**Czech Technical University in Prague**

Faculty of Electrical Engineering

Department of Electroenergetics

# Harmonic currents compensation in industrial applications

Diploma thesis

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|---|---|
| Study programme: | Electrical Engineering, Power Engineering and Management |
| Field of study: | Electrical Power Engineering |
| Tutor: | Ing. et Ing. Jan Pígl |

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# DIPLOMA THESIS ASSIGNMENT

Student: **Bc. Šimon Szczotka**

Study programme: Electrical Engineering, Power Engineering and Management
Specialisation: Electrical Power Engineering

Title of Diploma Thesis: **Harmonic currents compensation in industrial applications**

Guidelines:

1. Explore the types of electrical grids in industrial applications (low and medium voltage)
2. Explore the sources of harmonic currents in industrial applications
3. Explore the standard ČSN EN 61000 (Electromagnetic compatibility)
4. Explore the types of compensation of harmonic currents in industrial applications (active and passive filters)
5. Assess sources of harmonic currents and design a suitable method of their compensation in real industrial grid

Bibliography/Sources:

[1] ČSN EN 61000 - Elektromagnetická kompatibilita (EMC)
[2] FENCL, Frantiąek. Elektrický rozvod a rozvodná zařízení. Vyd. 4. Praha: Česká technika - nakladatelství ČVUT, c2009, 198 s. ISBN 978-80-01-04351-6
[3] Francisco C. De La Rosa. Harmonics and Power Systems (Electric Power Engineering). 1st Edition. CRC Press (May 22, 2006), 208 s., ISBN 0849330165

Diploma Thesis Supervisor: Ing. Jan Pígl et Ing.

Valid until the end of the winter semester of academic year 2017/2018

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Prague, April 18, 2016

# Abstract

This work deals with the harmonic distortion in industrial applications. Electric installations in industry will be described, especially topology and equipment. We will explain basic theory concerning harmonic distortion. The most frequent sources of harmonic currents in industrial applications will be explored. These sources will be predominantly modelled in Matlab Simulink. Methods of harmonic currents compensation will be describd. Standards ČSN and IEEE stipulating limits of harmonic distortion will be clarified. In conclusion of this work, harmonic distortion in real industrial application will be assessed and subsequently the optimal method of its compensation will be designed.



Keywords: harmonic currents, electrical installation, harmonic distortion, THD, passive filter, active filter, detuned reactor, input reactor, DC reactor, rectifier, distortion limits



# Abstrakt

Tato práce se zabývá problematikou harmonického zkreslení v průmyslových aplikacích. Bude popsána typická průmyslová elektrická instalace. Bude vysvětlena základní teorie týkající se harmonického zkreslení. Představíme nejčastější zdroje harmonických proudů v průmyslových instalacích. Většina těchto zdrojů bude namodelována v programu Matlab Simulink. Budou popsány metody používané k omezení negativních vlivů harmonických proudů. Seznámíme se s maximálními hodnotami harmonického zkreslení, definovanými normami ČSN i IEEE. V závěru práce bude provedena studie harmonického zkreslení v reálné průmyslové aplikaci a bude navrženo vhodné řešení.



Klíčová slova: harmonické proudy, elektrická instalace, harmonické zkreslení, THD, pasivní filtr, aktivní filtr, hradící tlumivka, vstupní tlumivka, stejnosměrná tlumivka, usměrňovač, limity pro harmonické zkreslení

## Prohlášení

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne 18.12.2016

……………………………………..
Šimon Szczotka

## Declaration

I hereby declare that this diploma thesis is my own work and that I cited all information sources in accordance with the Methodical instructions on observance of ethical principles in diploma thesis writing.

In Prague On 18th December 2016

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Šimon Szczotka

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## Preface

Electric power quality requirements are very high nowadays. This quality is assessed by means of many of parameters, including harmonic distortion, which means, that voltage or current waveform is not perfectly sinusoidal. Such distortion is caused by harmonic currents, generated by nonlinear loads. It has negative effects on electric power quality. It was not such a problem earlier, as number of nonlinear loads was not so large, although they existed. Nevertheless, with expansion of semiconductor devices, problem of harmonic distortion became more significant. Typical application facing this problem could be big industrial plant with large amount of induction motors, or office building with large number of personal computers or fluorescent lamps. We have to perform a study of harmonic distortion in such objects, and alternatively take necessary steps to reduce it. Such study is aim of this work. However, before we will perform this study, we have to acquaint with typical electrical installation in industrial applications (chapter 1). In chapter 2, we will explain a harmonic currents theory and we will show important parameters, we will work with later. In this chapter we will also describe the most typical sources of harmonic currents. In chapter three, we will describe usual methods used to harmonic currents compensation. On the basis of these three chapters we will be able to perform a study of harmonic currents in Eaton Innovation Centre in Roztoky, which is typical industrial application, comprising:

- analysis of electrical scheme and evaluating sources of harmonic currents
- defining degree of harmonic distortion on the basis of measurements
- determine, whether harmonic distortion is within the limits defined by standards
- design a suitable solution leading to meet the standards and to eliminate issues caused by harmonic distortion

# Contents

# Table of Figures

# 1 Electrical installation in industrial plants

Aim of this chapter is to describe electrical grid in typical industrial application that is different from conventional electric installation. We will describe only topology of electrical grid and parameters of its most important equipment. Scheme of typical electrical grid in industrial application is shown in figure 1.1. It is example of grid supplied from HV grid, with two MV/LV transformers and MV loads. It corresponds to bigger industrial plant with installed power about 10 MW.

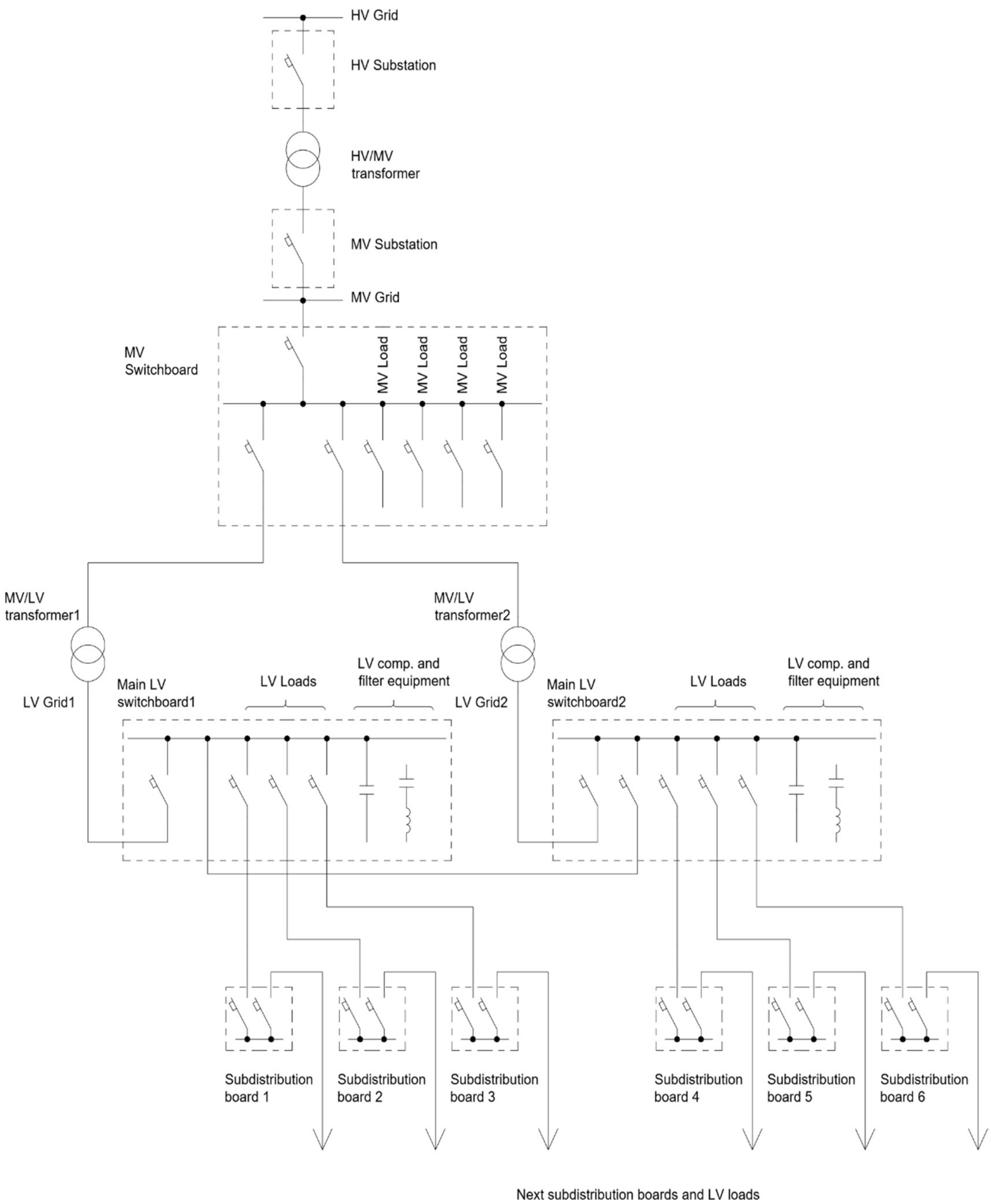



*Figure 1.1 - Example of electrical grid in industrial plant*

Electrical grid in figure 1.1 consists of:

1) *HV grid.* Power supply at HV is used only at plants with big installed power and MV loads. In other cases, supply at medium voltage grid is enough. Parameters of HV grid are shown in table 1-1. Power lines (conductors) are almost always overhead, HV cables are used rarely.

| **Parameter** | **Value** |
|---|---|
| Phase-to phase rms voltage $U_n$ | 3x110 kV/50 Hz |
| 3-phase short-circuit level $S_k$“ | 3000-12000 MVA |
| Reactance vs. resistance ratio X/R | 5-12 |

*Table 1-1 - HV grid parameters [1]*

2) *HV Substation.* Its purpose is to connect the HV/MV transformer to HV grid. HV substation is usually outdoor. Its main components are switching devices as circuit breakers, switch-disconnectors and disconnectors, current and voltage transformers, protective devices, surge arresters and HV/MV transformer.

3) *HV/MV transformer.* As said above, HV/MV step down transformer is located at HV substation. Neutral point at MV side is usually grounded through a reactor or resistor, depending of distribution company preferences. Secondary voltage of new HV/MV transformers is nowadays always 22 kV, as MV grid is being unified, but we can still find transformers with turns ratio 110/10 kV and 110/35 kV. Parameters of common 110/22 kV transformers used for supply of industrial plants is shown in table 1-2.

| **Parameter** | **Value** |
|---|---|
| Nominal power and frequency $P_n$ | 10, 16, 25, 40, 63 MVA |
| Primary winding voltage $Un_1$ | 110 kV |
| Primary winding voltage $Un_2$ | 35, 22, 10 kV |
| Short circuit voltage $u_k$ | about 10 % |

*Table 1-2 - Parameters of common HV/MV transformers in industrial plants [2]*

4) *MV Grid.* As mentioned above, the most of industrial plants are connected to MV grid. Parameters of MV grid are shown in table 1-3. Conductors at MV voltage can be overhead or cables, but for MV grids in industrial plants, cables predominate.

| **Parameter** | **Value** | | | |
|---|---|---|---|---|
| Phase-to phase rms voltage $U_n$ | 3x6 kV /50 Hz | 3x10 kV /50 Hz | 3x22 kV /50 Hz | 3x35 kV /50 Hz |
| 3-phase short-circuit level $S_k$“ | 130-520 MVA | 216-866 MVA | 240-953 MVA | 485-1516 MVA |
| Reactance vs. resistance ratio X/R | 5-12 | | | |

*Table 1-3 - MV grid parameters [1]*

5) *Main MV Switchboard*. It may consist of several sections:
   a. Incoming section
   b. Outgoing sections for MV/LV transformers or MV loads
   c. Metering section
   d. Section for filter and compensation equipment

Metering of electrical energy is usually performed in MV switchboard, but it can be placed at LV switchboard as well. To the contrary, filtering and compensation devices are usually placed in LV switchboard.

6) *MV/LV transformer.* Usually situated in the substation, along with MV switchboard. Transformer 22/0,4 kV Dy1 is used most often. Depending on installed power, various number of transformers can be installed. Neutral on the LV side is usually directly earthed as TN-C-S system is mostly used. Parameters of MV/LV transformers are shown in table 1-4.

| **Parameter** | **Value** |
|---|---|
| Nominal power and frequency $P_n$ | 100, 160, 250, 315, 400, 630, 800, 1000, 1250, 1600, 2000, 2500 kVA |
| Primary winding voltage $Un_1$ | 35, 22, 10, 6 kV |
| Primary winding voltage $Un_2$ | 0,4 kV (sometimes 0,5; 0,69 kV) |
| Short circuit voltage $u_k$ | usually 4 or 6 % |

*Table 1-4 - Parameters of common MV/LV transformers*

7) *LV grid.* Voltage of LV gird is normally 400 V, but rarely it can be 500 V or 690 V. As written above, TN-C-S system is used the most often. Paramters of LV grid are shown in table 1-5. Conductors is practically always cables, or busbars (if busbar system is used).

| **Parameter** | **Value** |
|---|---|
| Phase-to phase rms voltage $U_n$ | 400 V (500, 690) |
| 3-phase short-circuit level $S_k$“ | tens of kVA up to 100 MVA |
| Reactance vs. resistance ratio X/R | about 1 |

*Table 1-5 - MV grid parameters [1]*

8) *Main LV switchboard.* Every MV/LV transformer has its own main LV switchboard. As MV switchboard, also LV switchboard includes several sections, as incoming, outgoing, section for filtering and compensate equipment etc. LV switchboards can be variously interconnected in order to improve supply reliability. Various number of sub distribution boards is connected to the main switchboard. Other boards can be connected to these sub distribution boards etc. Number of these boards depends on number of loads and installed power.

# 2 Sources of harmonic currents

Ideally, an electricity supply should invariably show a perfectly sinusoidal voltage signal at every customer location. However, for a number of reasons, utilities often find it hard to preserve such desirable conditions. The deviation of the voltage and current waveforms from sinusoidal is described in terms of the waveform distortion, often expressed as harmonic distortion.[3]

This distortion is caused by the sources of harmonic currents or harmonic voltage. Not every voltage sources make an ideal sinusoidal voltage signal. For example, synchronous generator generates distorted voltage waveform because of discrete distribution of winding in slots. There are also many of loads producing harmonic currents, because of their nonlinear V-A characteristic. Only sources of harmonic currents will be discussed in this work, because they are much more frequent than sources of harmonic voltages. In this chapter we will analyse the main sources of harmonic currents, which occur in industrial applications. Nevertheless, first, we have to show and explain how and what harmonic currents are and how they arise.

## 2.1 Harmonics, interharmonics and sub-harmonics

As said above, nonlinear loads draw a distorted current, different from the sinusoidal. Such a current is composed of sinusoidal components with different frequency. They are divided depending on frequency as follows:

- Harmonic components, $f = h.f_{fundamental}$, h is an integer, h>=1
- Interhamonic components, $f = m.f_{fundamental}$, m is not an integer
    - If m<1, they may be called sub-harmonic components
- DC component, f = 0

Every periodic waveform consist of these components. However, we have to say, that harmonic components occur more frequently in power grid than sub-harmonics or interhamonics.

## 2.2 Fourier series

By definition, a periodic function, $f(t)$, is that where $f(t) = f(t + T)$. This function can be represented by a trigonometric series of elements consisting of a DC component and other elements with frequencies comprising the fundamental component and its integer multiple frequencies. [3]

The expression for such a series is called a Fourier series, and can be written as

$$f(t) = \frac{a_0}{2} + \sum_{h=1}^{\infty} a_h \cos\left(2\pi hft\right) + b_h \sin\left(2\pi hft\right) \tag{1.1}$$

Series can be simplified

$$f(t) = c_0 + \sum_{h=1}^{\infty} c_h \sin\left(2\pi hft + \phi_h\right) \tag{1.2}$$

Where

$$c_0 = \frac{a_0}{2} \tag{1.3}$$

$$c_h = \sqrt{a_h^2 + b_h^2} \tag{1.4}$$

$$\phi_h = \arctan\frac{a_h}{b_h} \tag{1.5}$$

| | |
|---|---|
| *h* | order of harmonic component |
| f | fundamental frequency |
| $c_0$ | DC component magnitude |
| $c_h$ | hth component magnitude |
| $\phi_h$ | hth component phase angle |

Coefficients $a_0$, $a_h$, $b_h$ can be found as

$$a_0 = \frac{2}{T}\int_{\frac{-T}{2}}^{\frac{T}{2}} f(t)dt \tag{1.6}$$

$$a_h = \frac{2}{T}\int_{\frac{-T}{2}}^{\frac{T}{2}} f(t)\cos(2\pi hft)dt \tag{1.7}$$

$$b_h = \frac{2}{T}\int_{\frac{-T}{2}}^{\frac{T}{2}} f(t)\sin(2\pi hft)dt \tag{1.8}$$

Distorted waveform example is shown in figure 2.1. Summary waveform is represented by sum of harmonic components, 5th, 7th, 9th 13th and 15th harmonic are present here. Harmonic components magnitudes $c_h$ (harmonic spectrum) can be computed from equation written above. We usually displayed computed values $c_h$ in bar plot, as shown in figure 2.2. Values are ordinarily displayed in percent of fundamental component $c_h(\%) = (c_h/c_1)*100\%$.

