voltage amplitude.

- Negative sequence voltage harmonics, 5 and 11, where found to be lower than positive sequence harmonics, 7 and 13. This can be due to lower impedance in electrical machines for negative sequence low order harmonics. At low voltage level negative sequence harmonics are in general the highest.

- The distortion level for a specific harmonic in a certain point along the line can be totally different compared to another point of the line, also between the phases due unbalance. This is valid both for harmonic voltages and currents.

- Harmonic interaction between cities or large industries due to differences in fundamental voltage phase angle can increase or decrease the current distortion in a node or at a generator. The differences in fundamental voltage phase angle between two locations are mainly due to the active power flow between them. The phase angle of the harmonic currents is related to the fundamental voltage phase angle at the load terminals.

- The distortion levels, at the high voltage levels, are:
  $I_{THD} = 1 - 5\ \%$
  $U_{THD} < 2\ \%$.

# 5 Harmonic active power flow

This chapter shows the principles of harmonic active power flow in radial low and medium voltage distribution systems. The main emphasis is on the interaction between loads and the power system. The interaction is due to the change in source impedance caused by e.g. harmonic filters or capacitor banks and a mix of single and three phase non-linear and linear loads.

The active harmonic power flow in a certain point in a power system, with non-linear loads, does in most cases not represent the actual flow to the loads in the downstream system, see also chapter 4. The harmonic active power is partly or completely included in the fundamental active power, depending of the mix of loads.

Some basic examples will be shown in addition with measurements from a low voltage system equipped with harmonic filters, feeding a non-linear load.

The voltage and the current distortion cause additional losses in power system components and in linear loads. The flow of the harmonic active power components supplying these losses, between different parts of the power system or different loads, depends on the configuration of the power system and the mix of loads. This power flow, at a certain point, can be positive (towards the load), negative (from the load) and sometimes it is not seen at all.

## 5.1 General characteristics

**Active power and losses**

The current distortion causes increased losses in power system components. For each harmonic, $n$, the losses can be written as:

$$P_{(n)} = R_{(n)} \cdot I_{(n)}^{2} \qquad (5.1.1)$$

with $R_{(n)}$ the resistance for harmonic, $n$.

Voltage distortion causes, in the same way as the current, increased losses in linear loads connected to the power system and in shunt-connected capacitor banks.

The total increase of the losses in a system is the sum of the losses, at each harmonic, for all components and loads:

$$\Delta P_{tot} = \sum_{Comp} \sum_{n \neq 1} P_{(n)} \, . \qquad (5.1.2)$$

From the earlier discussion and from (5.1.1) and (5.1.2) it is obvious that the active harmonic losses from one non-linear load are affected by the feeding power system and by other loads, i.e. the path for the harmonic currents.

At a certain point in the power system the instantaneous power flow, including fundamental and harmonic flow, is the time derivative of the exchange of energy between the electrical systems, or between an electrical system and a mechanical system:

$$p(t)_{tot} = \frac{dW(t)}{dt} \, . \qquad (5.1.3)$$

The active power is the average over one cycle of the instantaneous power flow.

Expressed in voltages and currents Fourier components the total active power, the instantaneous power averaged over the time T, is

$$P_{tot} = \frac{1}{T}\int_{0}^{T} u(t)\cdot i(t)dt = P_{(1)} + \sum_{n\neq 1}^{\infty} P_{(n)}\ . \qquad (5.1.4)$$

The active power flow to a non-linear load consists in most cases of a positive fundamental flow and a negative harmonic flow; i.e. the harmonic part is due to the additional losses in the feeding power system. From the law of conservation of energy and (5.1.3) it follows that the harmonic active power is converted from the fundamental power by the non-linear load. This means that the fundamental active power to a non-linear load, or a non-linear system, includes the harmonic part [6][7][8], (5.1.4) can be rewritten as

$$P_{(1)} = P_{tot} - \sum_{n\neq 1}^{\infty} -\left|P_{(n)}\right| = P_{tot} + \sum_{n\neq 1}^{\infty}\left|P_{(n)}\right|. \qquad (5.1.5)$$

Linear loads, contrary to non-linear loads, only consume fundamental and active harmonic power, which means that the fundamental power does not include the harmonic part.

This reasoning holds, strictly speaking, only for the equipment terminals. Elsewhere in the system, e.g. at secondary side of a transformer, the harmonic power flow may be towards the load or away from the load, depending on the system configuration and the mix of loads (linear and non-linear). The active power flow in a certain point will in most cases not represent the actual flow at harmonic frequencies to the loads.

## 5.2 Interaction load - system

Consider a non-linear load taking a (nth harmonic) current $I_{(n)}$ from an otherwise non-distorted supply. The source impedance at the equipment terminals for harmonic $n$ is:

$$Z_{(n)} = R_{(n)} + \mathrm{j}X_{(n)}. \qquad (5.2.1)$$

The losses in the system due to harmonic $n$ are equal to:

$$P_{(n)} = R_{(n)} \cdot I_{(n)}^{2}. \qquad (5.2.2)$$

The total losses due to harmonic distortion are the sum of the losses due to the individual harmonics.

The harmonic voltage distortion due to the current distortion is equal to the voltage drop over the source impedance:

$$U_{(n)} = -\left(R_{(n)} + \mathrm{j}X_{(n)}\right) \cdot I_{(n)}. \qquad (5.2.3)$$

The apparent power to the load at harmonic $n$ is:

$$S_{(n)} = U_{(n)} \cdot I_{(n)} = -\left(R_{(n)} + \mathrm{j}X_{(n)}\right) \cdot I_{(n)}^{2} \qquad (5.2.4)$$

The active power is the real part of the apparent power, so that

$$P_{(n)} = -R_{(n)} \cdot I_{(n)}^{2} \qquad (5.2.5)$$

which is equal to the harmonic losses in the system.

When the active power is measured somewhere in the system, i.e. not at the terminals of the non-linear load, the harmonic active power measured is equal to the losses upstream of the measurement location.

Let

$$Z_{\mathrm{Up}(n)} = R_{\mathrm{Up}(n)} + \mathrm{j}X_{\mathrm{Up}(n)} \tag{5.2.6}$$

be the source impedance at the measurement location, for harmonic *n*, and

$$Z_{\mathrm{Down}(n)} = R_{\mathrm{Down}(n)} + \mathrm{j}X_{\mathrm{Down}(n)} \tag{5.2.7}$$

the impedance between the load and the measurement location, for harmonic *n*. Similarly as before it can be shown that the active power flow measured is equal to:

$$P_{\mathrm{Up}(n)} = -R_{\mathrm{Up}(n)} \cdot I_{(n)}{}^{2}. \tag{5.2.8}$$

The total additional losses due to the nonlinear load are however:

$$P_{(n)} = \left(R_{\mathrm{Up}(n)} + R_{\mathrm{Down}(n)}\right) \cdot I_{(n)}{}^{2} \tag{5.2.9}$$

so the losses downstream of the measurement location are not included in the harmonic active power measurement. Thus, it is only the exchange of the harmonic power between the two systems that is monitored.

Some theoretical examples will be given below.

*Case 1*

A transformer with a radial distribution system, without shunt branches, feeding a non-linear load can be represented as in figure 5.2.1. In this case we assume there is no background distortion from the voltage level above, only the fundamental voltage exist. The distorted load current will cause voltage distortion, $U_{k(n)}$ and $U_{N(n)}$. The total harmonic losses in the system are $\Sigma P_{k(n)}+\Sigma P_{N(n)}$ but the harmonic active power measured in the monitoring point "ab" is $-\Sigma P_{k(n)}$.

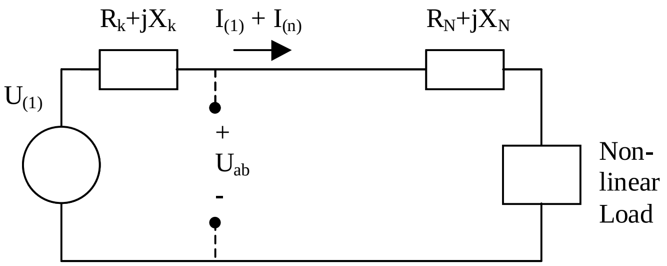


Figure 5.2.1 Radial distribution system, $Z_{k(n)} > Z_{N(n)}$.

*Case 2*

When a harmonic shunt filter is used, as in figure 5.2.2, the total harmonic losses are $\Sigma P_{N(n)}$ but the harmonic active power measured in the monitoring point "ab" is now zero.

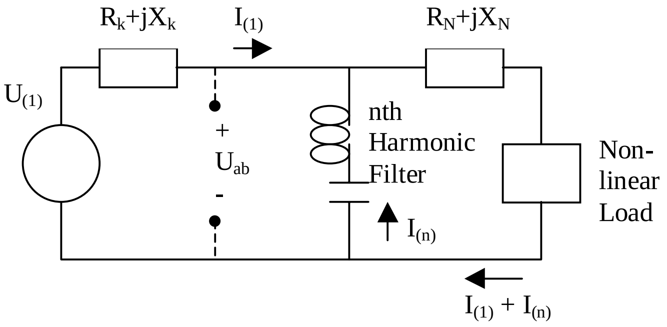


Fig. 2. Radial distribution system with harmonic filter.