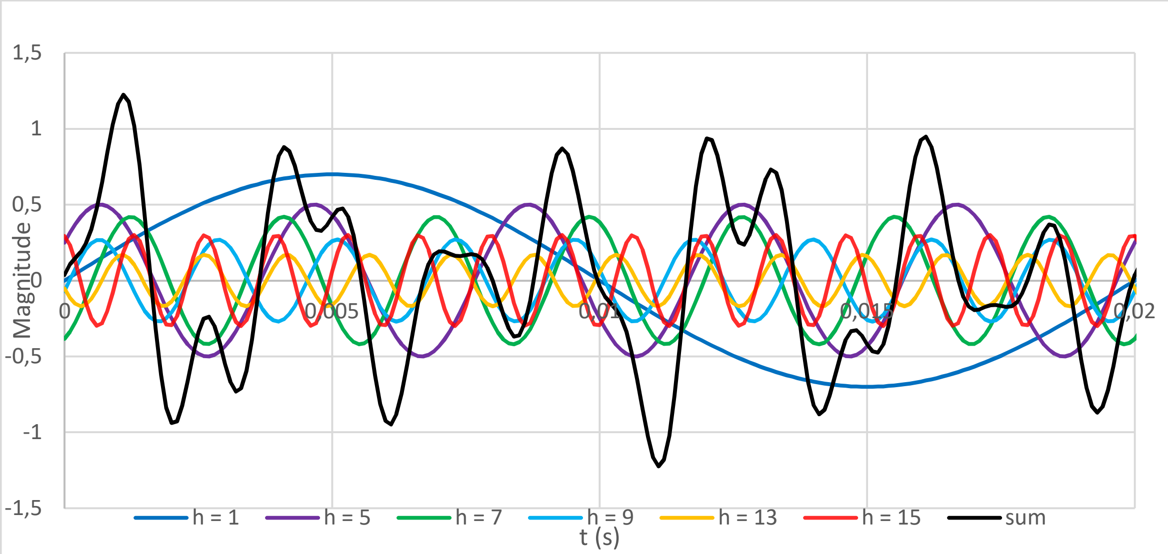



*Figure 2.1 - Distorted waveform example*

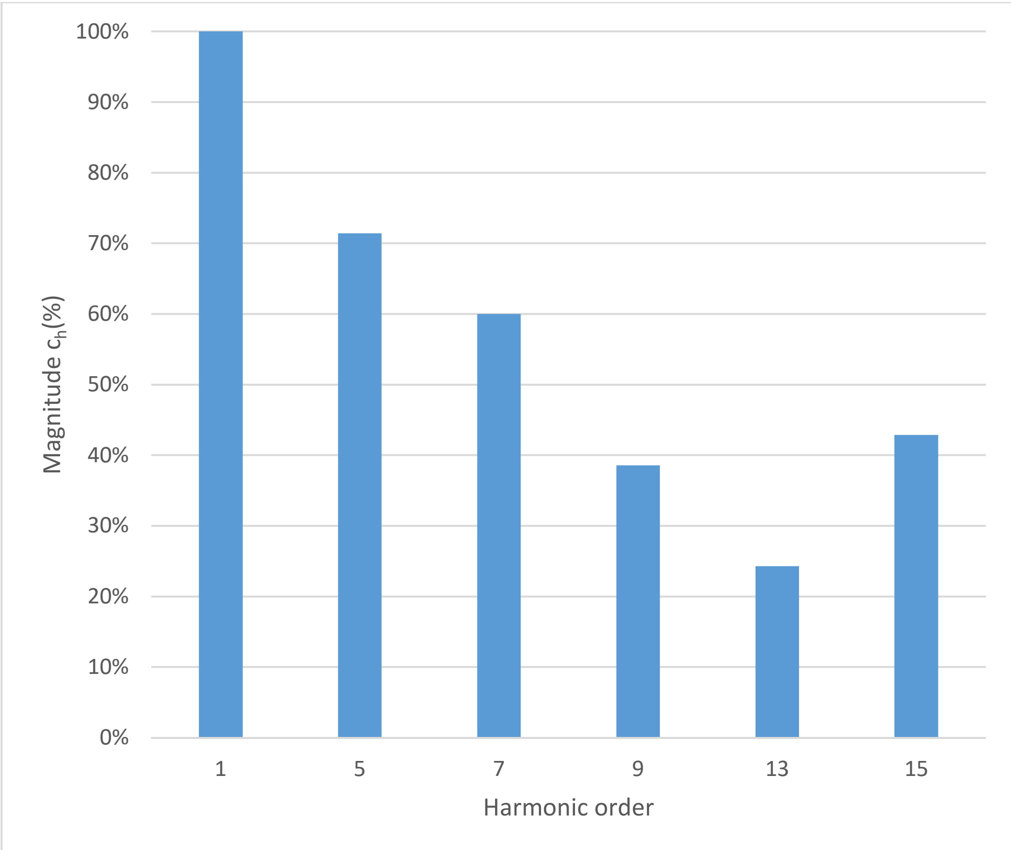



*Figure 2.2 - Fourier transform analysis (harmonic spectrum) of a waveform in figure 2.1*

However, continuous Fourier transform is not usable in practice. For this reason, discrete Fourier transform (DFT) was invented. Discrete Fourier transform (DFT) converts a finite sequence of equally spaced samples of a function into the list of coefficients of a finite combination of complex sinusoids, ordered by their frequencies, that has those same sample values. [4]

Discrete fourier transform can be expressed as

$$X_k = \sum_{n=0}^{N-1} x_n \cdot \left( \cos\left( -2\pi k \frac{n}{N} \right) + i \sin\left( -2\pi k \frac{n}{N} \right) \right), \quad \mathrm{k} \in \mathbb{Z} \tag{1.9}$$

We may write this equation in matrix form as

$$\begin{pmatrix} X_1 \\ X_2 \\ . \\ X_{N-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 & . & . & 1 \\ 1 & W & W^2 & . & W^{N-1} \\ 1 & W^2 & W^4 & . & W^{N-2} \\ 1 & W^3 & W^6 & . & W^{N-3} \\ . & . & . & . & . \\ 1 & W^{N-1} & W^{N-2} & . & W \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \\ . \\ x_{N-1} \end{pmatrix} \tag{1.10}$$

Inverse discrete Fourier transform is discrete analogy of the formula for the coefficients of a Fourier series

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k \cdot \left( \cos\left( 2\pi k \frac{n}{N} \right) + i \sin\left( 2\pi k \frac{n}{N} \right) \right), \quad n \in \mathbb{Z} \tag{1.11}$$

$X_k$ is a complex number, which carry information about both, amplitude and phase of sinusoidal component $e^{2\pi ikn/N}$ of function $x_n$.

Since DFT algorithm is slow, computer use the Fast Fourier transform. As said above, Fourier analysis converts a signal from its original domain to a representation in the frequency domain and vice versa. An FFT rapidly computes such transformations by factorizing the DFT matrix (in equation 2.10) into a product of sparse (mostly zero) factors. As a result, it manages to reduce the complexity of computing the DFT from $O(n^2)$, which arises if one simply applies the definition of DFT, to O(n.logn), where n is the data size. [5]

## 2.3 Power quality indices and power quantities under nonsinusoidal situations

### 2.3.1 Total harmonic distortion (THD)

The most important index, showing ratio of harmonic components to fundamental component in distorted waveform is called total harmonic distortion. It is defined for both, current (THDI) and voltage (THDU). THDU and THDI are expressed as

$$THDU = \frac{\sqrt{\sum_{h=2}^{H} U_h^2}}{U_1} \cdot 100\% \ [\%] \tag{1.12}$$

$$THDI = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \cdot 100\% \ [\%] \tag{1.13}$$

Where

| | |
|---|---|
| $U_h$, $I_h$ | hth harmonic component voltage or current value (RMS or magnitude) |
| $U_1$, $I_1$ | Fundamental component voltage or current value (RMS or magnitude) |
| h | Equals 50 by standard IEC 61000-2-4, 25 if higher order harmonics are negligible |

Maximum value of THDU is defined by standards. We have to distinguish between environments, in which we consider THDU, because limits defined by standards are different for any environment. In our thesis, we will follow standard IEC 61000-2-4, that defines limits for industrial plants at IPC point (see appendix A). Limits for distribution grid, (at PCC point), are defined in standards IEC 61000-2-2 and IEC 61000-2-12, alternatively ČSN EN 50160

Standard IEC 61000-2-4 does not stipulate limits for harmonic currents. It means, that is enough, when limits for THDU are met. But it is suitable to keep THDI within the limits. In North America, standard IEEE-519 is used (see appendix A). In comparison to standards IEC, standard IEEE-519 stipulates limits for both THDU and THDI. Exists standards IEC governing equipment, that stipulate limits of THDI for LV equipment rated current up to 16 A (IEC 61000-3-2) and up to 75 A (IEC 61000-3-12).

For example, THD of waveform from figure 2.1 is

$$THD = \frac{\sqrt{\sum_{c=5}^{15} c_h^2}}{c_1} \cdot 100\% = \frac{\sqrt{c_5^2(\%) + c_7^2(\%) + c_9^2(\%) + c_{13}^2(\%) + c_{15}^2(\%)}}{c_1(\%)} \cdot 100\% =$$

$$\frac{\sqrt{71^2 + 60^2 + 39^2 + 24^2 + 43^2}}{100} \cdot 100\% = 112\%$$

### 2.3.2 **Active, reactive and apparent power**

Every harmonic provides a contribution to the average power that can be positive or negative. However, the resultant harmonic power is very small relative to the fundamental frequency active power.[3] We can practically say, that harmonic currents carry only reactive power. They carry active power only when voltage waveform is distorted as well (when THDU is greater than zero)

$$P = \sum_{h=0}^{\infty} U_h I_h \cos\varphi_h = \sum_{h=0}^{\infty} P_h \text{ [W]} \tag{1.14}$$

Reactive power can be expressed as

$$Q = \sum_{h=0}^{\infty} U_h I_h \sin\varphi_h = \sum_{h=0}^{\infty} Q_h \text{ [VAr]} \tag{1.15}$$

Where

| | |
|---|---|
| $U_h$, $I_h$ | hth harmonic component RMS value |
| $\varphi_h$ | Angle between hth component voltage and current |

An expression for apparent power, generally accepted by IEEE and IEC is that proposed by Budeanu in Antoinu [3]

$$S^2 = P^2 + Q^2 + D^2 = \sum_{h=0}^{\infty} U_h I_h \cos\varphi_h + \sum_{h=0}^{\infty} U_h I_h \sin\varphi_h + D^2 \text{ [VA]} \tag{1.16}$$

where D is so called distortion (deforming) power.

$$S = \sqrt{\sum_{h=0}^{\infty} U_h^2} \cdot \sqrt{\sum_{h=0}^{\infty} I_h^2} = U_{r.m.s.} \cdot I_{r.m.s.} \text{ [VA]} \tag{1.17}$$

Where

$\sqrt{\sum_{h=0}^{\infty} U_h^2} = U_{r.m.s.}$ [V] RMS value of voltage

$\sqrt{\sum_{h=0}^{\infty} I_h^2} = I_{r.m.s.}$ [A] RMS value of current

Note, that there is an inequality between apparent, active and reactive power, because of distortion power

$$S \geq P^2 + Q^2 \tag{1.18}$$

We introduce term total (true) power factor, that takes into account harmonic distortion. General equation for total power factor is

$$TPF = \frac{\frac{1}{T}\int_0^T u_h \cdot i_h dt}{\sqrt{\sum_{h=0}^{\infty} U_h^2} \cdot \sqrt{\sum_{h=0}^{\infty} I_h^2}} = \frac{\sum_{h=0}^{\infty} U_h \cdot I_h \cdot \cos\varphi_h}{\sqrt{\sum_{h=0}^{\infty} U_h^2} \cdot \sqrt{\sum_{h=0}^{\infty} I_h^2}} \text{ [-]} \quad (1.19)$$

where

$u_h$, $i_h$ Instantaneous voltage and current value

As THDU used to be small, we can assume that harmonic components of voltage higher than one are equal to zero. Thus, we may write

$$TPF = \frac{U_1 \cdot I_1 \cdot \cos\varphi_1}{U_1 \cdot \sqrt{\sum_{h=0}^{\infty} I_h^2}} = \frac{I_1 \cdot \cos\varphi_1}{I_{r.m.s.}} = DPF \cdot \cos\varphi_1 \text{ [-]} \quad (1.20)$$

Where

$DPF = \frac{I_1}{I_{r.m.s.}}$ [-] Distortion power factor

$\cos\varphi_1$ Displacement power factor

Total power factor consists of product of two components – distortion power factor and displacement power factor. If no harmonic distortion is present, $I_1$ equals $I_{r.m.s.}$, and total power factor equals $\cos\varphi_1$. In non-sinusoidal situation, total power factor is lower than $\cos\varphi_1$, because $I_{r.m.s.}$ increases due to harmonic currents. We may rewrite equation for distortion power factor using equation 2.12 (we assume DC component being equal to zero)

$$DPF = \frac{I_1}{I_{r.m.s.}} = \frac{I_1}{\sqrt{I_1^2 + \sum_{h=2}^{\infty} I_h^2}} = \frac{I_1}{\sqrt{I_1^2\left(1 + \frac{\sum_{h=2}^{\infty} I_h^2}{I_1^2}\right)}} = \frac{1}{\sqrt{1 + \left(\frac{THDI}{100}\right)^2}} \text{ [-]} \quad (1.21)$$

Equation 2.21 shows us, how distortion power factor depends on THDI. The greater THDI, the lower total power factor, as shown in figure 2.3.

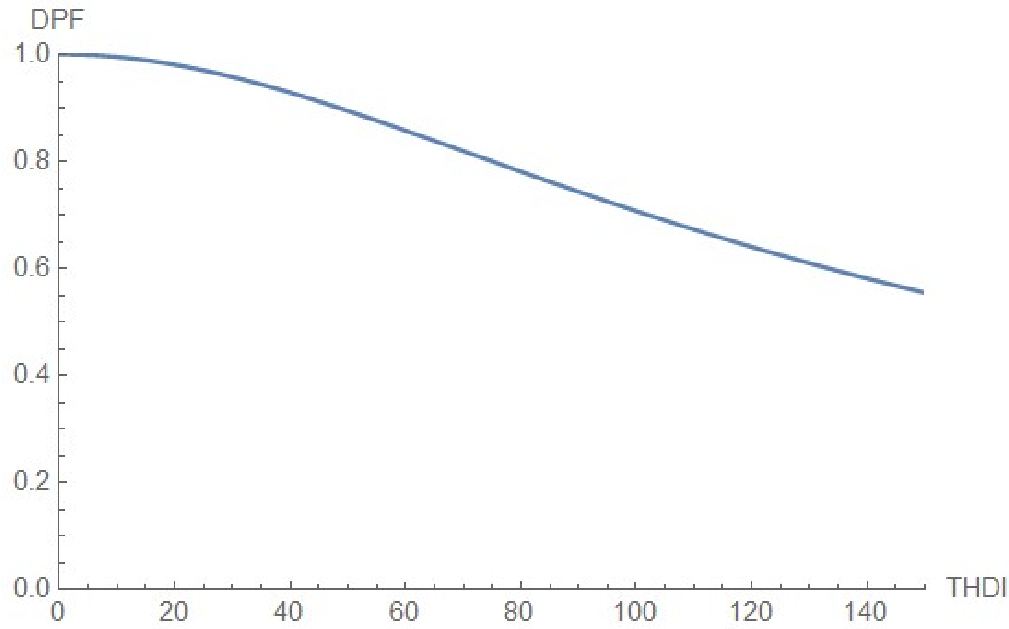


*Figure 2.3 - Distortion power factor DPF vs.THDI*

### 2.3.3 **Crest factor**

Crest factor is ratio between the peak value (magnitude) of current or voltage and its RMS value. It can be written as

$$CrestFactor = \frac{U_{peak}}{U_{RMS}} or \frac{I_{peak}}{I_{RMS}} [-] \qquad (1.22)$$

If waveform is perfectly sinusoidal, crest factor is equal to $\sqrt{2}$, in case of distorted waveform it is greater or less.

## 2.4 Harmonic phase sequences

It is well known, that current or voltage waveform of fundamental harmonic in balanced system consist only of positive sequence component. However, this is not always true for higher harmonic components. Have a look at the figure 2.4 – there is current waveform I(t) distorted by 5th harmonic (2.4 a) and waveform distorted by 3rd harmonic (2.4 b).Waveforms are shown for all three phases A, B and C. We consider balanced conditions. As we can see, 5th harmonic components are shifted from each other by 120 degrees, but the sequence is not A - B - C, but it is A - C - B, which means, that 5th harmonic is negative sequence. On the other hand, 3rd harmonic components are in phase, so 3rd is zero sequence.

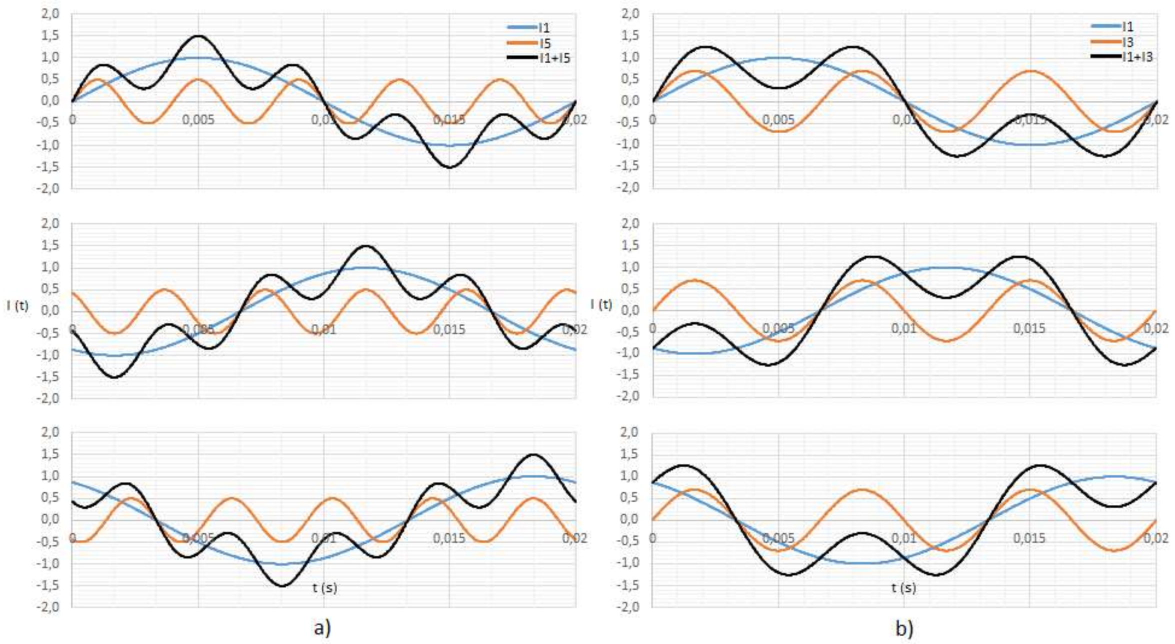



*Figure 2.4 - a) Phase A, B and C current waveform with 5th harmonic; b) Phase A, B and C current waveform with 3rd harmonic*

This can be also explained in different way – phase shift of phases A, B and C is 0, 240 and 120 degrees. If we multiply each of phase shift by harmonic order, we obtain phase shift of harmonic component. For example, for 5th harmonic we get :

- A: 0°.5 = 0°
- B: 240°.5 = 1200° = 720° + 360° + 120° ≡ 120°
- C: 120°.5 = 1200° = 720° - 120° ≡ 240°

, which corresponds with the above-mentioned text. For 3rd harmonic we get

- A: 0°.3 = 0°
- B: 240°.3 = 720° ≡ 0°
- C: 120°.3 = 360° ≡ 0°

for 4th harmonic we obtain

- A: 0°.4 = 0°
- B: 240°.4 = 960° = 720° + 240° ≡ 240°
- C: 120°.4 = 480° = 360° + 120° ≡ 120°

and the like.

If summarize these findings, we can say:

- Harmonic components with order 1, 4, 7, 10… are positive sequence
- Harmonic components with order 2, 5, 8, 11… are negative sequence
- Harmonic components with order 3, 6, 9, 12… are zero sequence

We have to note that this is true only for balanced system.

## 2.5 Origin of harmonic currents

### 2.5.1 Circuits with nonlinear load

Look at the model of circuit with nonlinear load in figure 2.6. There is a source of sinusoidal voltage (block AC Voltage Source) feeding the load, representing by block Controlled Current Source. This block generates current depending on voltage on the input s. The relationship between load voltage $U_{load}$ and load current $I_{load}$ is nonlinear, as written in equation bellow and shown in figure 2.5.

$$I_{load} = -0,5U_{load}^3 + 2U_{load}^5 \tag{1.23}$$

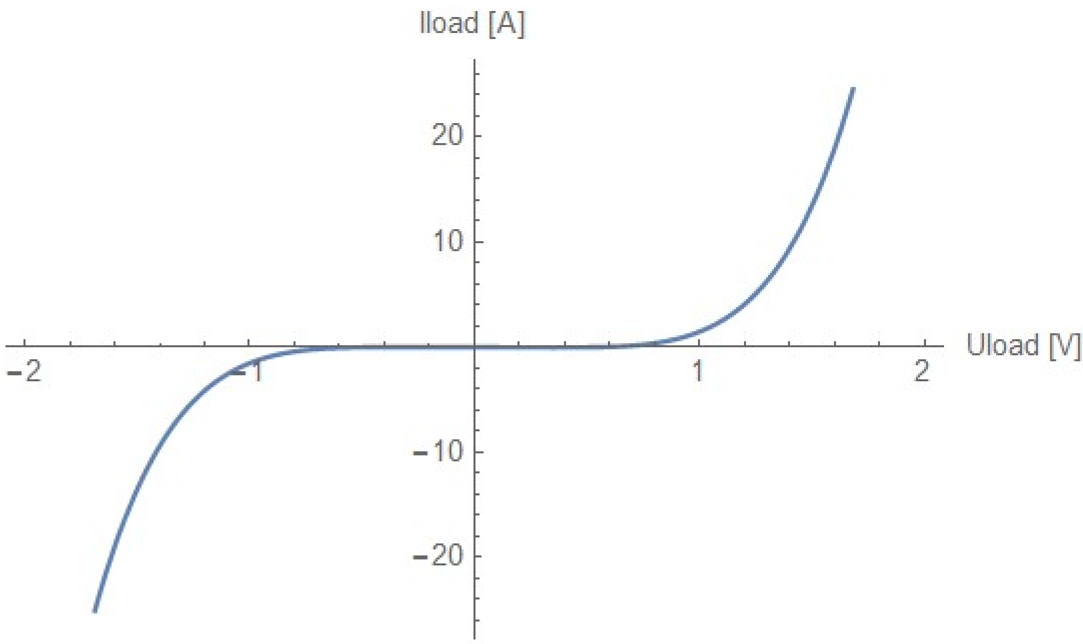



*Figure 2.5 - Nonlinear VA characteristic*

Load voltage enters the block Fcn, that computes current signal according to equation above. That signal subsequently enters block Controlled Current Source, that generates current in the model circuit.

Parameters of blocks used in model are shown in table 2.1

| | |
|---|---|
| AC Voltage Source | $U_{peak}$ = 1 V; f = 50 Hz |
| Line impedance R | R = 0,1 Ω |
| Function blodk Fcn | Expression: -0.5*u^3+2*u^5 |

*Table 2-1 - Blocks parameters*

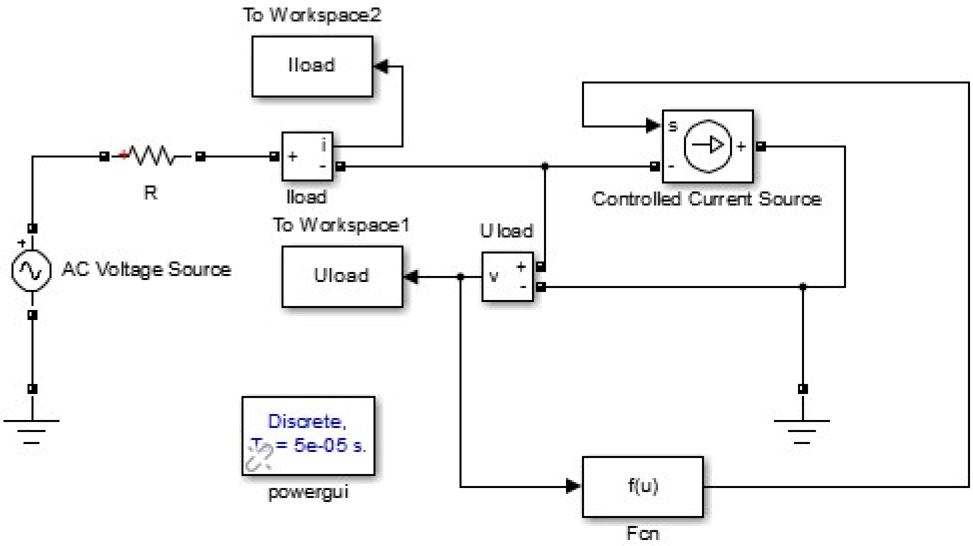



*Figure 2.6 – Model of circuit with linear load*

If we assume, that voltage $U_{load}$ is sinusoidal, and substitute variable Uload in equation 2.23 with sin(ωt), we get

$$I_{load} = 0{,}875\sin(\omega t) - 0{,}5\sin(3\omega t) + 0{,}125\sin(5\omega t) \quad (1.24)$$

As we can see, current $I_{load}$ contains three harmonic components – 1st, 3rd and 5th. That is caused because of nonlinear VA characteristic. Simulation results are shown in figure 2.7. As we can see, current waveform is distorted. Voltage waveform is distorted as well, although it is not very apparent. Voltage distortion is caused by current flowing through impedance R, which results in nonlinear voltage drop.

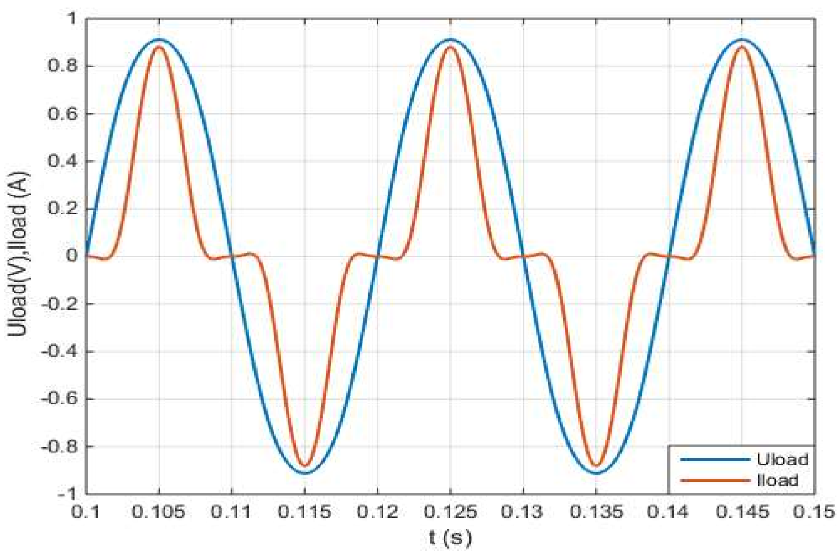



*Figure 2.7 - Load voltage and current in circuit with nonlinear load*

Spectral analysis of current and voltage is shown in figure 2.8. As we can see, 7th harmonic component appeared. This is caused because of distorted voltage waveform.

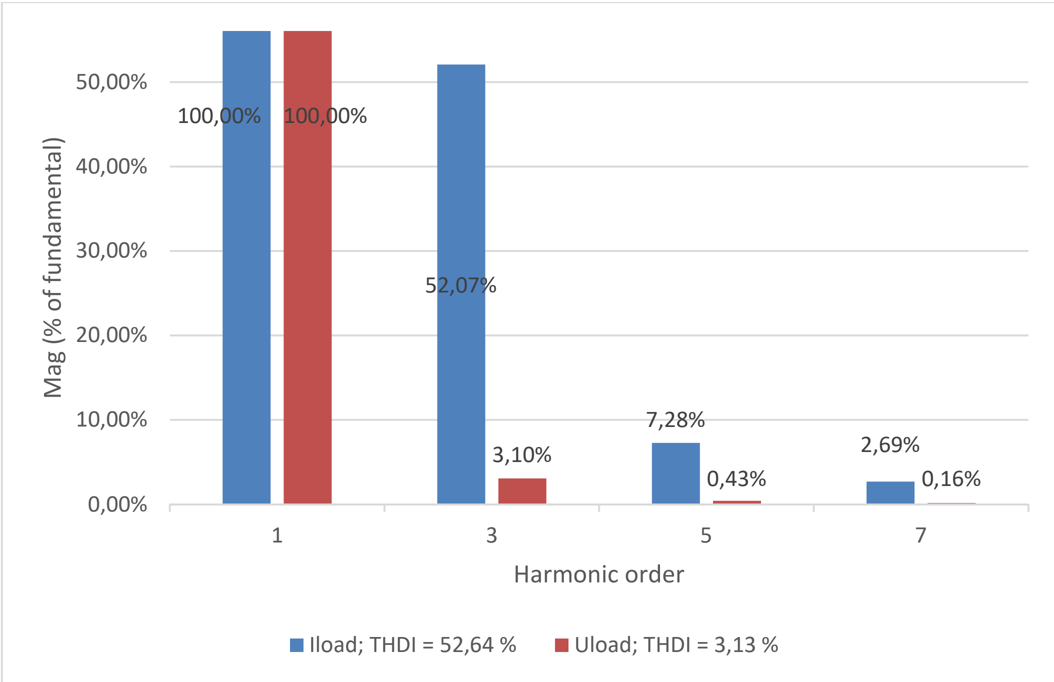



*Figure 2.8 - Spectral Analysis of current and voltage from figure 2.7*

## 2.6 Transformers

Real transformer has nonlinear magnetization characteristic, as shown in figure 2.9. If supply voltage u(t) on primary winding of transformer is sinusoidal, the flux Φ(t) will be sinusoidal as well (in steady state), as we can see in equation below

$$u(t) = \frac{d\Phi(t)}{dt} \Rightarrow \Phi(t) = \int u(t)dt = \int U_{\max} \sin(\omega t)dt = \Phi_{\max} \cos(\omega t)[\mathrm{V}] \qquad (1.25)$$

Real transformer flux-current loop and flux as a function of time are shown in figure 2.9. When the flux is zero and increasing, the instantaneous current is (1) on the hysteresis loop. When the flux is (a) and increasing, the current is (2) on the hysteresis loop. By plotting the values 1, 2, 3, 4, 5 for the current along the time axis on the flux values 0, a, b, c, d, the waveform of the current is obtained. [6]

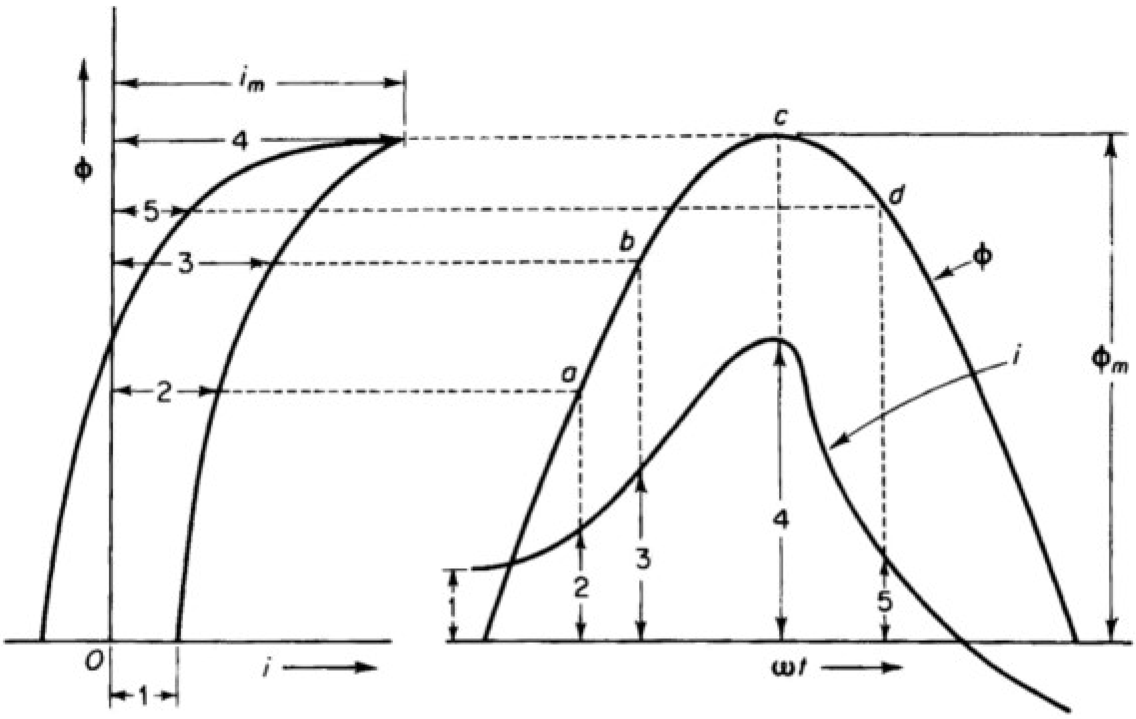



*Figure 2.9 – Origin of harmonic currents in transformer [6]*

Software Matlab Simulink allow us to make a model of a saturable transformer. Scheme of such a model is shown in figure 2.10. There is a sinusoidal voltage source, breaker, line impedance (RLC Branch) and saturable nonlinear transformer with nominal power 310 kVA. Scope records primary winding voltage and current and transformer flux. Secondary winding is disconnected. At first, we simulate a steady state operation of no-load transformer. The results are shown in figure 2.11. Model parameters are shown in table 2-2.

| | |
|---|---|
| AC Voltage Source | $U_n$ = 22 kV; f = 50 Hz |
| Line impedance | R = 0,002 Ω; L = 0,006 Ω |
| Saturable transformer T1 | $S_n$ = 310 kVA; $U_1$ = 22 kV; $U_2$ = 0,23 kV; $u_k$ = 12 %; r = 0,2 % |