*Case 3*

When a non-linear load with a current distortion with opposite sign, compared to the existing non-linear load, replaces the harmonic filter the harmonic losses become as in *Case 2*. This phenomenon can be found between single- and three phase non-linear loads, especially for the 5:th and 7:th harmonics.

*Case 4*

With background distortion, from the voltage level above, harmonic filters on the low voltage side can show low impedance for that voltage and cause a current through the transformer. The total harmonic losses in the system are $\Sigma P_{k(n)}+\Sigma P_{N(n)}$ but the harmonic active power measured in the monitoring point "ab" is $\Sigma P_{k(n)}$.

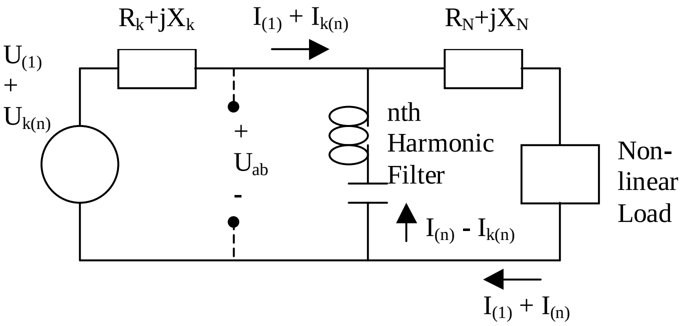


Figure 5.2.3. Radial distribution system with background distortion.

*Case 5*

Linear loads connected to a system with an existing background distortion, figure 5.2.4, will cause harmonic currents through the transformer and the total harmonic losses become $\Sigma P_{k(n)}+\Sigma P_{N(n)}+\Sigma P_{L(n)}$ but the harmonic active power measured in the monitoring point "ab" is $\Sigma P_{N(n)}+\Sigma P_{L(n)}$.

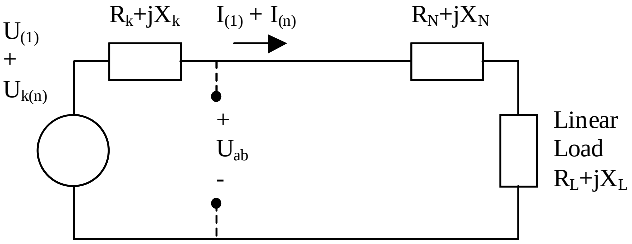


Figure 5.2.4. Radial distribution system with linear load.

In reality there is of course a much more complex mixture of loads that are connected to the power systems. To verify *CASE 4*, with and without harmonic filters connected, field measurements will be shown in the next part.

## 5.3 Field measurements of harmonic interaction

A low voltage industrial system, feeding a non-linear load, was studied, figure 5.3.1. The system was radial with a 20/0.4 kV, 1 MVA, 6 %, Dyn11-connected transformer and a 800 kVA six pulse, current stiff, diode rectifier load ($\cos\varphi \approx 1$). The system was equipped with 5:th and 7:th harmonic filters on the secondary side of the transformer (0.4 kV side), with 170 + 100 kvar at 50 Hz. The filters where fine tuned at 250 and 350 Hz. The voltage background distortion, on the 20 kV-level, was about 1 to 2 % ($THD_U$).

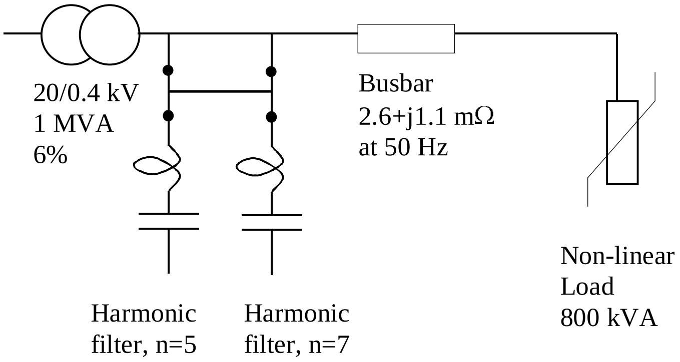
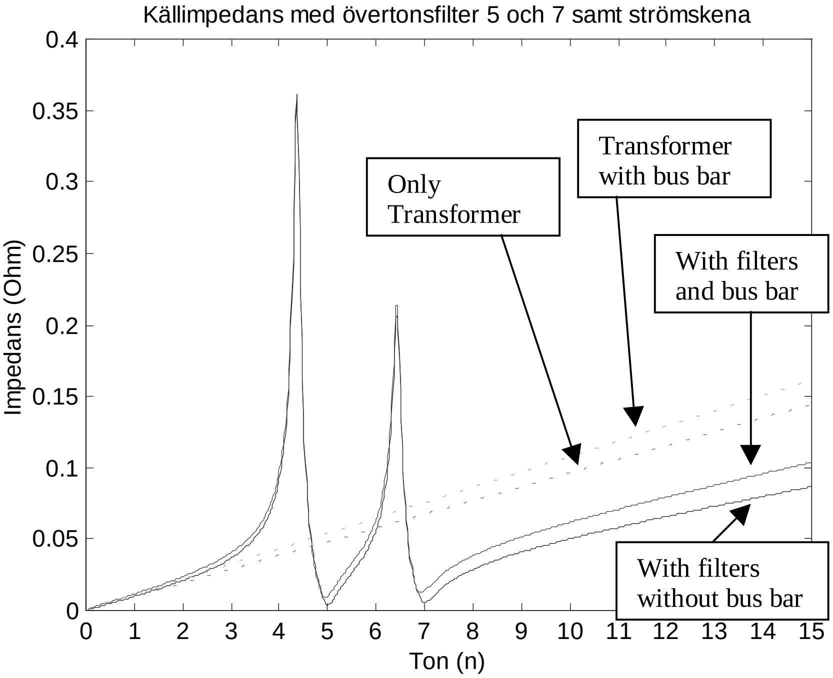


Figure 5.3.1. Radial distribution system with harmonic filters and a non-linear load.

Both the filters where connected and disconnected, at the same time, and the line to neutral voltage and the line current was measured on the secondary side of the transformer, before and after the switching.

The source impedance, seen from the load side and at the filter side of the bus bar, is shown in figure 5.3.2. The increase of the resistance with frequency in the transformer and filter inductances is taken into account as $R = R_{50Hz} \cdot n^{\frac{1}{2,5}}$, where n is the harmonic order.



5.3.2. Source impedance.

The low impedance at the 5:th and the 7:th harmonics is due to the harmonic filters. The high impedance, at harmonic 4.2 and 6.3, is caused by a parallel resonance with the transformer inductance. The source impedance is slightly higher when the bus bar impedance is taken into account and the resonance frequency becomes somewhat lower at series resonance of the filters. The source impedance is not fine tuned at 250 and 350 Hz as was intended, due to the bus bar impedance.

In figure 5.3.3 and 5.3.4 the voltage and current waveforms are shown, without and with filters respectively.

The voltage has large notches caused by the stiff current. The current is almost in phase with the voltage, cos$\varphi$ = 0.96 (ind.).

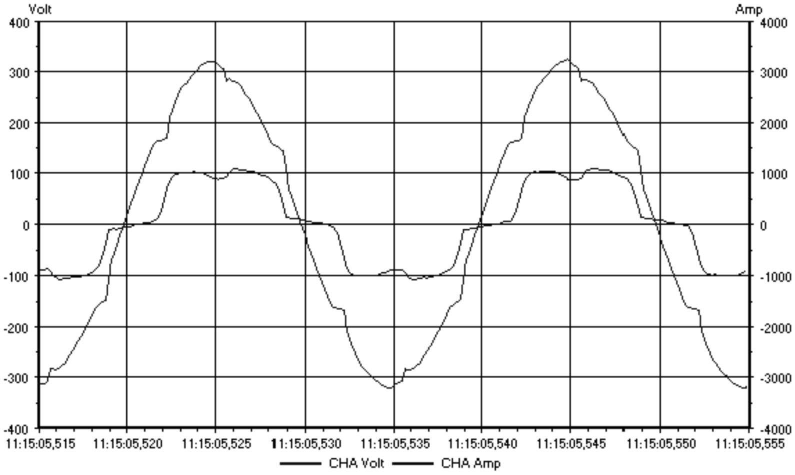


Figure 5.3.3 Voltage and current waveforms, without the filters connected.

With the filters connected the notches become smaller. The current is now capacitive, with cos$\varphi$ = 0.92 (cap.).

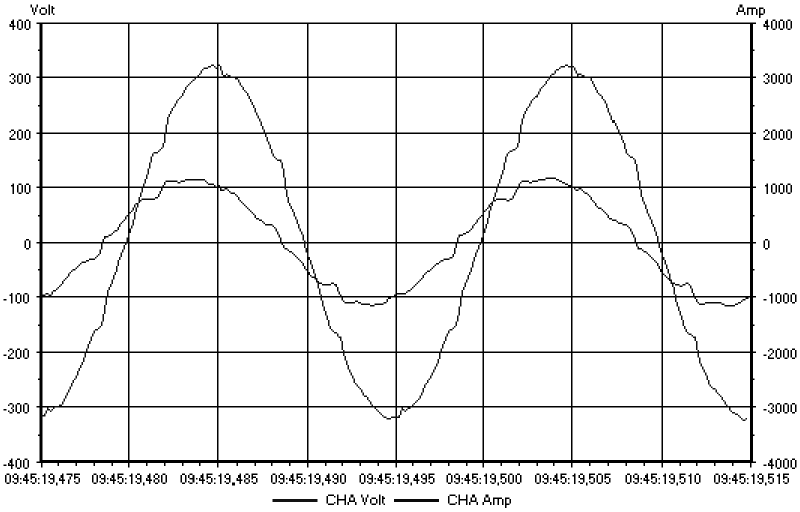


Figure 5.3.4 Voltage and current waveforms, with the filters connected.

The voltage and the current harmonics, in RMS, at full load can be seen in figure 5.3.5 and figure 5.3.6.

With the filter connected the voltage distortion is 2.7 % and the current distortion is around 6 %. Without the filter the voltage distortion is 5.5 % and the current distortion is around 23 %.

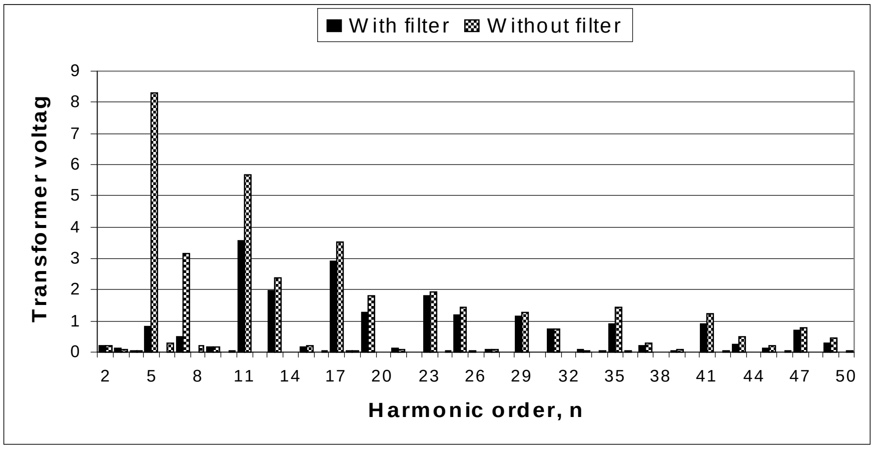


Figure 5.3.5. Voltage distortion on transformer secondary side.

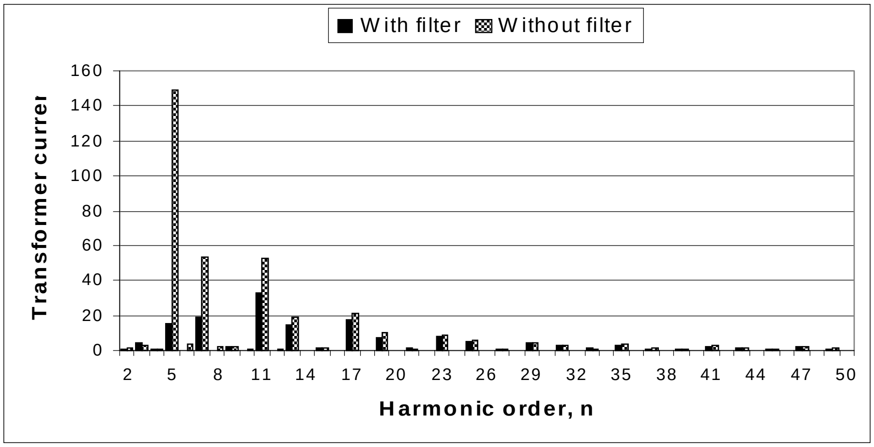


Figure 5.3.6. Current distortion on transformer secondary side.

The harmonic active power flow is shown in figure 5.3.7. The amplitude is in percent of the fundamental active power component, about 500 kW. The largest change can be seen in the 5:th harmonic component when the filter is disconnected (the same change is also seen in the current spectrum, figure 5.3.6). The power flow changes sign, from positive to negative, and the amplitude increases with a factor of 10. The positive 7:th component, when the filter is disconnected, is due to the voltage background distortion.

With the harmonic filter connected, both the 5:th and the 7:th component is positive which is due to the voltage background distortion and the low filter impedance at these frequencies.

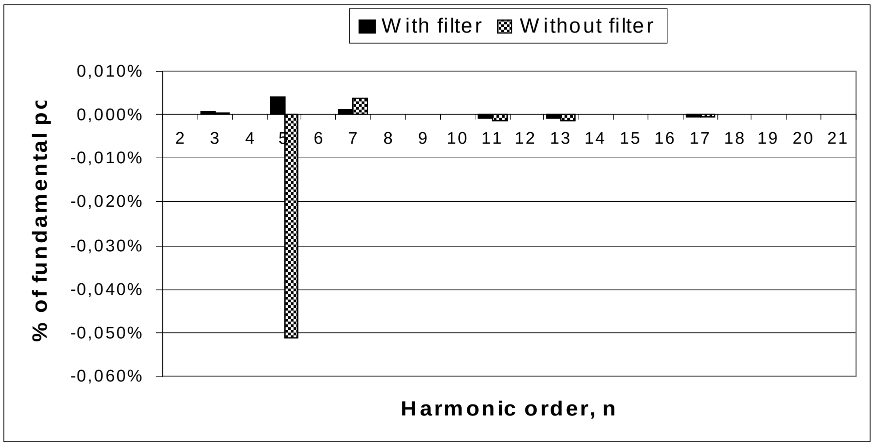


Figure 5.3.7. Harmonic active power on transformer secondary side.

The harmonic active power flow, with the filter connected, is 0.8 % of the calculated fundamental losses in the transformer. Without filter the harmonic active power flow is -9.3 %. The major part of this negative power is formed by the additional losses in the transformer and the rest are the losses at the voltage level above.

The harmonic losses in the bus bar, which not is included in the power flow in figure 5.3.7, is 5.7 % and 7.5 % respectively of the calculated fundamental transformer losses with and without filter connected. Note that filters do not affect the load current in the bus bar (there is a small change due to a small variation in the load).

The use of harmonic filters has a two-fold effect. The first is to bypass the harmonic currents that normally flow through the transformer. The second is to provide the system with the right amount of reactive power in the fundamental component. The harmonic losses in the system are affected, as shown before, by the filters but the fundamental component losses will also be affected. Additional affects caused by the change of the fundamental voltage amplitude are changes in the current distortion generated by non-linear loads, see also chapter 3. In this case this effect is negligible.

When the harmonic filters are connected the harmonic losses were shown to be reduced in the transformer, but additional fundamental and harmonic losses are added in the filters. The total losses (fundamental + harmonic), given by the manufacturer, are for the 5:th harmonic filter 580 W and 210 W for the 7:th harmonic filter.

The transformer resistance is assumed to be 0.0015 Ω per phase at 50 Hz and 0.003 Ω at the 5:th and 7:th harmonic. The resistance in each filter, per phase, at 50 Hz can be estimated to

$$R \approx \frac{\frac{P_{\text{Losses\_total}}}{3}}{I_{(1)}^2 + 2 \cdot I_{(n)}^2}, \text{ where n = 5 or 7.} \qquad (5.3.1)$$

This gives for the 5:th harmonic filter R=1.7 mΩ and for the 7:th harmonic filter R=2.5 mΩ. Table 5.3.1 shows the calculated losses at full load and no load, with and without filters connected.

| | Trafo Fnd losses (W) | Trafo Harm. losses (W) | Filter 5 total losses (W) | Filter 7 total losses (W) | Total system losses (W) |
|---|---|---|---|---|---|
| No load with filter | **500** | **5** | **320** | **170** | **995** |
| No load without filter | **65** | **0** | **0** | **0** | **65** |
| Full load with filter | **2880** | **20** | **580** | **210** | **3690** |
| Full load without filter | **2565** | **260** | **0** | **0** | **2825** |

Table 5.3.1 System losses with and without the filters connected.

The total financial cost for the losses with filter and full load, based on 2000 production hours per year and 0.5 SEK/kWh, is 3690 SEK/year. The difference of the costs, without filter, is 865 SEK/year.

The total financial cost for the losses with filter and no load, based on 6760 hours per year and 0.5 SEK/kWh, is 3360 SEK/year. The difference of the costs, without filter, is 3140 SEK/year.

In both cases, with full and no load, the total losses increased with the filter connected and the financial costs also increased.

In addition to the above costs the cost for the losses in the bus bar is about 5500 SEK/year, independent of the connection of the filters.

To install both the filters the investment cost was about 200 000 SEK. From the costs for the losses and the fundamental reactive power point of view the filter installation was not motivated. The only possible motivation can be the reduced voltage distortion, with the filters connected, if there are other sensitive loads on the same transformer, but no such problem was reported when the system was operated for long periods without the filters.

A similar study made in the USA, on commercial office buildings [17], also concluded that the installation of harmonic filters not was motivated to reduce harmonic losses and the investment cost was not paid back over the estimated lifetime (12 years).