*Table 2-2 – Parameters of model from figure 2.10*

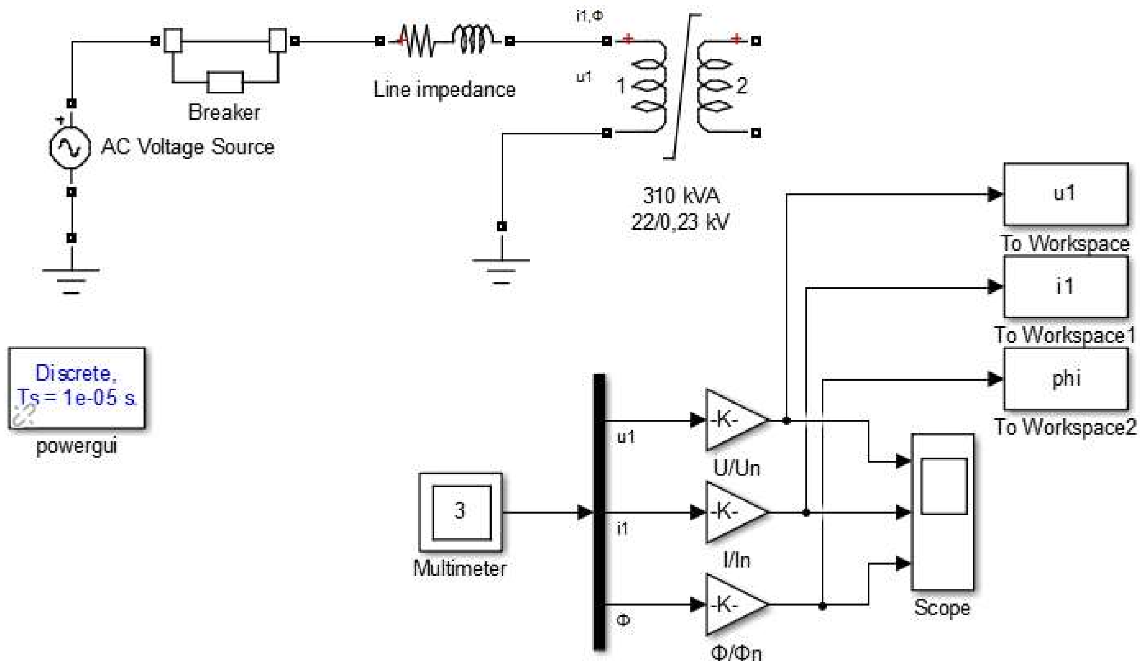



*Figure 2.10 – Model of saturable transformer*

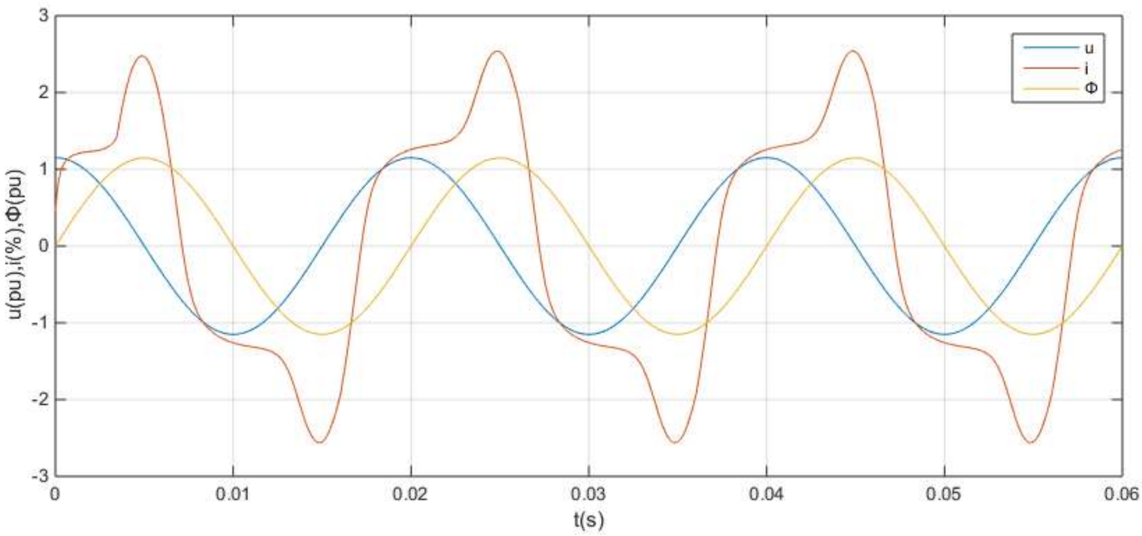



*Figure 2.11 - Transformer magnetizing current, voltage and flux under no-load conditions during steady state operation*

As we expected, current waveform is distorted, and it is similar to current waveform in figure 2.12. Spectral analysis of this current is shown in figure 2.15. We see, that current is composed from odd harmonics.

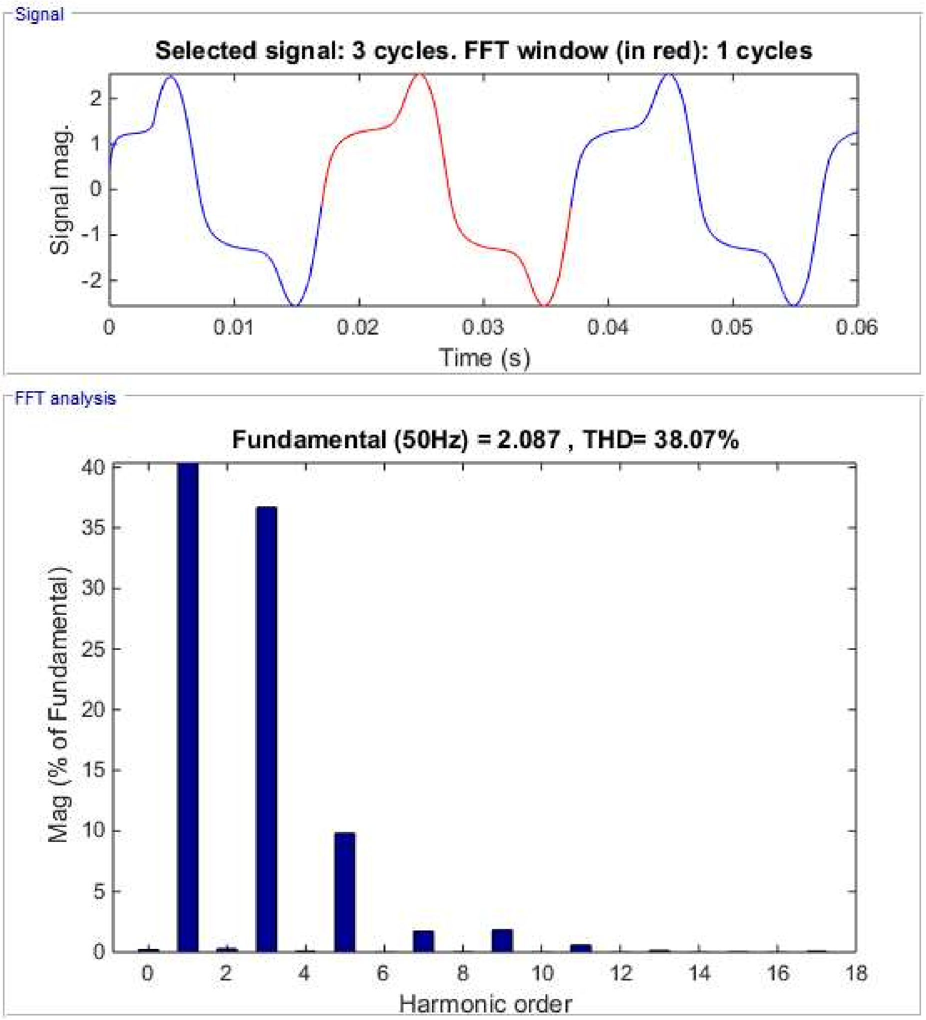



*Figure 2.12 - FFT analysis of the transformer magnetizing current during steady state operation*

Magnetizing current in steady state is very small, it is about 1% of nominal current and thus effect on grid is insignificant. Bigger impact on the grid has so called energizing current resulting from reapplication of voltage to a transformer, which has been previously deenergized. Such magnetizing current may be in some circumstances ten times bigger than rated current and can least few seconds. Assuming, that supply voltage is

$$u(t) = U_{max} \cdot \cos(\omega t + \theta)[V] \tag{1.26}$$

Magnetic flux can be expressed as

$$u(t) = U_{max} \cdot \cos(\omega t + \theta) = \frac{d\phi(t)}{dt}[V] \tag{1.27}$$

$$\phi(t) = \phi(0) + \phi_{max} \sin(\omega t + \theta) - \phi_{max} \sin(\theta)[Wb] \tag{1.28}$$

As we can see in equation 2.28, the maximum value of flux upon energization contains DC components. Magnetic core is oversaturated, which results in big energizing current, which amplitude decreases because of resistances in the circuit. We simulate transformer energizing with the same model that was used above. To simulate an effect of energizing, the breaker switches off at time 0,16 s and then reopens at time 0,2 s. Simulation results are shown in figure 2.13.

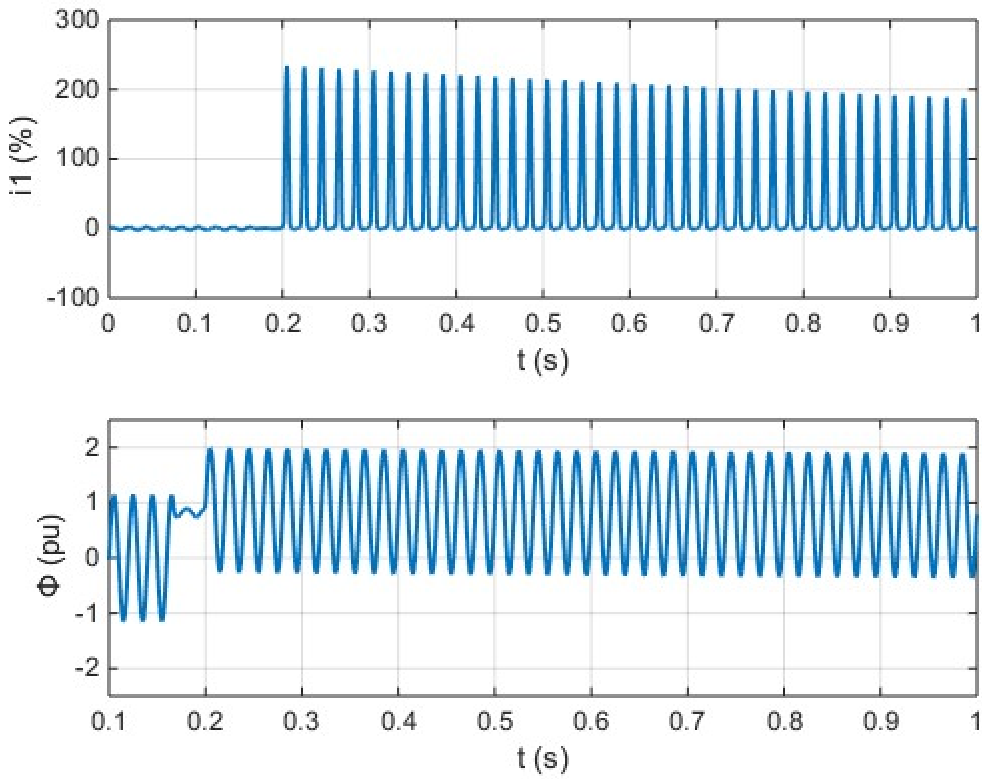



*Figure 2.13 - Energizing current and flux of transformer*

We can see in figure 2.13, that flux and current amplitude are approximately two times bigger than rated values. Also flux has DC components, that fades out with time. Spectral analysis of energizing current is shown in figure 2.14. Unlike magnetizing current during steady state operation, energizing current contains wider spectrum of harmonic currents, including odd and even harmonics. The most dominating is 2nd harmonic. There is a significant DC component as well. Harmonic currents presented during energizing process, especially 2nd harmonic, may cause incorrect work of protection devices.

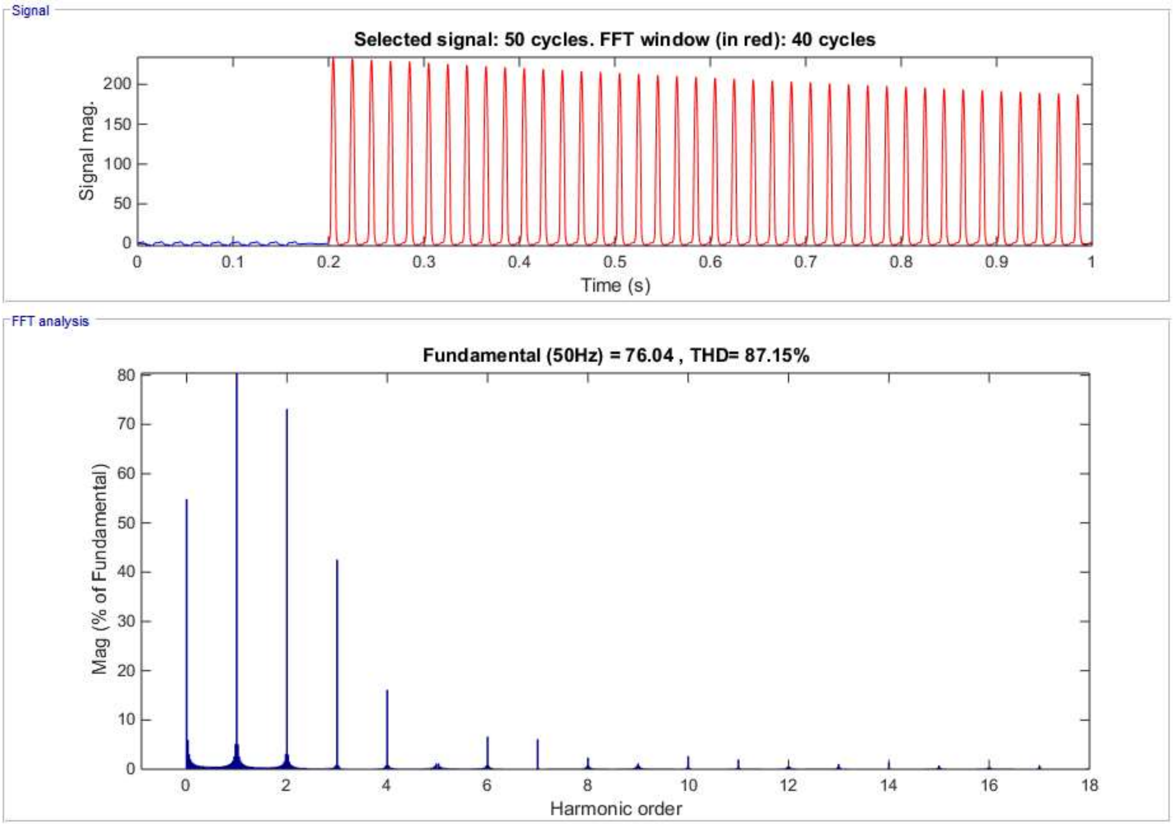



*Figure 2.14 - Spectral analysis of energizing current*

## 2.7 Power converters

Progress in semiconductor devices and microprocessor technologies caused, that power converters became inseparable part of electrical installation, whatever it is installation in big industrial plant, or installation in small commercial buildng. However, function of these devices is associated with harmonic distortion. They are the most commonly used source of harmonic currents nowadays.

Basically, power converters (from the point of view of harmonic current generation) can be divided into three groups:

- Large power converters like those used in the metal smelter industry and in HVDC transmission system. [3]
- Medium-size power converters like those used in the manufacturing industry for motor speed control and in the railway industry [3]
- Small power rectifiers used in residential entertaining devices, including TV sets and personal computers. Battery chargers are another example of small power converters. [3]

### 2.7.1 **Six pulse rectifier**

Power rectifiers are used for converting AC current to DC current. They are used virtually in all electronic equipment, either as a main device for loads needing DC current (rectifier for furnace, traction rectifier), or as an secondary device in converters for loads working on AC current The most used type of rectifier in power converters, especially in variable-frequency drives, is six-pulse rectifier.

The model of six-pulse bridge diode rectifier is shown in figure 2.15. There is a three-phase sinusoidal voltage source Three-Phase source, metering block Three-Phase V-I Measurement, DC smooth capacitor and R load. Block Measurements is used for data processing. Model parameters are shown in table XXXX

| | |
|---|---|
| Three-Phase Source | Un = 400 V; f = 50 Hz; Sk” = 10 MVA; X/R = 1 |
| C | C = 8 mF |
| R | R = 2,57 Ω ≈ 110 kW |

*Table 2-3 - Parameters of six pulse rectifier model*

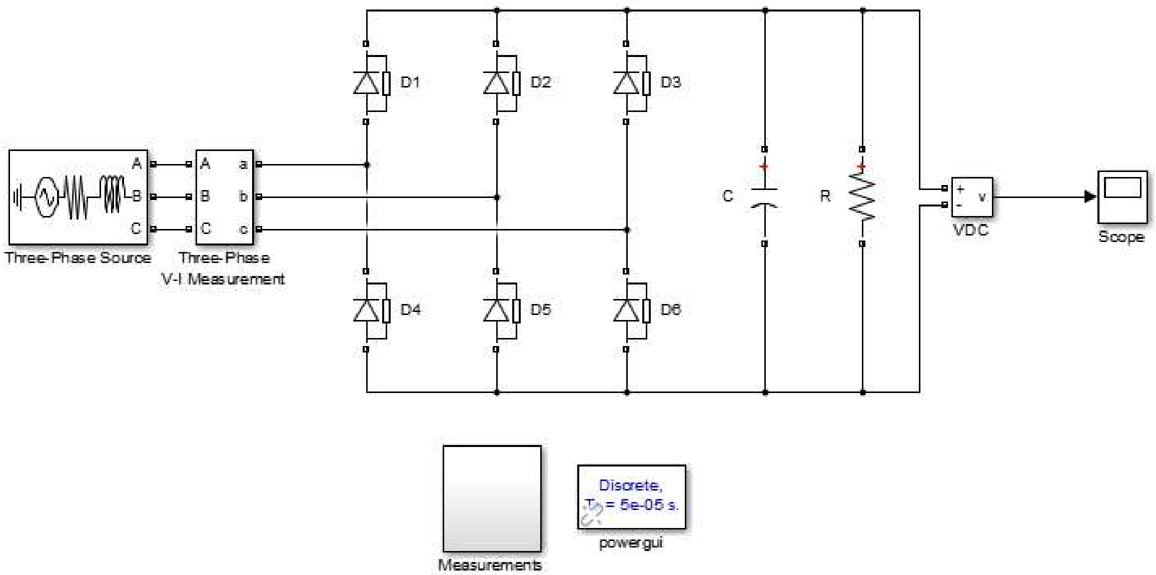



*Figure 2.15 - Model of six-pulse rectifier*

The work of this type of rectifier is described in the figure 2.16, where are the simulation results. First graph show us voltage on DC side, as well as absolute values of line to line voltages Vab and Vac. Second graph show us current through phase A and the third graph show us line to ground voltage Va. As we can see in second graph, DC capacitor is charged in relatively small periods, which caused pulse current waveform. We can say, that capacitor is charged, when relevant line to line voltage is larger than capacitor voltage. We can see in the third graph, that current waveform causes notches in supply voltage.

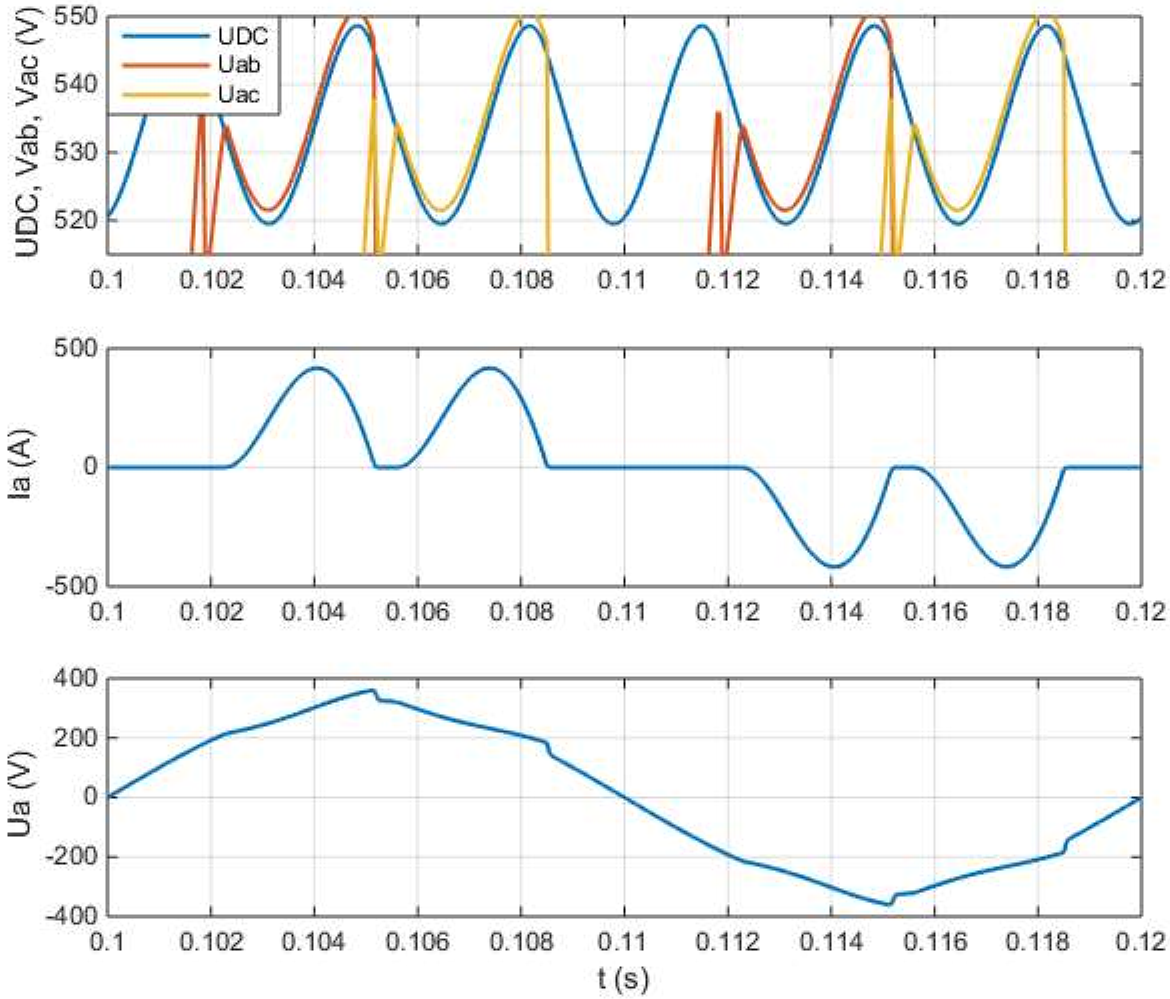



*Figure 2.16 – Simulation results of six pulse recitifier model*

Spectral analysis of phase current is shown in figure 2.17. As we can see, curent contains 5th, 7th, 11th, 13th, 17th, 19th etc. harmonic. It can be derived, that six-pulse rectifier creates harmonics with order

$$h = 6n \pm 1 \tag{1.29}$$

Where

n 0, 1, 2, 3, 4…..

h harmonic order

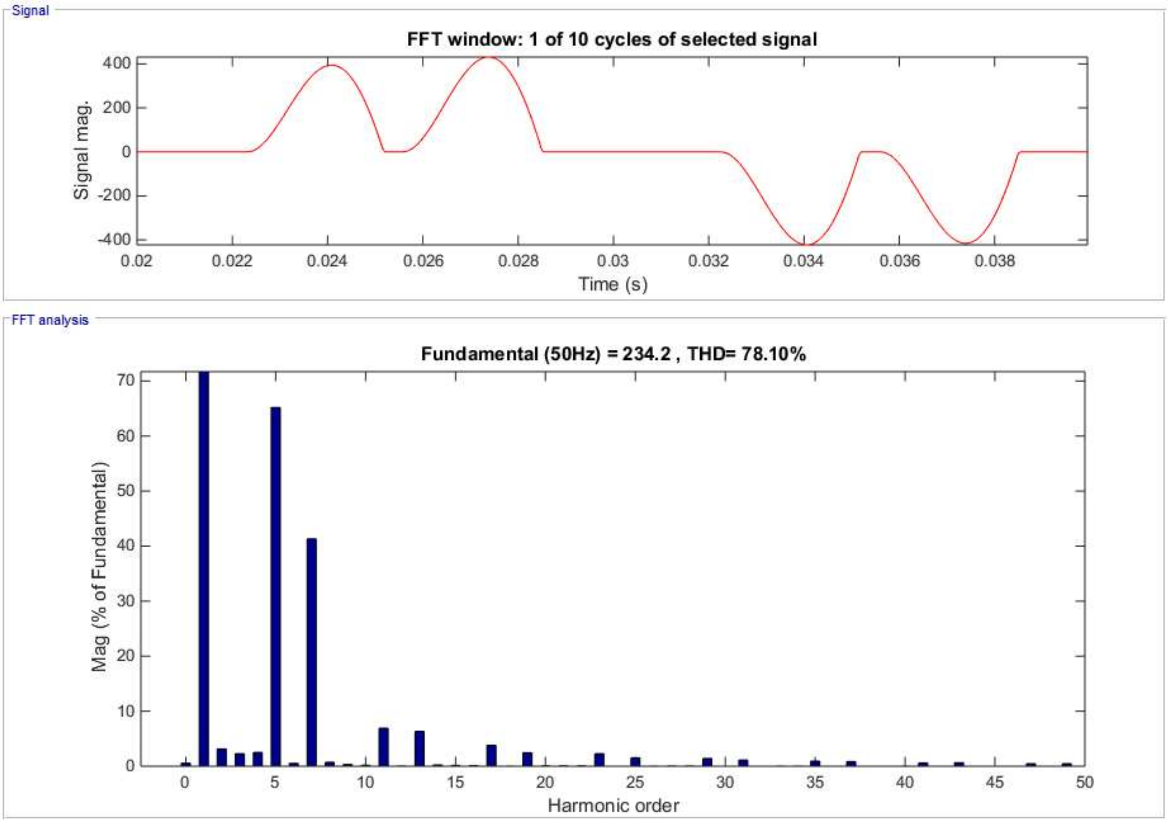



*Figure 2.17 - Spectral analysis of input current of 6 pulse rectifier*

As we can see in figure 2.17, THDI is almost 80 %, which is considerable value, especially for high power drives. For this reason, smooth AC or DC reactors are used with large power variable frequency drives (see chapter 3.2).

### 2.7.2 **Cycloconverters**

Cycloconverters are devices converting single or three-phase AC current to one or three-phase AC current with different magnitude or frequency. They convert energy directly without DC stage, contrary to variable frequency drive. Cycloconverters are usually used for high power applications, for example cement mill drives, rolling mill drives, ore grinding mills or mine winders [7]. Cycloconvertors are usually used with thyristors because of their easy commutation.

Model of six-pulse cycloconverter is shown in figure 2.18. This model is adopted from the Matlab demonstration models [8]. Model consists of three sources of sinusoidal voltage, three transformers, three blocks of thyristors and three phase load. This type of cycloconverter contains 36 thyristors overall (not including parallel and series thyristors). Block Cycloconverter control generates impulses for thyristors in each rectifier. Model parameters are shown in table 2-4.

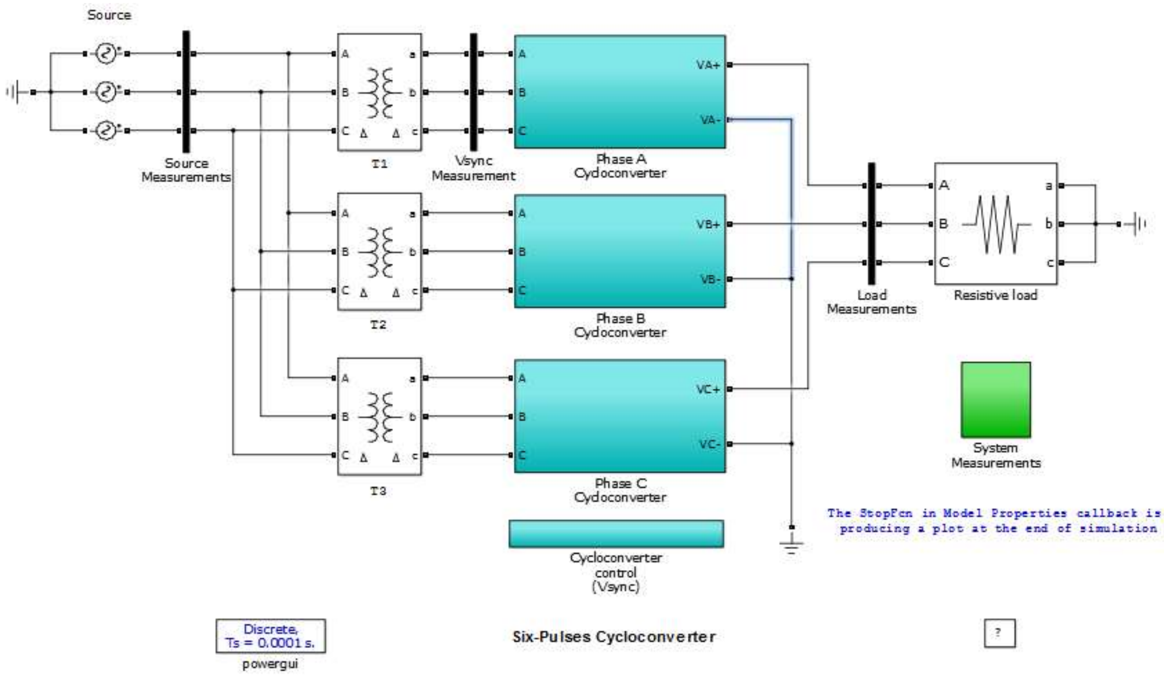



*Figure 2.18 - Six-pulse cycloconverter model[8]*

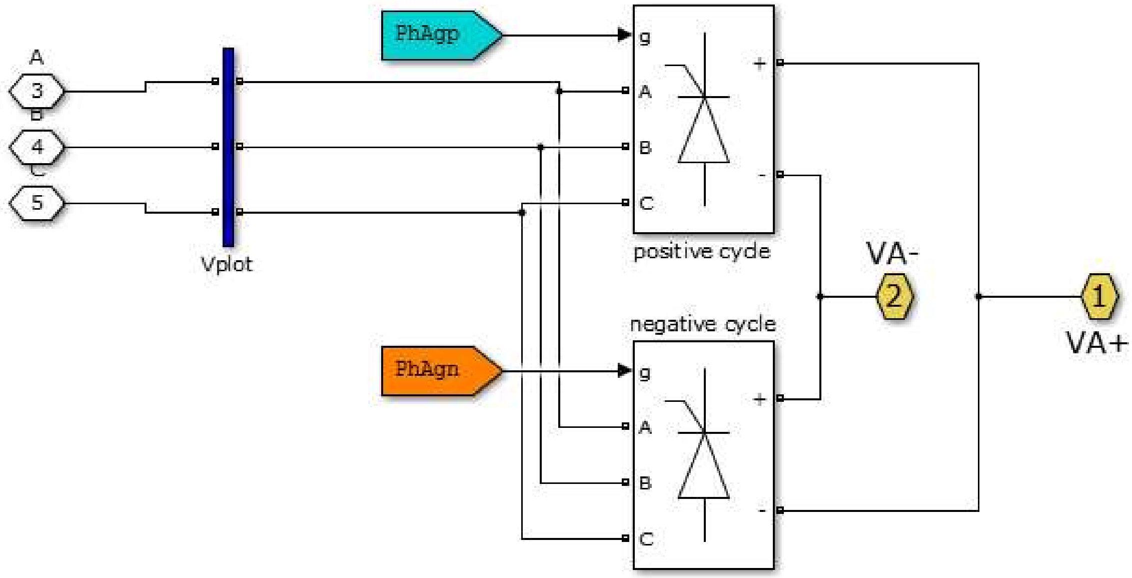



*Figure 2.19 - Phase A Cycloconverter block from figure 2.17*

| | |
|---|---|
| Source | $U_n$ = 3x6600 V; 60 Hz |
| T1, T2, T3 | $S_n$ = 3 MVA; $U_1$ = 6600 V; $U_2$ = 6600 V; r = 1e-8 |
| Resistive load | R = 10 Ω |

*Table 2-4 - Parameters of model of cycloconverter*

Simulation results are shown in figure 2.20. Input current, output currents and output voltages are displayed here. Output frequency is set on 6,5 Hz and output voltage is set on 6600 V (RMS). Thyristors are switching in a specific way in order to reach less distorted output voltage waveform. Firing angle is not constant. It is clear, that input current in such a case is much distorted and contains wide spectrum of harmonic currents. Spectral analysis of input current is shown in figure 2.21.

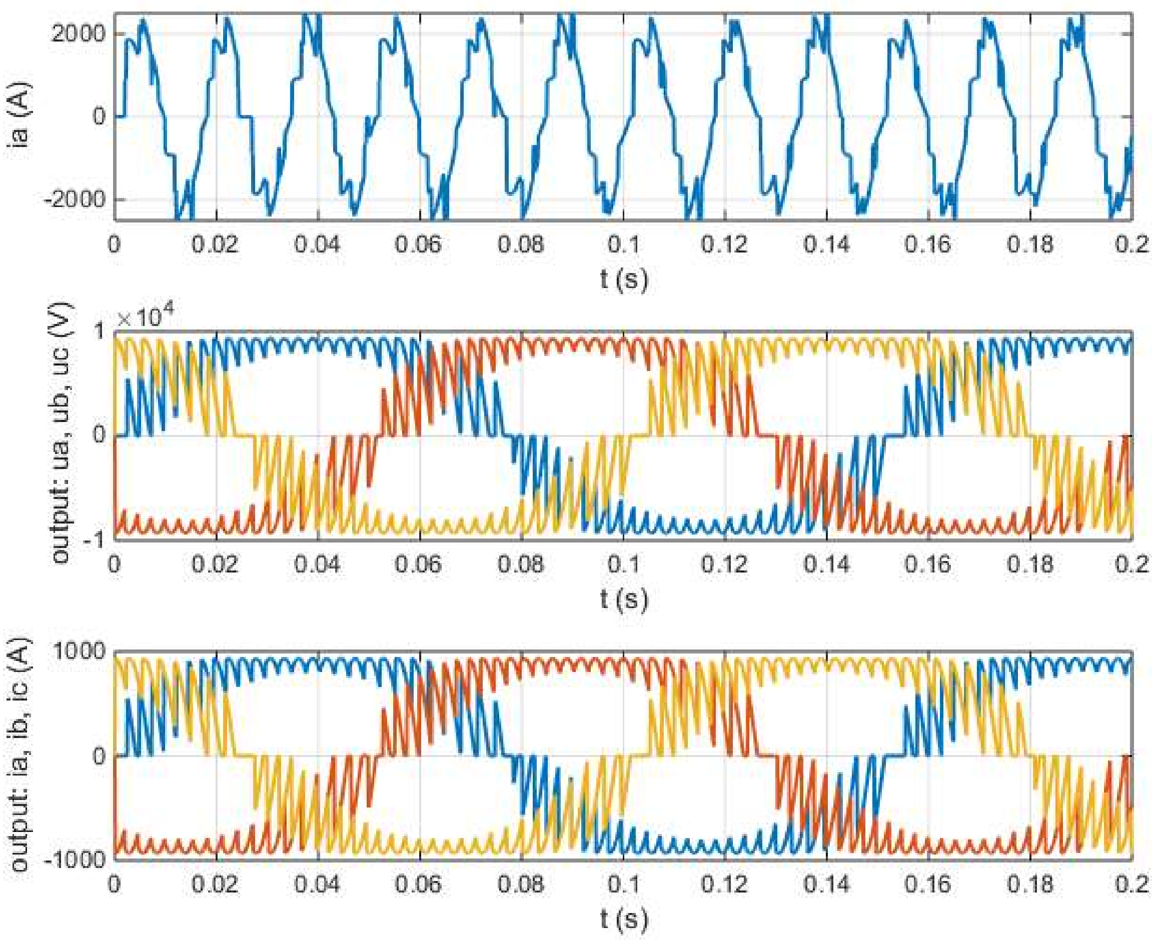



*Figure 2.20 – Input current in phase a, output currents and output voltages in cycloconverter*