The benefit of using harmonic filters in general has to be studied very carefully, both economically and technically. Several parameters are important:

- load current distortion
- background voltage distortion
- the need for reactive fundamental power
- fundamental and harmonic losses
- resonance at not expected frequencies
- the location of the filter in the system

Additional to the above it is also important to study effects on the lifetime on system components, the possibility of reduction of high magnetic fields, reduction of audible noise, etc.

# 6 Conclusions

Sources of distortion are different at different voltage levels. At higher voltage levels HVDC-links (High Voltage Direct Current), arc furnaces and SVC's (Static Var Compensators) can be dominating sources. At medium and low voltage levels wind turbines are becoming more frequently connected. At low voltage level all kinds of non-linear loads are connected, which globally is the main source of distortion at all voltage levels.

## 6.1 General conclusions

The following characterizes harmonic distortion in power systems:

- The fundamental voltage, applied on a non-linear load, causes harmonic currents (called characteristic harmonics). Three phase unbalanced voltages cause also non-characteristic harmonic currents for three-phase equipment, see chapter 3 and [4][5]. Harmonic voltages also effect the current distortion, but they only give a minor change in the harmonic currents amplitude and phase angle. In most cases the voltage distortion due to a given load reduces the distortion of the load current.

- The distorted load current causes voltage distortion; i.e. the voltage harmonics are in general, not responsible for the current harmonics. This means that it is not possible to apply the harmonic voltages, as voltage sources, in a real power system to obtain the current harmonics.

- The source impedance affects both the voltage and current distortion. Some system components have a two-fold effect that affects a certain harmonic frequency and also affects the fundamental voltage or current, e.g. passive harmonic filters. Interaction between loads, mainly non-linear loads, affects also the source impedance seen from the load side. See chapter 5.

- The voltage and current distortion is, in general, higher at lower voltage levels and decreases at higher levels. There are local differences depending on the mix of linear and non-linear loads and the relation between the size of the non-linear loads and the source impedance of the power system, see chapter 4. Resonance in the system can also, locally, increase the distortion levels.

- The main distortion consists of odd multiples of the fundamental component (50 or 60 Hz) and occurs in a frequency range up to 1 kHz. Newer equipment, during the last ten years, has introduced frequency components at 30 kHz and above. See chapter 3.

- Additional losses in the power system are globally negligible, less than one tenth of a percent of the total active power flow. Locally it can be high, some percent, depending on the type o load and system configuration. See chapter 4 and 5.

- Equipment failure, mal-functioning, pre-aging, etc and telephone interference can locally be a severe problem, at all voltage levels.

Monitoring the distortion is important to get real data of the harmonics amplitude and phase angle and of the variation over the time, i.e. the day, week or year. But there are several possible sources of error when analyzing the monitored data, not only the technical measurement, due to harmonic interaction in the system.

Simulations are important to study the harmonic penetration in power systems and the effects on loads, but also here there is often difficult to obtain corresponding values to the monitored ones. This is due to the lack of accurate harmonic models of aggregated loads, linear and non-linear, and the power system.

## 6.2 Conclusions summary from chapter 3, 4 and 5

A summary is given for the most important conclusions.

**Loads**

- Single phase non-linear loads have a current distortion, THD, around 120 %. All odd harmonics exist in the current spectrum.
- Three phase non-linear loads have a current distortion, THD, up to 200 %. All odd harmonics exist in the spectrum, except triplen harmonics.
- Fundamental voltage unbalance supplying three phase non-linear loads causes non-zero sequence triplen harmonic currents.
- The design of the DC-link has a strong influence on the current distortion and on the sensitivity for voltage background distortion and fundamental voltage unbalance.
- The current distortion for industrial non-linear loads can include even and interharmonics. The distortion can also be fluctuating.
- Current interaction between single and three phase non-linear loads reduces the total distortion.
- Background voltage distortion, caused by single phase non-linear loads, reduces the current distortion from these loads.

## The system

- The low order voltage and current harmonics, below order 19, are present at all voltage levels. The distortion is lowest at high voltage levels, below 2 % voltage and 5 % current distortion.

- The main, global, source of the distortion is the use of television receivers at evening time, at all voltage levels. The dominating voltage harmonics are the 5:th and the 7:th. Locally at any voltage level, other sources can contribute more, e.g. industrial loads, HVDC-links.

- The use of capacitor banks and harmonic filter affects, except from the fundamental voltage and current components, the voltage and current distortion. Resonance at expected, and at not expected, frequencies is present. Filtering the background voltage distortion of an overlaying voltage level can be present due to series resonance at lower voltage levels. This was found for the 7:th harmonic voltage at the 130 kV level and for the 13:th harmonic voltage at the 400 kV level.

- The HVDC-links near Gothenburg caused dominating 11:th and 13:th harmonic voltages at the 400 kV level at the transformer station in Timmersdala, about 150 km from the HVDC stations.

- Long line resonance, harmonic current interaction due to difference of the fundamental voltage phase angle between nodes, and meshed systems makes the voltage and current distortion very complex at higher voltage levels.

- Fundamental voltage unbalance, around 0.8 % negative sequence, was present at 130 and 400 kV levels.

- The harmonic active power flow in the monitoring point is small, below one tenth of a percent of the fundamental power flow, at higher voltage levels. At low voltage level, close to the terminals of a television receiver, the flow was around 1.7 %.

- The harmonic active power flow in a monitoring point, at higher voltage levels, does in most cases not represent the harmonic losses in the down stream system.

- Reduction of the harmonic losses with harmonic filters, in the study in chapter 5, was not motivated due to high financial investment costs for the filters. This is confirmed in other studies published in the international literature, e.g. in [17].

## 6.3 Discussion

The source impedance, seen from non-linear load terminals is in most case not linear for harmonic currents, both in respect to increased frequency and to the relation between the resulting voltage due to an increased current at a certain frequency (harmonic order). This is due to resonance between inductive and capacitive components or due to current interaction between non-linear loads or due to background voltage distortion.

The load impedance for harmonic voltages, seen from the network, is not linear close to non-linear loads. At higher voltage levels the impedance also affects by resonance due to capacitor banks.

The cross coupling between the fundamental voltage and current harmonics is strong close the non-linear loads.

The non-linearity is more or less obvious depending of the configuration of the network and the composition of loads, linear and non-linear.

# 7 Future work

A short overview is given of the most important subjects that are to be studied to access the consequences of harmonic distortion and for the modeling of the system with loads.

- Equipment emission and immunity and the coupling between the voltage and the current.
- Component failure and maltrip / malfunctioning due to distortion.
- Harmonic interaction in high voltage transmission and distribution systems due to fundamental voltage phase angle displacement.
- Difference of the ratio in negative and positive sequence voltage harmonics at different voltage levels. (Difference of positive and negative sequence source impedance.)
- Magnetic fields from cables and transformer substations caused by zero sequence harmonics.
- Interharmonics: a time variation of the harmonic distortion?
- Load modeling.
- Sound levels in transformers and electrical machines due to harmonic distortion.

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# Appendix A

## Frequency spectra of the voltage and current

The amplitudes for the voltages and currents, in one phase, are given at nighttime, morning time, daytime and evening time for the high voltage measurements (130 and 400 kV), in chapter 4.

The amplitudes are given as rms-values, phase to neutral, and the phase angles are given in degrees.

## Nighttime 130 kV

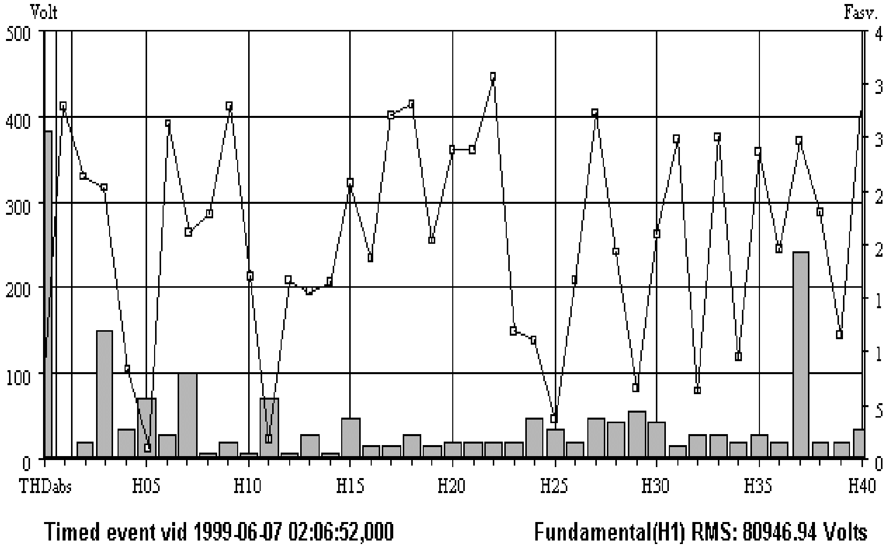


Figure A1. Voltage distortion at nighttime.

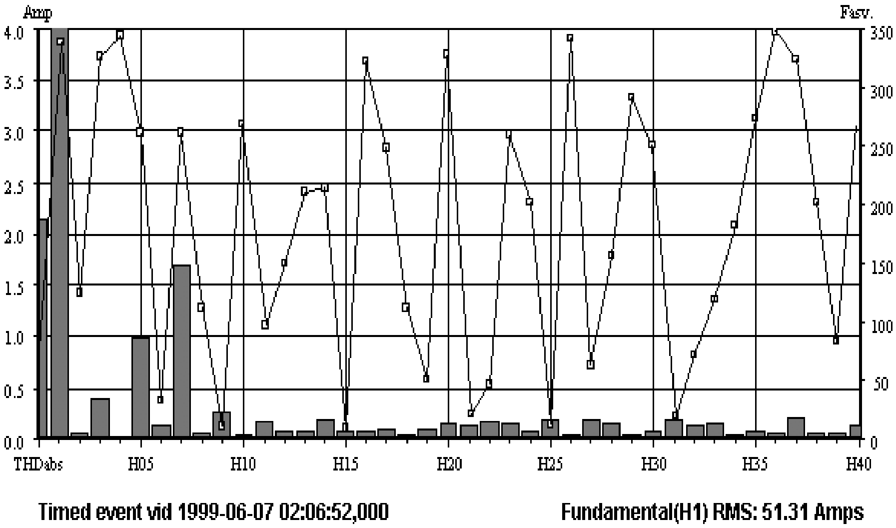
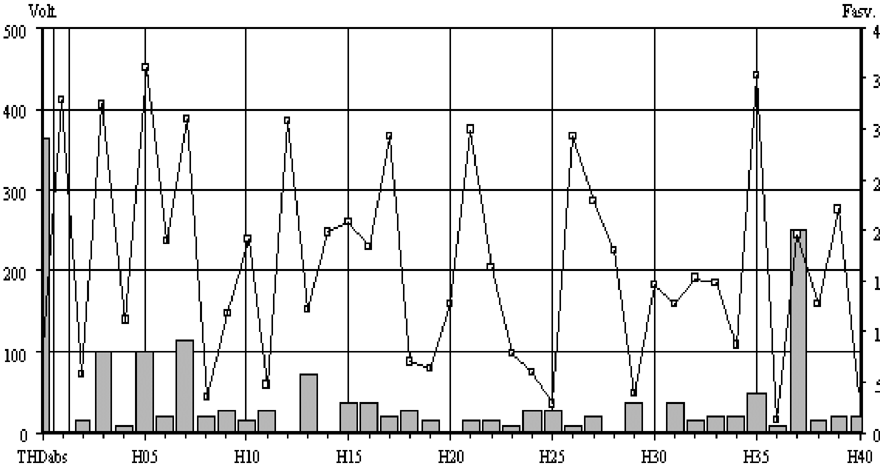


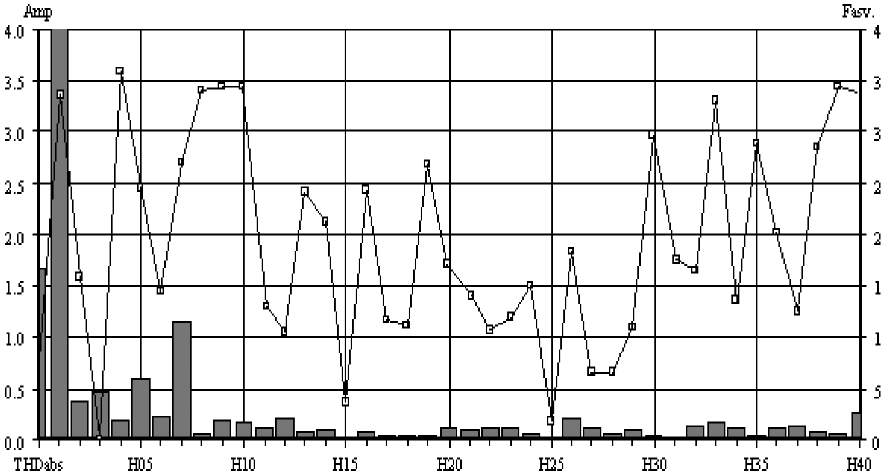
Figure A2. Current distortion at nighttime.

## Morning time 130 kV



**Timed event vid 1999-06-03 07:20:27,000** **Fundamental(H1) RMS: 80733.51 Volts**

Figure A3. Voltage distortion at morning time.



**Timed event vid 1999-06-03 07:20:27,000** **Fundamental(H1) RMS: 54.97 Amps**

Figure A4. Current distortion at morning time.

## Daytime 130 kV

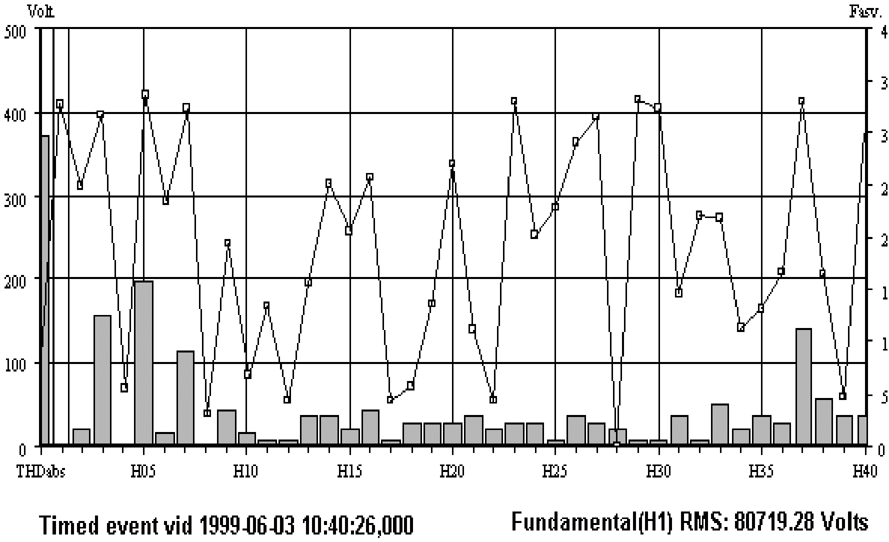


Figure A5. Voltage distortion at daytime.

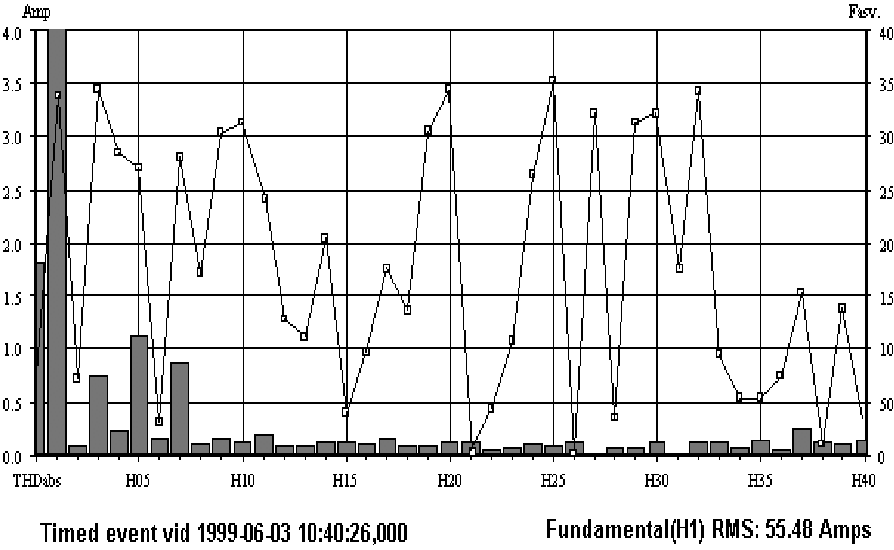


Figure A6. Current distortion at daytime.

## Evening time 130 kV

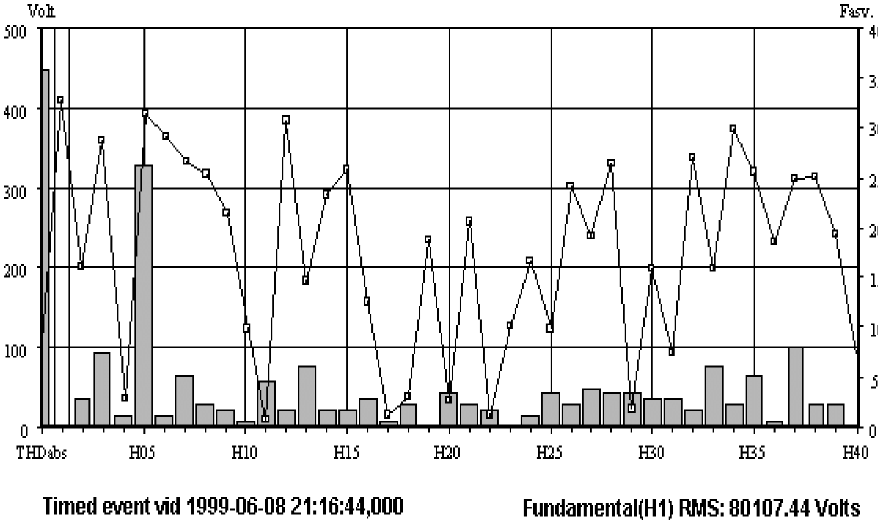


Figure A7. Voltage distortion at evening time.