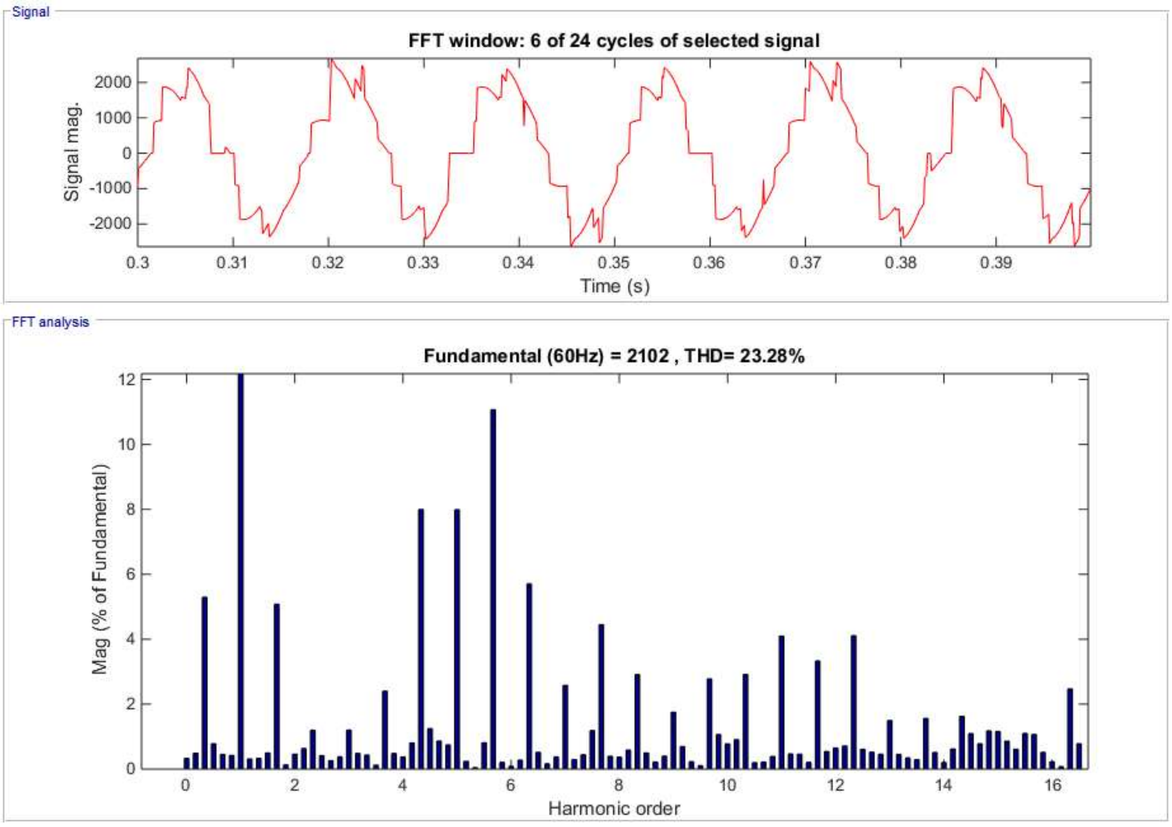



*Figure 2.21 - Spectral analysis of input current in cycloconverter*

Spectral analysis shows us, that spectrum of input current is very wide. DC component, subharmonic, interhamonic and harmonic currents are present. Cycloconverters are the most important sources of inteharmonic currents. Their impact is very significant, because they are usually used for high power applications.

Harmonic spectrum of cycloconverter can be calculated from equation (according to ČSN EN 61000-2-4)

$$h_{h,m} = \left(p_1 k_1 \pm 1\right) f \pm p_2 k_2 F \tag{1.30}$$

Where

| | |
|---|---|
| $h_{h,m}$ | Harmonic and interhamonic components |
| $p_1$, $p_2$ | Number of input/output pulses |
| $k_1$, $k_2$ | integers (0, 1, 2, 3, 4….) |

### 2.7.3 Switched-mode power supplies

A switched-mode power supply is device converting usually AC current to DC current. They are used basically in all small loads working on DC supply, such as personal computers, mobile phone chargers etc. The basic schematic of such a power supply is shown in figure 2.22.

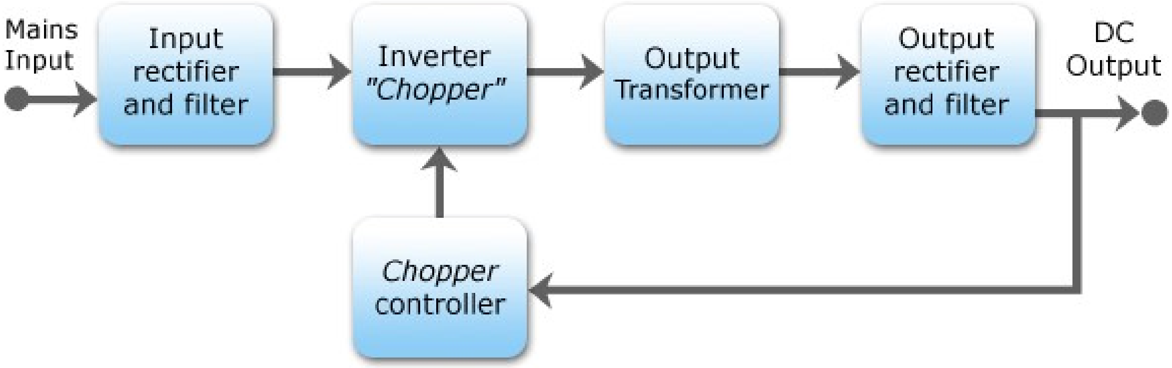



*Figure 2.22 - Block diagram of mains operated AC/DC switched-mode power supply with output voltage regulation [9]*

Input rectifier is the most important part important from the point of view of harmonic current production. Bridge rectifier is usually used with output capacitor ensuring smoother DC output voltage. Model of such a rectifier is shown in figure 2.23. There is sinusoidal voltage source U1, bridge rectifier containing diodes D1-D4, LC DC capacitor, and resistive load.

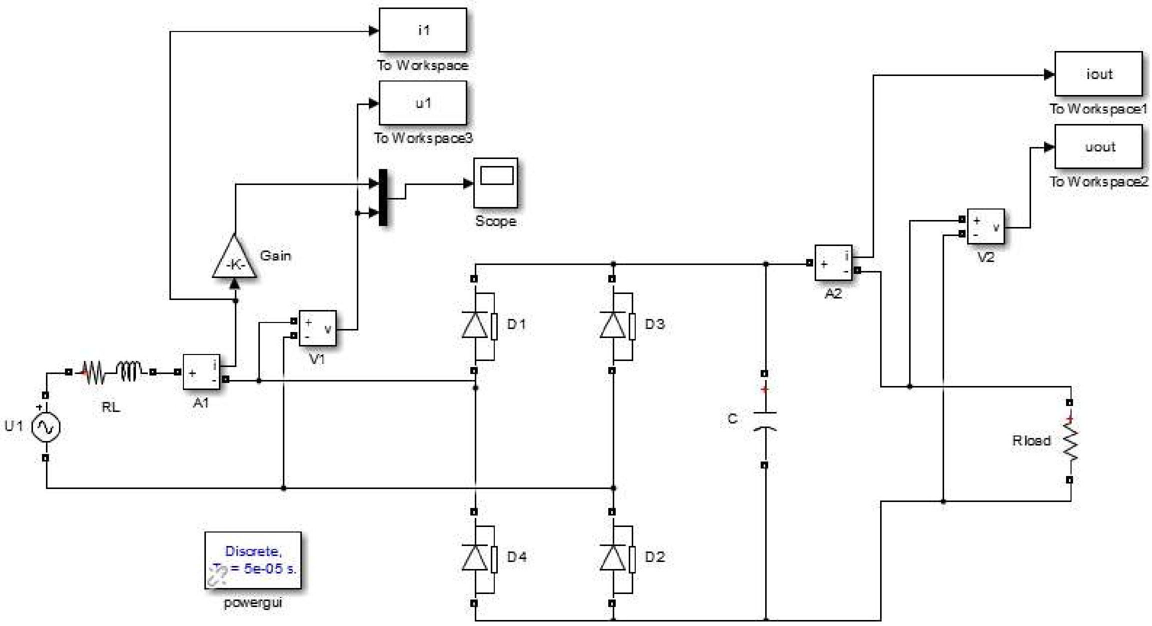



*Figure 2.23 – Model of bridge rectifier*

Model parameters:

| | |
|---|---|
| U1 | $U_n$ = 230*sqrt(2) V; f = 50 Hz |
| RL | R = 1 Ω; L = 6e-3 H |
| C | C = 300 μF |
| Rload | 3 kΩ |

*Table 2-5 – Parameters of model of bridge rectifier*

Input voltage, input current and output DC voltage in this rectifier are shown in figure 2.24. As we can see, there are current peaks, caused by charging a capacitor. Capacitor is charged in time t1 and it is discharged in time t2.

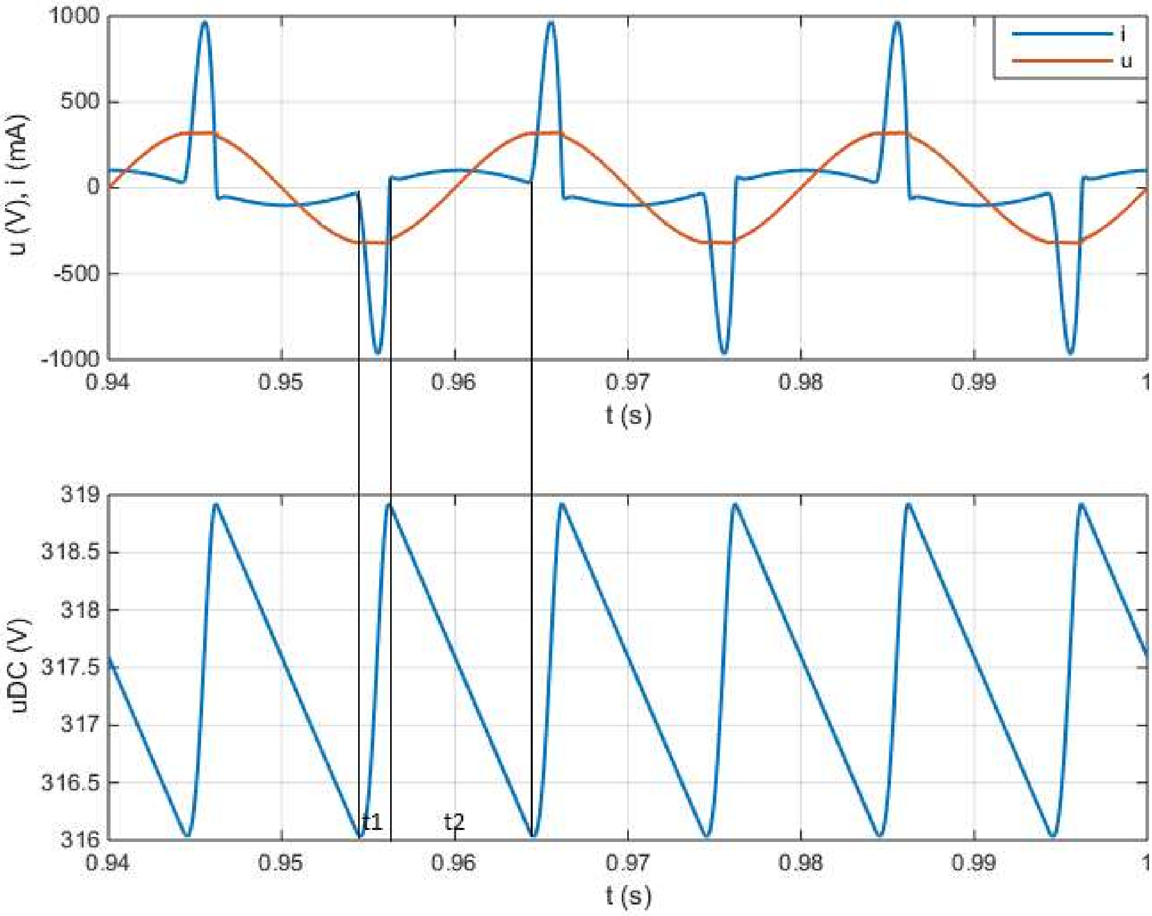



*Figure 2.24 - Input current and voltage and output voltage in bridge one-phase rectifier*

Spectral analyis of input current is shown in figure 2.25. Current contains only odd harmonics. THDI is about 150 %, which is considerably value. However, we have to say, that switched-mode power supplies usually contains input EMC filter, that reduces THDI. Nevertheless, even with input EMC filter, switched-mode power supplies are significant sources of harmonic currents. They presents problem particularly in large office buildings, where big amount of personal computers and lights equipped with switched-mode power supply is situated. Also, as said in chapter 2.4, third order harmonics are zero sequence, thus, there is danger of neutral conductor overloading.

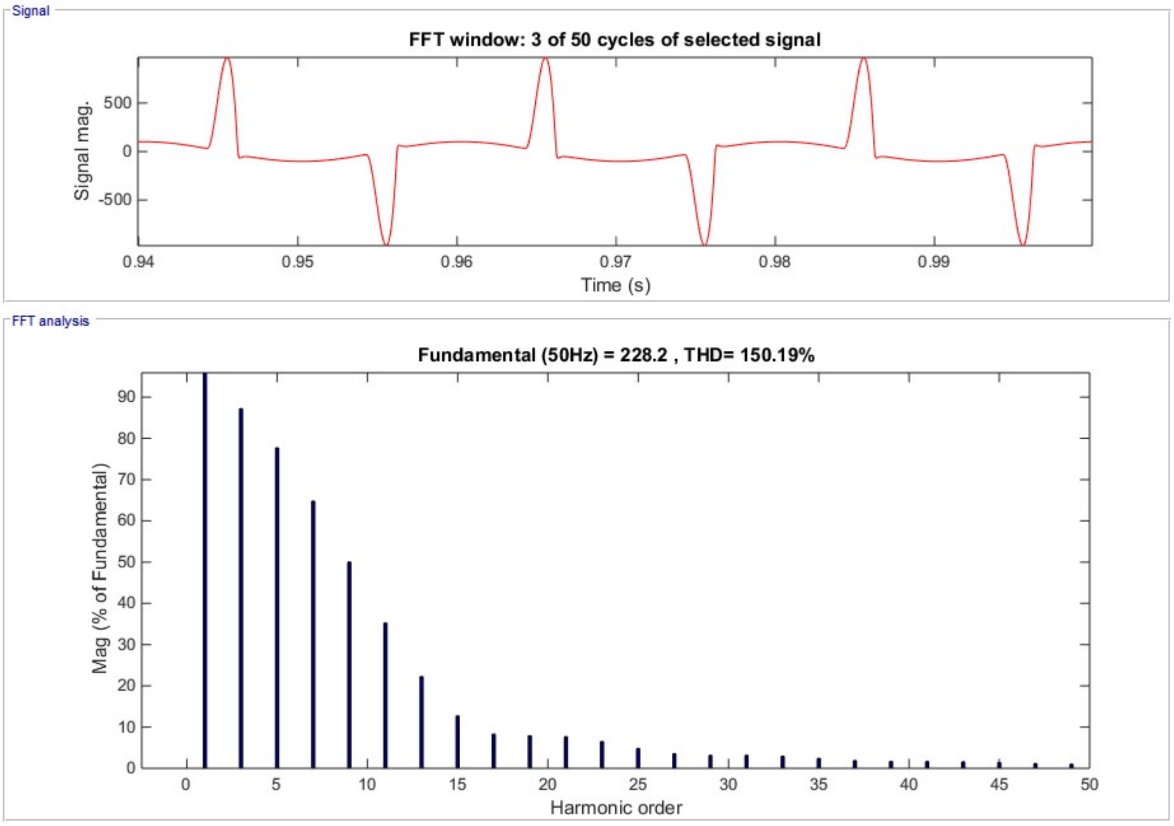



*Figure 2.25 – FFT analysis of input current in bridge rectifier*

## 2.8 Arc furnaces

Arc furnaces are relatively commonly used appliances for melting of steel. These furnaces melt steel by applying an AC current to a steel scrap charge by means of graphite electrodes. The melting process involves the use of large quantities of energy in a short time (1-2h) and in some instances the process causes disturbances in power grids. These disturbances have usually been characterized as “flicker” – brief irregularities in voltage a fraction of the 50 Hz cycle in length, and harmonic currents. [10]

Voltage-current characteristic of electric arc is shown in figure 2.26. Characteristic is nonlinear, asymmetrical and also hysteresis occurs there. Since length of arc in arc furnace varies with time, VI characteristic, that depends on arc length varies as well.

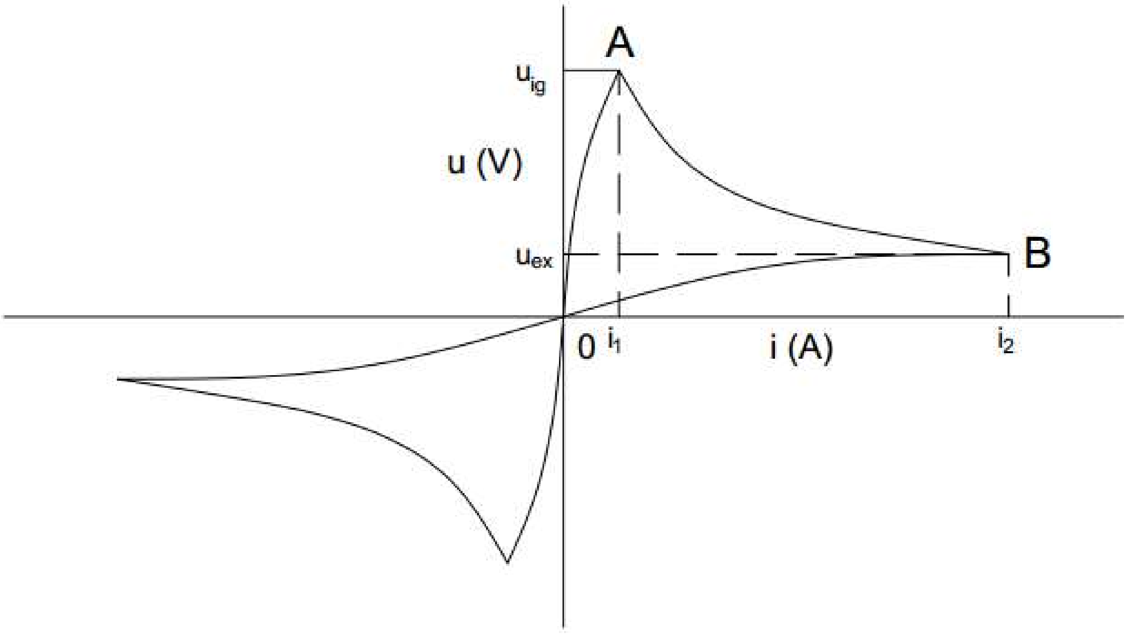



*Figure 2.26 – Electric arc VI characteristic*

In the first period, the arc begins to reignite from extinction. In the second period, the arc is established and the voltage drops from $u_{ig}$ to $u_{ex}$, the electrical conductivity of the arc (AB path) increases. During the third part, the arc begins to extinguish. The arc voltage continues to drop smoothly (B-0 path). [11]

Typical steelmaking phases are [12]:

- arc ignition period (start of power supply)
- boring period
- molten metal formation period
- main melting period
- meltdown period
- meltdown heating period

Arc impedance and length vary during these phases. This causes that current and voltage RMS values will vary with time as well, as shown in figure 2.27.