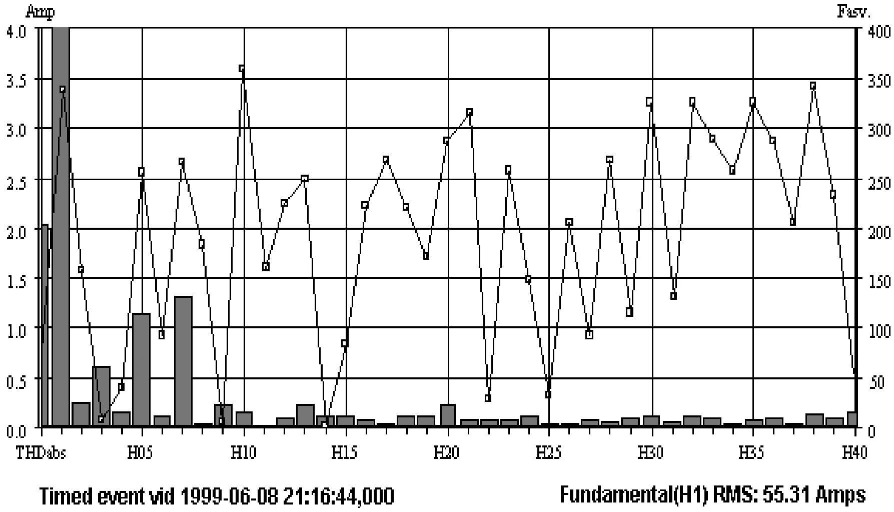


Figure A8. Current distortion at evening time.

## Weekend, daytime 130 kV

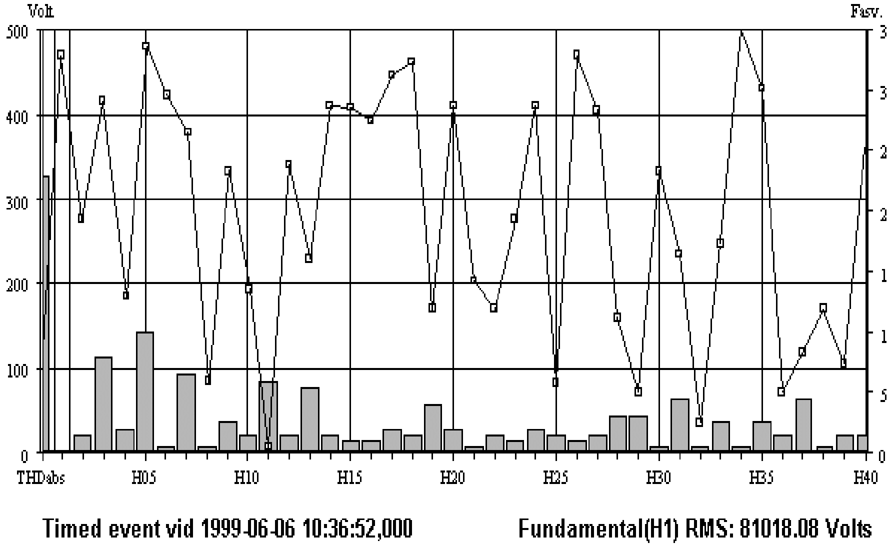


Figure A9. Voltage distortion at weekend, daytime.

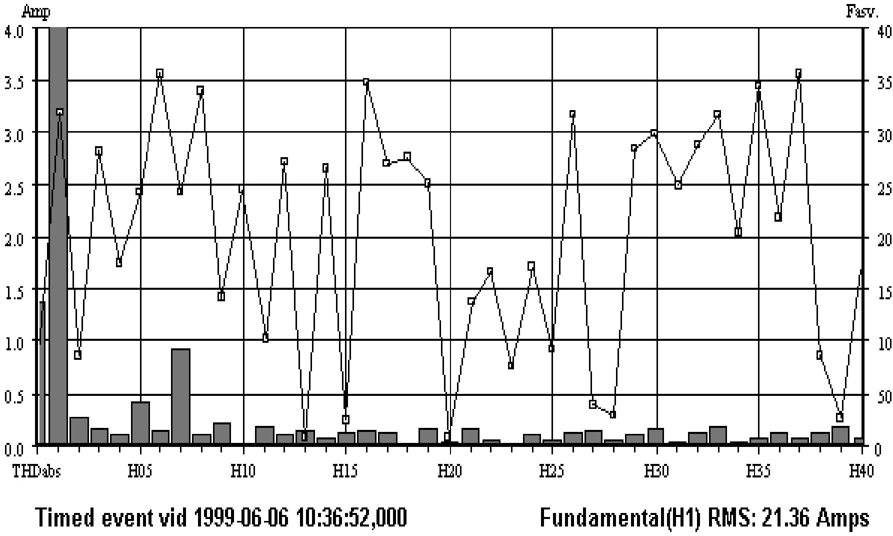


Figure A10. Current distortion at weekend, daytime.

## Saturday evening 130 kV

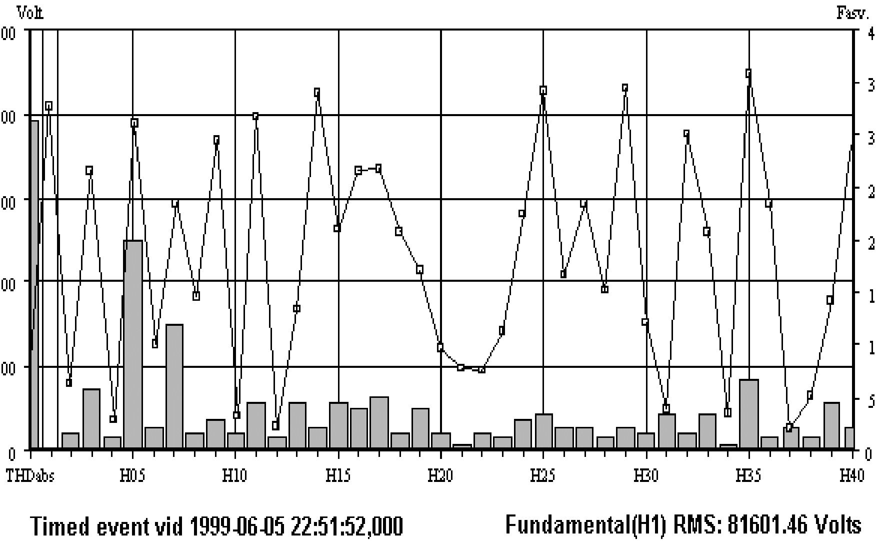


Figure A11. Voltage distortion at Saturday evening.

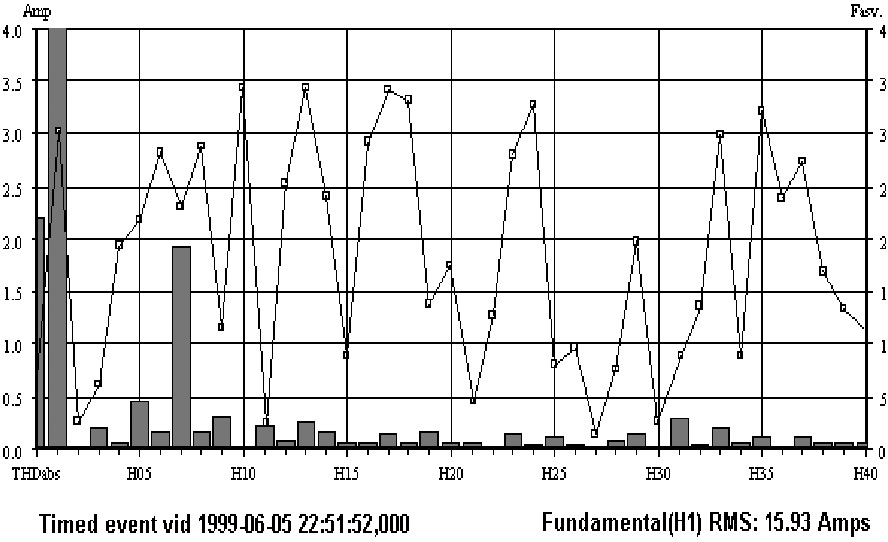


Figure A12. Current distortion at Saturday evening.

# Nighttime 400 kV (60 Mvar capacitor bank disconnected)

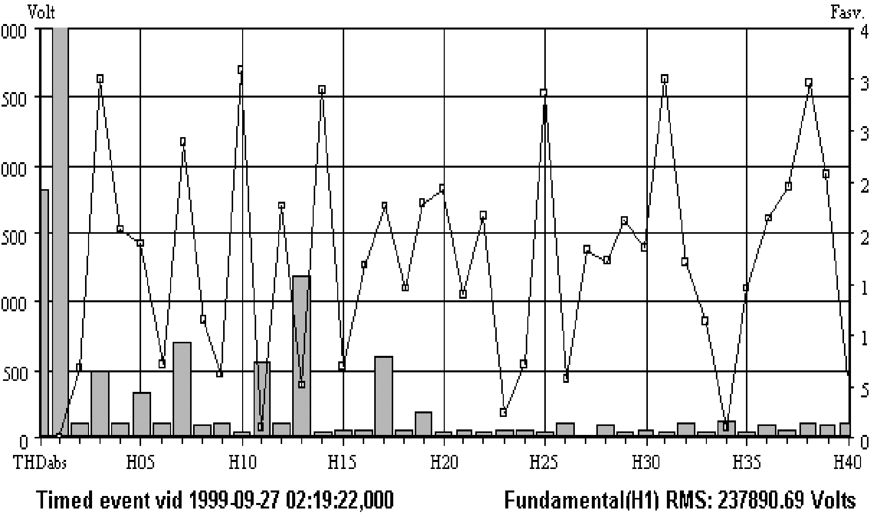


Figure A13. Voltage distortion at nighttime.

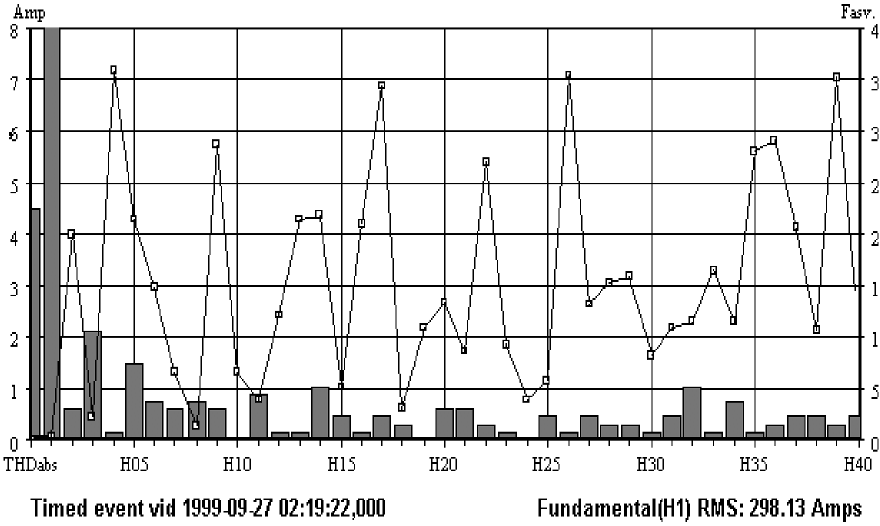


Figure A14. Current distortion at nighttime.

## Morning time (with 60 Mvar capacitor bank connected)

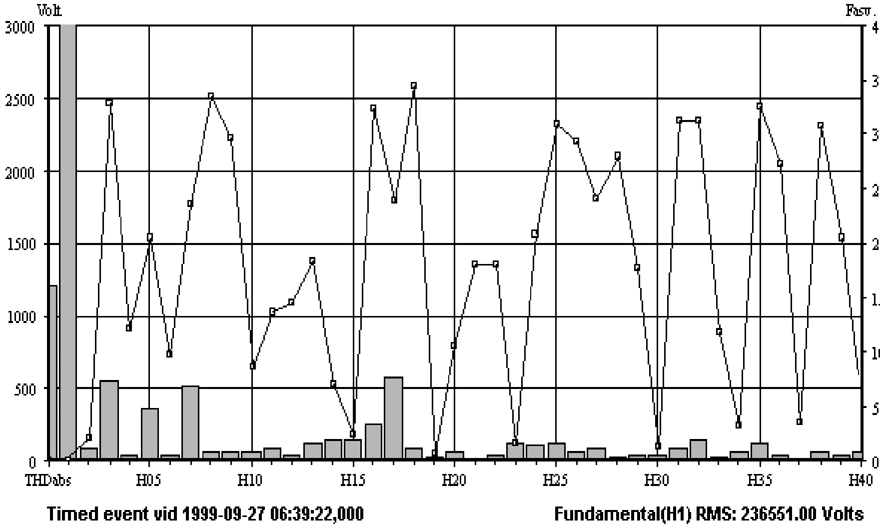


Figure A15. Voltage distortion at morning time.

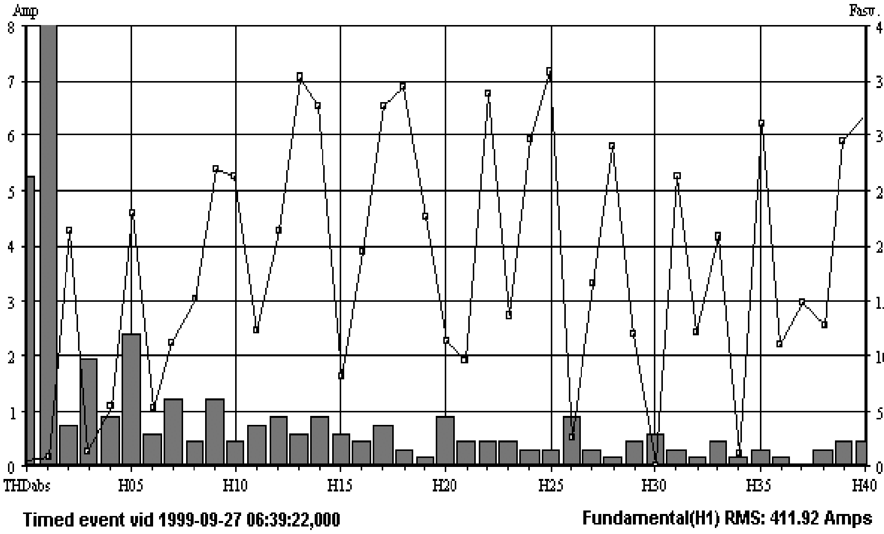


Figure A16. Current distortion at morning time.

## Daytime (with 60 Mvar capacitor bank connected)

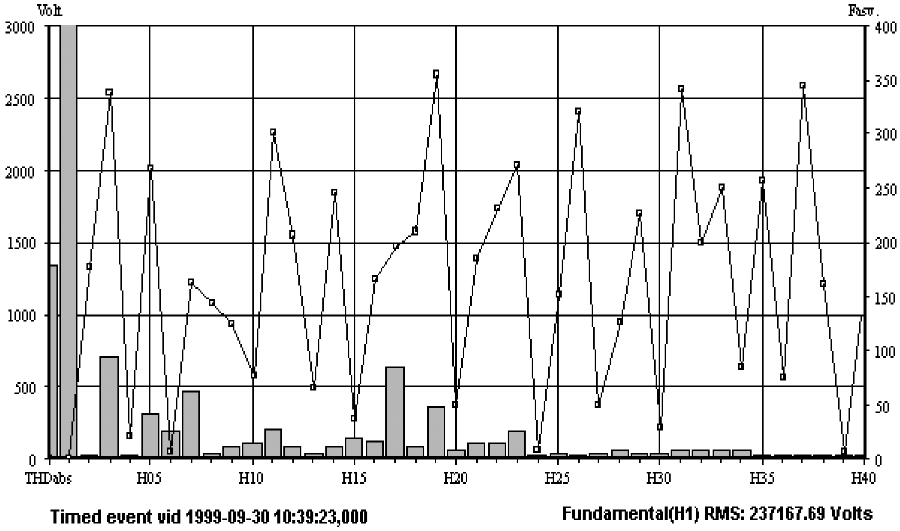


Figure A17. Voltage distortion at daytime.

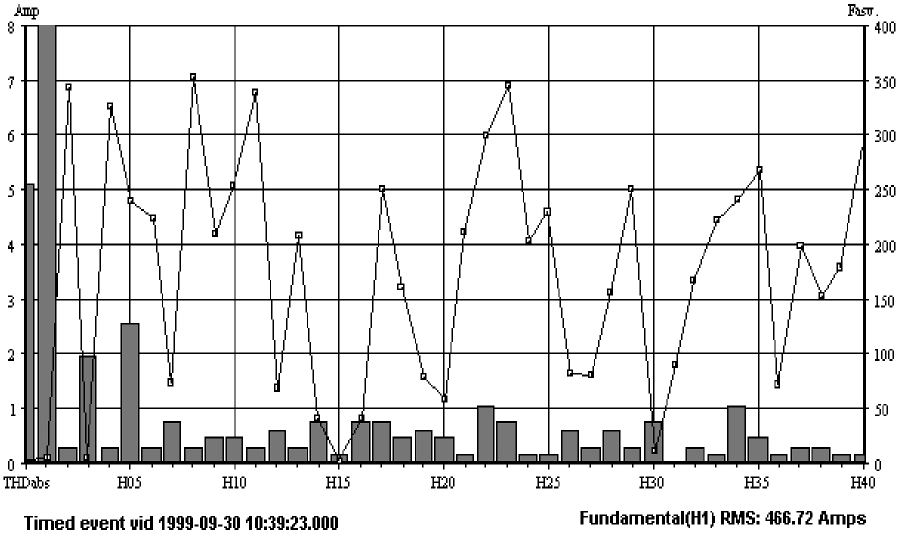


Figure A18. Current distortion at daytime.