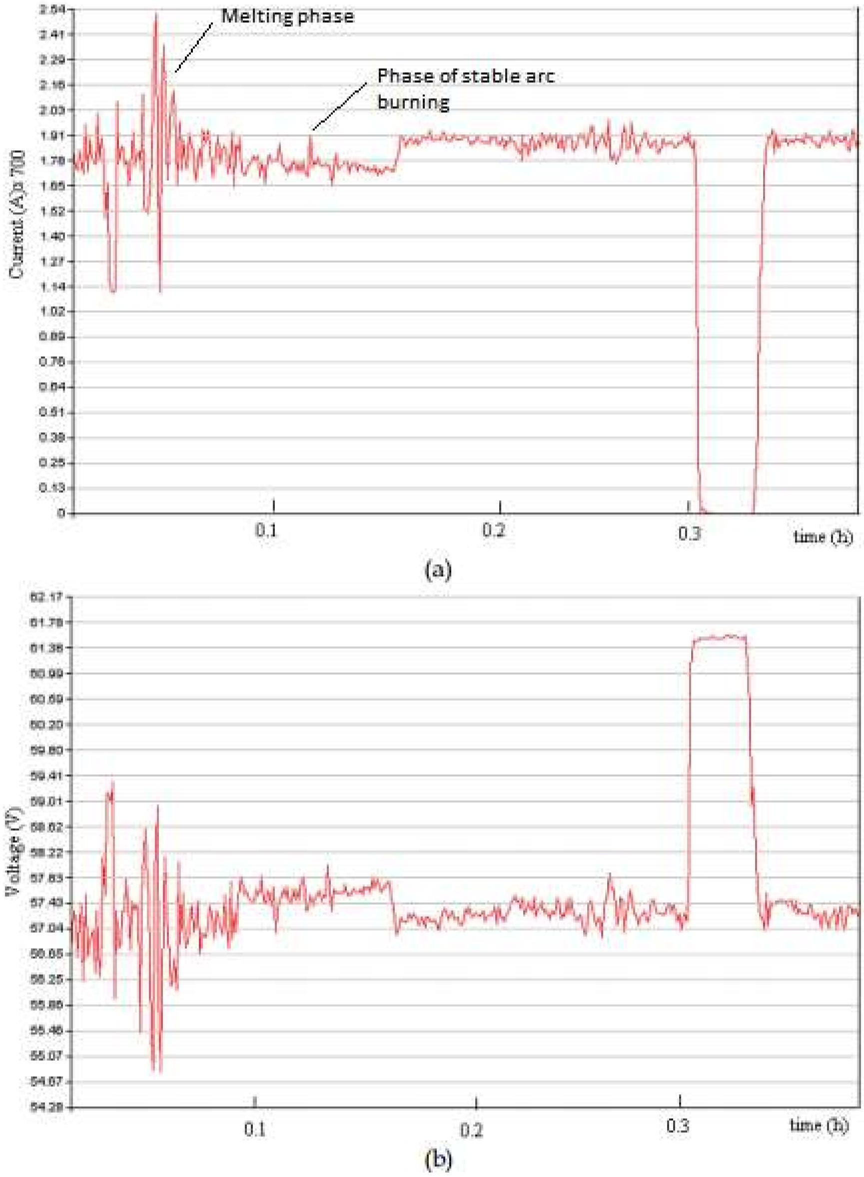



*Figure 2.27 - The real measurements for a technological cycle of electric arc furnace: a) current b) voltage [12]*

We can see, that in stable arc burning phase the electrical quantities are more reduced, than in melting phase. [13] It is clear, that THDI will also be greater in melting phase, as shown in figure 2.28. THDI in melting phase is more than two times bigger than THDI in stable arc burning. Current contains wide spectrum of harmonic currents, both odd and even as well as interharmonics.

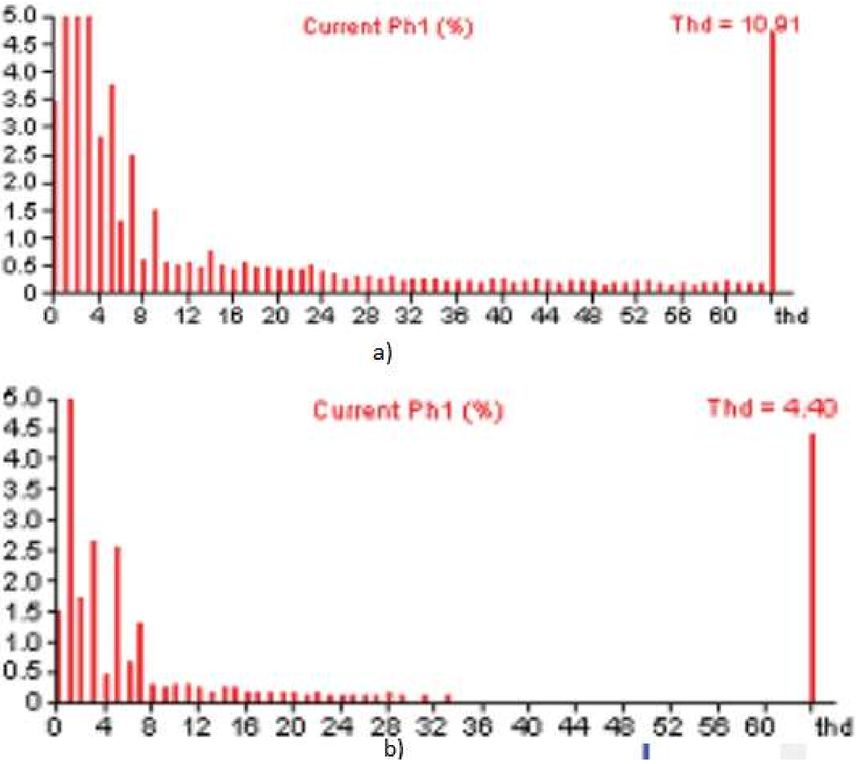



*Figure 2.28 - Current THD in melting phase and stable arc burning [12]*

Variation of THDI and THDU with time is shown in figure 2.29. THDI fluctuates between 7% and 30% in melting phase.

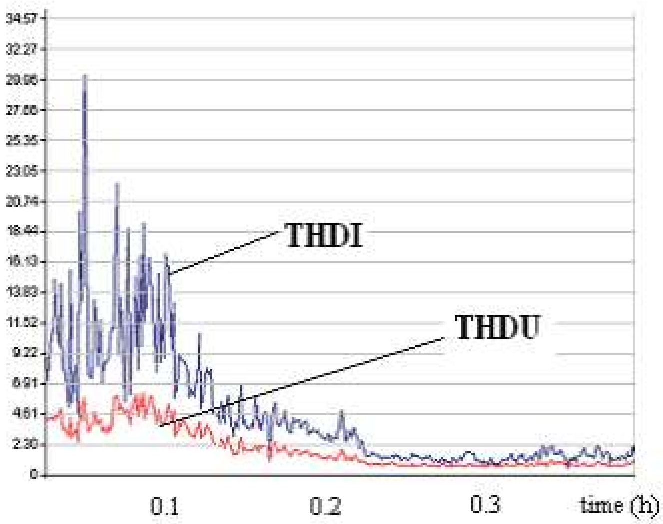



*Figure 2.29 –Arc furnace THDI and THDU variation with time [12]*

## 2.9 Fluorescent lamps

A fluorescent lamp or a fluorescent tube is a low pressure mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light. An electric current in the gas excites mercury vapor which produces short-wave ultraviolet light that then causes a phosphor coating on the inside of the lamp to glow. [13] Fluorescent lamps are used with electric or magnetic ballast, as shown in figure 2.30.

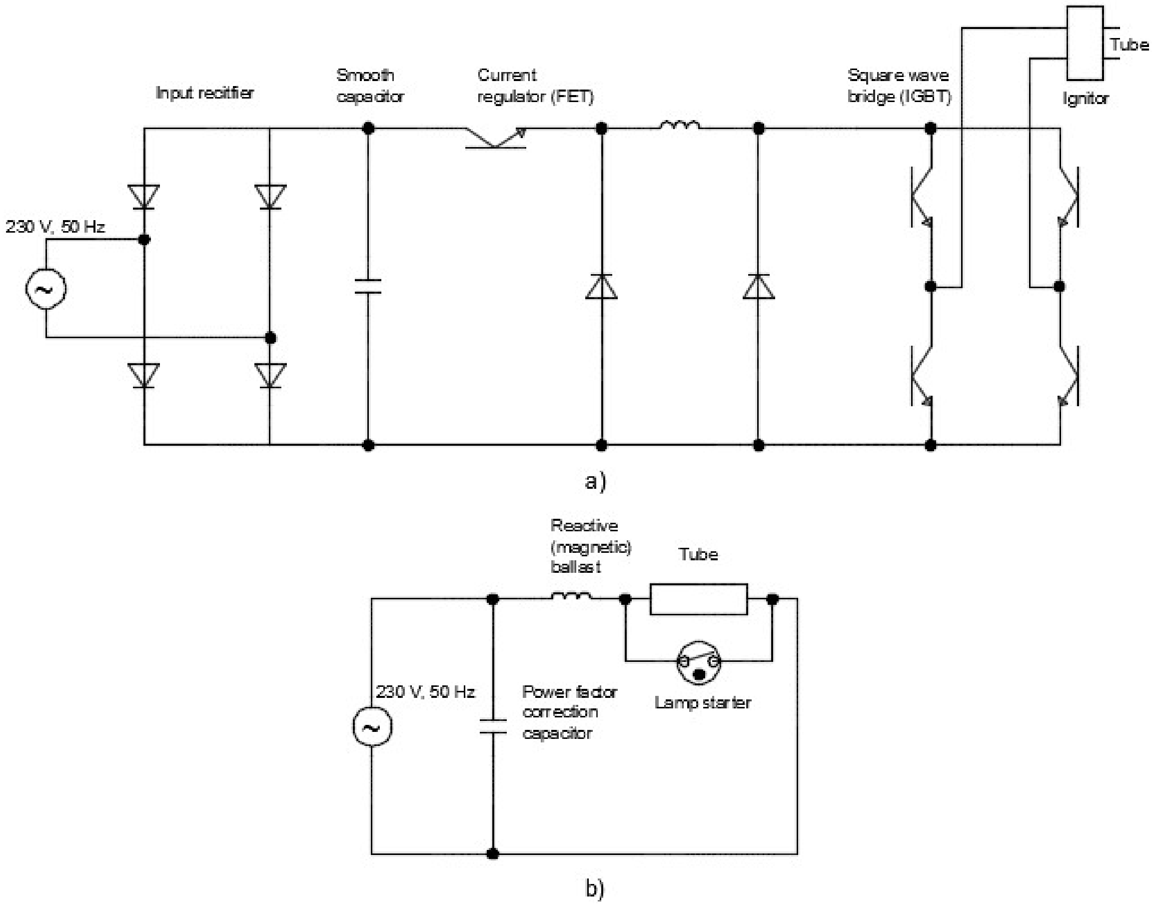



*Figure 2.30 – Fluorescent lamp with electric (a) [14] and magnetic (b) balast*

When using a lamp with magnetic ballast, harmonic currents are generated because of nonlinear VI characteristic of tube. Input phase current and input voltage in lamp with magnetic ballast is shown in figure 2.31. We can see lamp generates only odd harmonics with the most significant third and fifth order harmonics. THD is about 13 %.

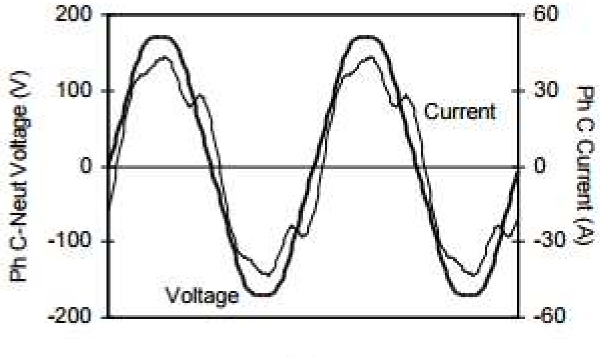



*Figure 2.31 - Input phase current and input voltage in fluorescent lamp with magnetic ballast [16]*

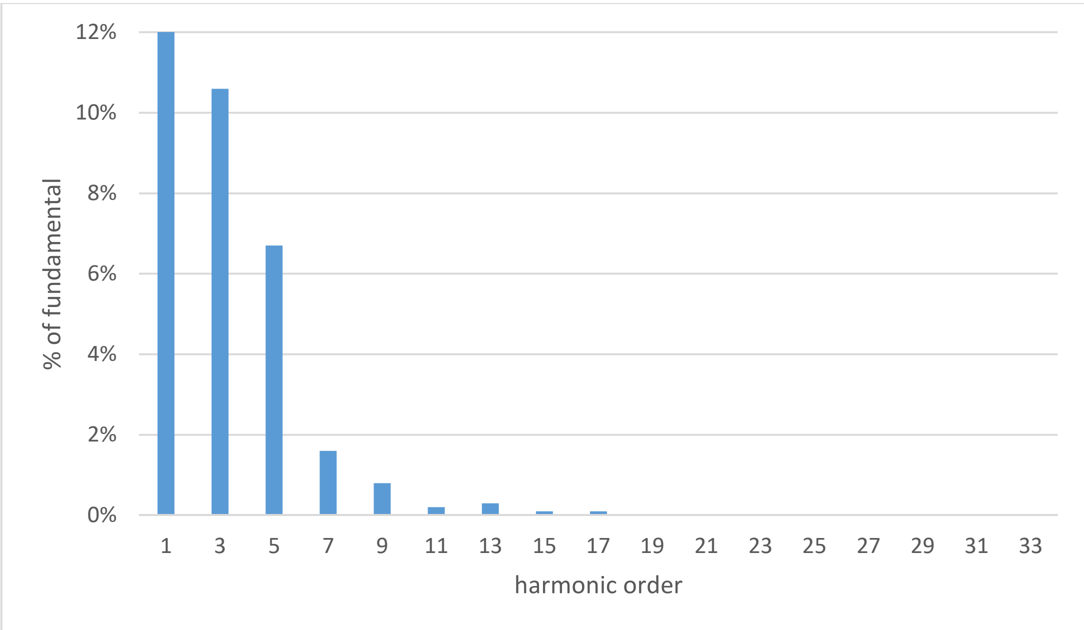



*Figure 2.32 - Harmonic spectrum of input phase current in fluorescent lamp with magnetic ballast (15)*

When using a lamp with electric ballast, an input rectifier is the main harmonic currents source. Since the most used rectifier is bridge with output filter, current harmonic spectrum will be very similar to this in switch-mode power supply, shown in figure 2.24 and it will contain only odd harmonics. Input phase current waveform in fluorescent lamp with electric ballast is shown in figure 2.33. THDI is 133,3 %, which is much larger than typical THDI of lamp with magnetic ballast.