## Evening time (60 Mvar capacitor bank disconnected)

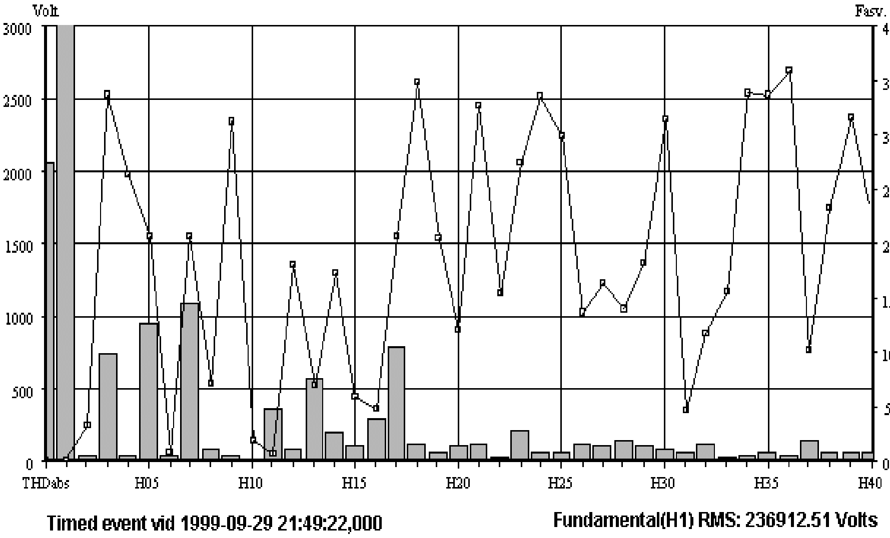


Figure A19. Voltage distortion at evening time.

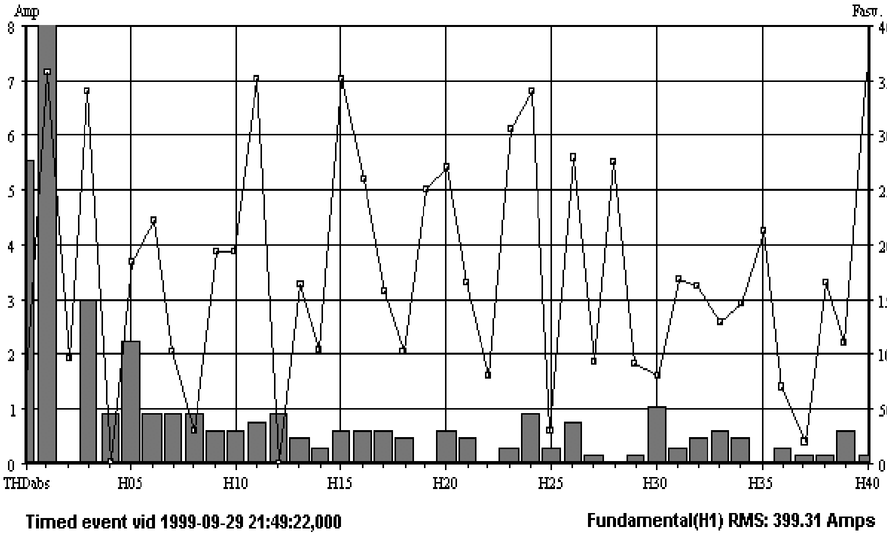


Figure A20. Current distortion at evening time.

## Weekend, daytime (60 Mvar capacitor bank disconnected)

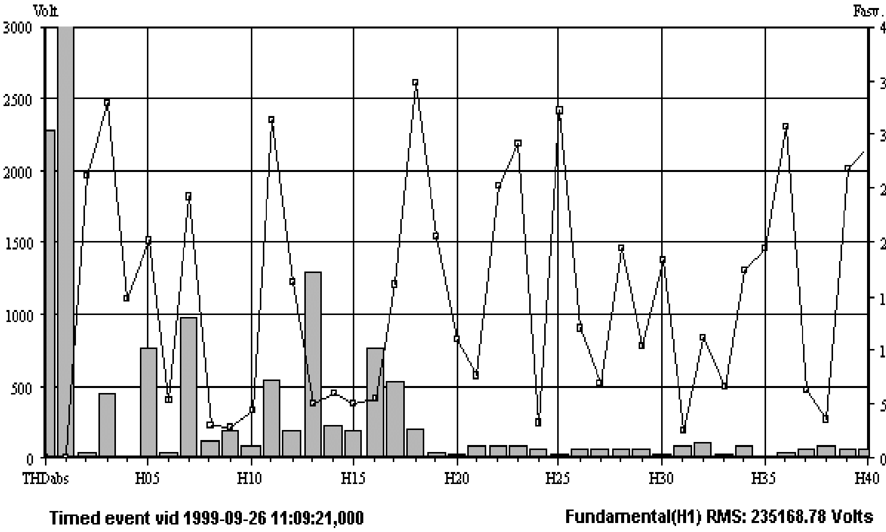


Figure A21. Voltage distortion at weekend daytime.

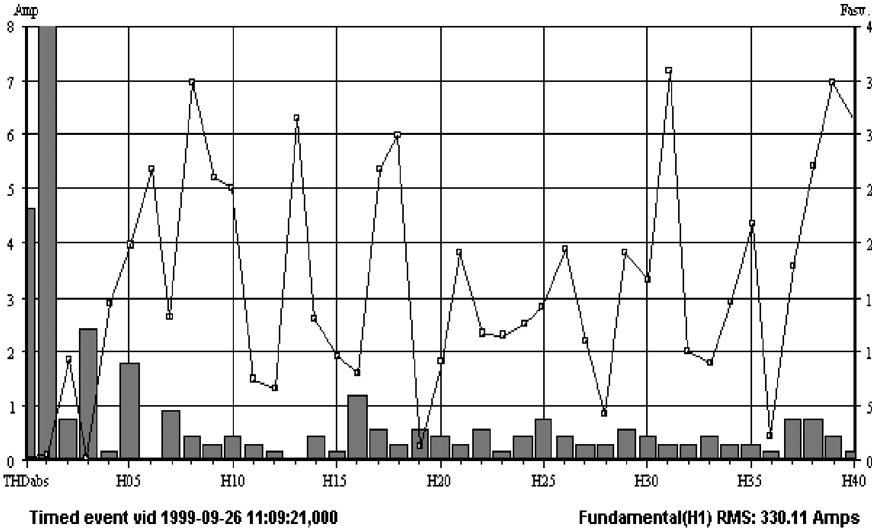


Figure A22. Current distortion at weekend daytime.

## Saturday evening (60 Mvar capacitor bank disconnected)

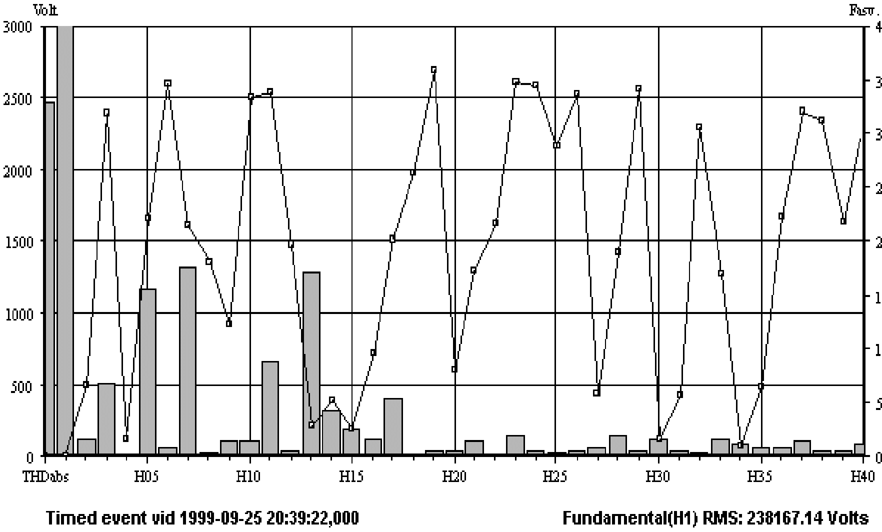


Figure A23. Voltage distortion at Saturday evening.

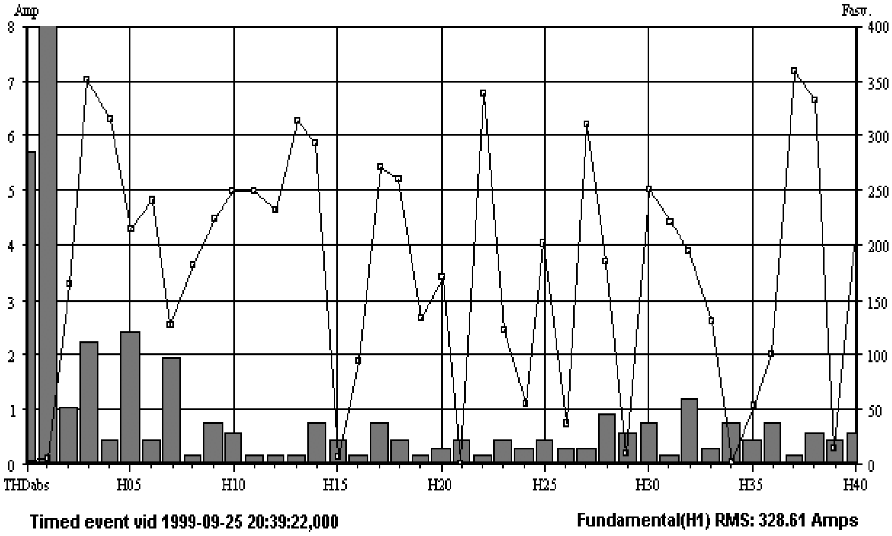


Figure A24. Current distortion at Saturday evening.