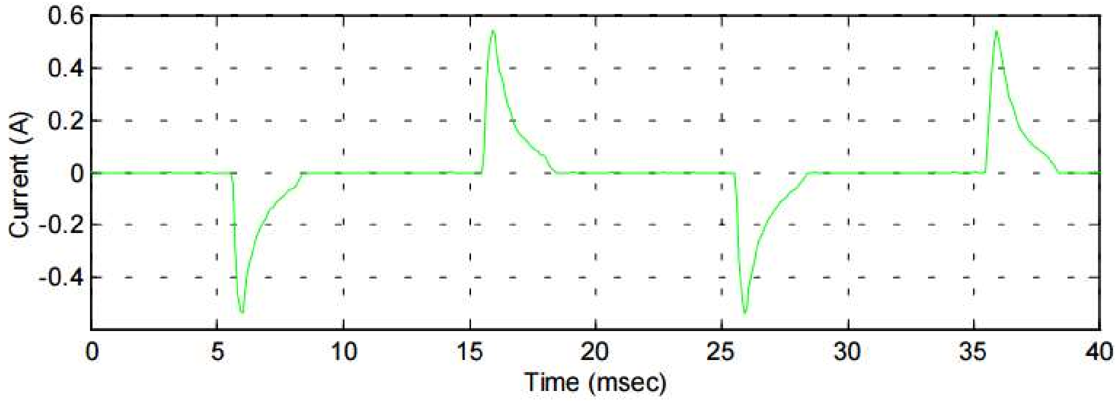



*Figure 2.33 - Input phase current in fluorescent lamp with electric ballast [16]*

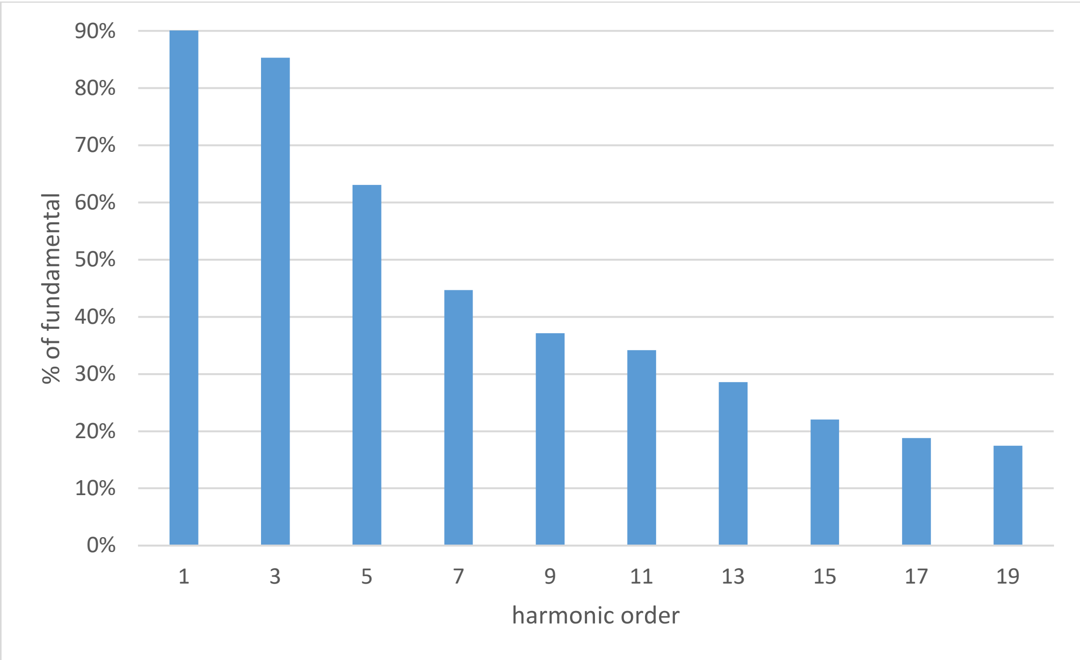



*Figure 2.34 - Harmonic spectrum of input phase current in fluorescent lamp with electric ballast [16]*

In three-phase systems that have a neutral conductor and a large number of single phase fluorescent lamps, the neutral conductor will carry a large percentage of each of the three phase conductors' current even under balanced load conditions. This is because fluorescent lamps draw a current which has a significant amount of triplen harmonics (3rd, 9th, 15th, etc.) Triplen harmonics are zero sequence harmonics which add in the neutral instead of canceling like positive sequence (1st, 7th, 13th, etc.) and negative sequence (5th, 11th, 17th, etc.). [15]

## 2.10 Main effects of harmonic currents

Harmonic currents cause many problems in electrical grid. Practically, there are three main ways they affect the electrical grid:

- Reactances in electrical grid may comprise parallel or series resonance circuit, which resonance frequency can equal to frequency of one of the harmonic currents, generated by non-linear loads. This leads to overvoltage and overcurrent, which can be dangerous for electrical equipment.
- Harmonic currents and voltages cause additional losses, which can lead to oversize an equipment and shortens the lifetime
- Distorted voltage waveform can cause dysfunction of sensitive loads and devices

### 2.10.1 **Capacitors**

*2.10.1.1 Overstressing*

Capacitor reactance decrease with frequency and the bank, therefore, acts as a sink for higher harmonic currents. This effect increase the heating and dielectric stresses. According to IEC 60831-1 standard ("Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1 000 V – Part 1: General – Performance, testing and rating – Safety requirements – Guide for installation"), the r.m.s. current flowing in the capacitors must not exceed 1.3 times the rated current. [17]

*2.10.1.2 Resonance*

A typical simplified scheme of industrial plant electrical grid is shown in figure 2.35 a, and its equivalent circuit is shown in figure 2.35 b. There is transformer, represented by reactance $X_T$ and resistance $R_T$, linear loads with reactance $X_{LIN}$ and resistance $R_{LIN}$ and PF correction capacitor with reactance $X_C$ and non-linear loads, that represent harmonic current source i(t). As reactance of linear loads is big compared to transformer reactance, we can ignore it. Also line impedances are neglected.

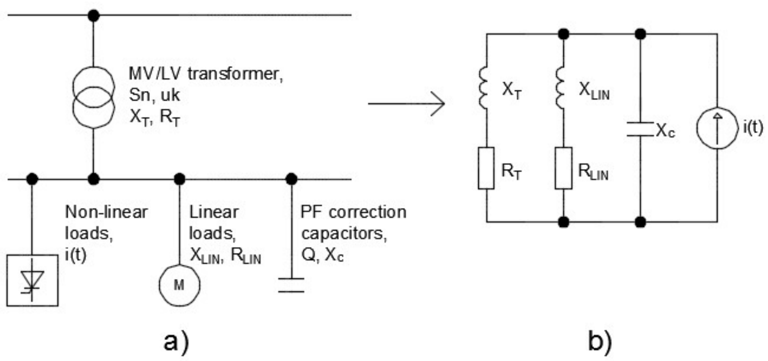



*Figure 2.35 – Simplified scheme of typical industrial plant installation (a) and its equivalent curcuit (b)*

When no PF correction capacitors are connected, harmonic currents flows toward the transformator, as its impedance is much lower than other loads impedance. However, if we connect PF correction capacitor, parallel RLC circuit will arise. The order $h_r$ of the natural resonant frequency between the system inductance and the capacitor bank is

$$h_r = \sqrt{\frac{Ssc}{Q}} \tag{1.31}$$

Where

| | |
|---|---|
| $S_{sc}$ | Short circuit power at the point of connection of the capacitor |
| Q | Capacitor bank rating |

For example, if we consider parameters $S_n$ = 1000 kVA; $u_k$ = 6 %; Q = 350 kVAr, we get

$$h_r = \sqrt{\frac{S_{sc}}{Q}} = \sqrt{\frac{\frac{S_n}{u_k}}{Q}} = \sqrt{\frac{\frac{1000}{0,06}}{350}} = 6,9 \tag{1.32}$$

Thus, resonant frequency is $f_{res} = h_r.f_{fund}$ = 6,9.50 = 345 Hz. As this frequency is very close to the 7th harmonic frequency 350 Hz, which is one of the most frequent harmonic in electric installations, condition very similar to resonance may set in. Impedance of parallel RLC increase dramatically in this case, as shown in figure 2.36 and harmonic voltage is increased dramatically as well. This is very dangerous for PF correction capacitors, and they will very likely not be able to withstand high harmonic current circulating between the capacitors and the distribution transformer. In addition, series resonance may occur, for example, when non-linear load is supplied from medium voltage busbars. Nevertheless, this is less common scenario.

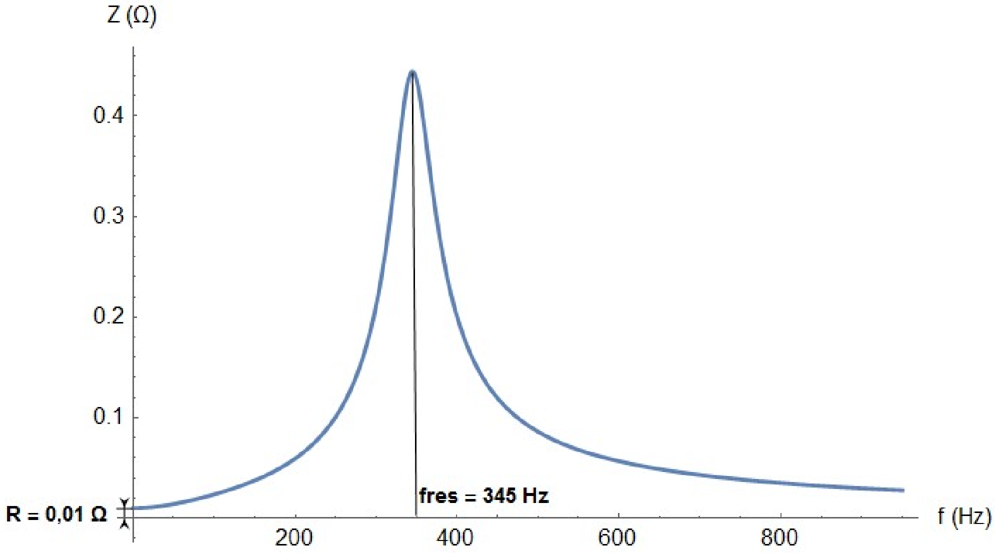


*Figure 2.36 - Frequency characteristic of the impedance of the circuit in figure 2.35*

Important indicator is percentage of non-linear loads, calculate by the formula

$$N_{LL(\%)} = \frac{Power\ of\ non-linear\ loads}{Power\ of\ transformer} \quad (1.33)$$

The higher the $N_{LL(\%)}$ value, the higher probability of resonance origin.

It is clear, that we have to take measures to prevent such a undesirable phenomenon. The possible solutions are:

- Using oversized capacitors with increased rated current and voltage.
- Using detuned reactors - reactors and capacitors are configured in a series resonant circuit, tuned so that the series resonant frequency is below the lowest harmonic frequency present in the system. The tuning frequency can be expressed by the relative impedance of the reactor (in %, relative to the capacitor impedance), or by the tuning order, or directly in Hz. The most common values of relative impedance are 5.7, 7 and 14 % (14 % is used with high level of 3rd harmonic voltages). [17]

### 2.10.2 **Conductors**

*2.10.2.1 Losses in conductors*

Energy is transferred from source to non-linear load by fundamental component $I_1$ of the current. However, r.m.s. value of current is bigger than the fundamental $I_1$ because of harmonic components, which is shown in equation 2.34

$$THDI = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1^2}} \cdot 100\% = \sqrt{\frac{I_{r.m.s}^2 - I_1^2}{I_1^2}} \cdot 100\% \Rightarrow I_{r.m.s} = I_1 \sqrt{\left(\frac{THDI}{100}\right)^2 + 1} [\%] \quad (1.34)$$

The increase in r.m.s current depending on THDI is shown in figure 2.37. There are also shown Joule losses, proportional to square of current value. If THDI is 100%, Joule losses increase twice in comparison when no harmonic currents are present. Skin effect and proximity effect are not taken into account there, but they also participate in conductor losses increase.

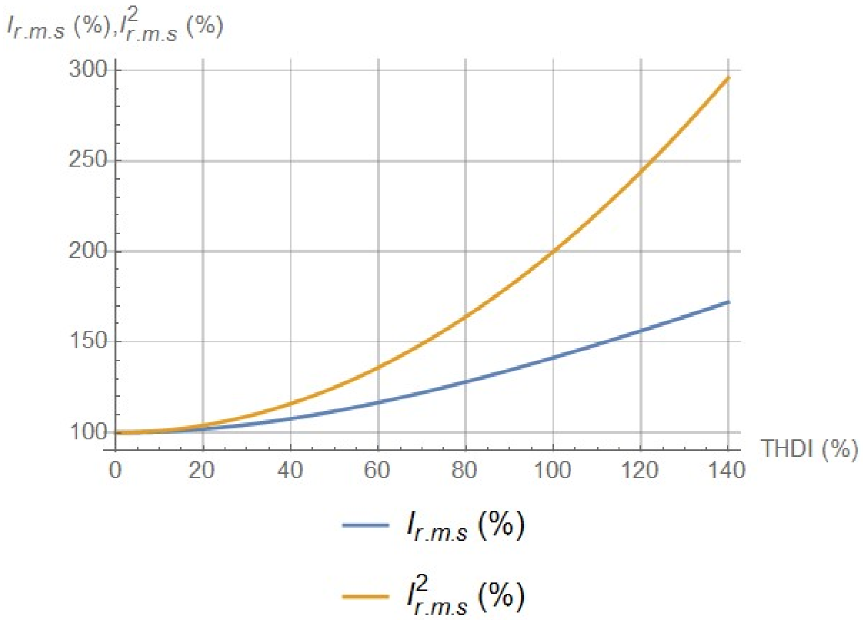



*Figure 2.37 - $I_{r.m.s.}$ and $I^2_{r.m.s}$ vs THD*

*2.10.2.2 Neutral conductor overloading*

As said in chapter 2.4, tripplen harmonic currents are zero sequence, which means, that they add in phase in the neutral conductor, even when system is balanced. This can cause neutral conductor overheating. The main source of tripplen harmonics may be, for example, office building with large numbers of personal computers or fluorescent lamps.

### 2.10.3 **Rotating machines**

*2.10.3.1 Additional losses in induction motors*

Additional losses in induction motors under distorted voltage waveform are caused by induction harmonic currents to the rotor. This increase iron and cooper losses, which lead to overheating. For example, when THDU is equal to 10%, additional losses are 6%. [17]

*2.10.3.2 Overload of generators*

Generators supplying non-linear loads must be derated due to the additional losses caused by harmonic currents. The level of derating is approximately 10% for a generator where the overall load is made up of 30% of non-linear loads. It is therefore necessary to oversize the generator, in order to supply the same active power to loads. [17]

*2.10.3.3 Overload of induction motors*

Standard IEC60034-1 ("Rotating electrical machines – Rating and performance") defines a weighted harmonic factor (Harmonic voltage factor) for which the equation and maximum value are provided below.[17]

$$HVF = \sqrt{\sum_{h=2}^{13} \frac{U_h}{h^2}} \leq 0,02 \qquad (1.35)$$

If HVF is greater than 0.02, machine must be derated.

*2.10.3.4 Pulsating torques in rotating machines*

Magnetomotive forces (mmf) induced by positive and negative sequence harmonics interact with the nominal frequency mmf force creating torque components of different frequencies. This may lead to problems on the shaft of rotating machines subject to the influence of harmonic torsional pairs including equipment fatigue, unexplained operation of mechanical fuses (bolts used to bond together turbine and generator shafts) and bearing wear out.

*2.10.3.5 Effect of distorted voltage on generator[3]*

Distorted voltage imposes the following consequences in the operation of generator:

- Production of positive and negative sequence current contributions that generate torsional torques and vibration mode shapes on the motor axis. The thermodynamic forces created in the rotor can prematurely wear out shaft bearings.
- Voltage waveform distortion on the supply circuit to the excitation system; this can produce voltage regulation problems.
- Excessive negative sequence currents; these can contribute to increased voltage unbalance.

### 2.10.4 **Transformers**

*2.10.4.1 Thermal effect on transformers*

Losses in transformers are increased in two ways. Harmonic currents cause an increase in Joule lossees (cooper losses) and iron losses (due to eddy currents). Harmonic voltages increase iron losses due to hysteresis. It leads to larger heating, compared with pure sinusoidal conditions. In utility distribution transformers, losses increase between 10 and 15%. [17]

*2.10.4.2 Transformer overloading*

As said above, total power factor depends on THDI, and it is small under high-distorted current. So we can not use full power capacity of transformer, because it has to carry harmonic currents, that do not transfer active power. The curve shown in figure 2.38 shows the typical derating required for transformer supplying electronic loads. [17]

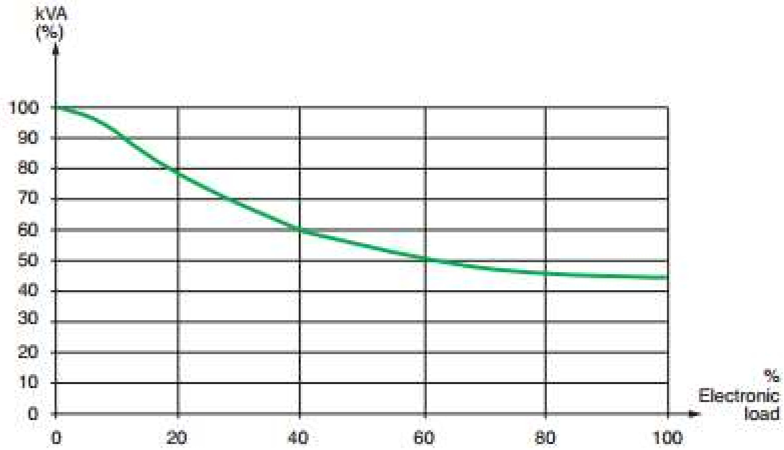


*Figure 2.38 - Derating required for a transformer suplying electronic loads [17]*

### 2.10.5 Lightning devices

Frequency components that are a noninteger multiple of the fundamental frequency, also called subharmonics or interharmonics, are prone to excite voltage oscillations that lead to light flickering. [3] Power-line flicker is a visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply. The voltage drop is generated over the source impedance of the grid by the changing load current of an equipment or facility. These fluctuations in time generate flicker. The effects can range from disturbance to epileptic attacks of photosensitive persons. [18] The main sources of subharmonic currents are cycloconverters and arc furnaces.

### 2.10.6 Uninterruptible power systems (UPS)

The current drawn by computer systems has a very high crest factor. A UPS sized taking into account exclusively the r.m.s. current may not be capable of supplying the necessary peak current and may be overloaded. [17]

### 2.10.7 Sensitive loads

Distortion of the supply voltage can disturb the operation of sensitive loads as a regulation devices, computer hardware and control or monitoring devices. [17] Harmonic currents can also cause distortion of telephone signals.

# 3 Harmonic currents mitigation and filtering

As described in previous chapter, harmonic currents cause many problems in electrical grid. For this reason, we have to mitigate them, if excced permissible limits. There are many ways to do it. Some methods just reduce the effect of the harmonic currents but do not eliminate them – this can by do by means of positioning, grouping or separating of non-linear loads. These methods are simple, but usually they are not sufficient when harmonic currents exceed the maximum permitted limits. Very effective solution to eliminate some orders of harmonic currents may be using transformers with various winding connections – for example, broadly used is Y/Y/D transformer, where tertiary D winding prevents tripplen harmonic currents from their propagation. Passive series or shunt filters are the most common solution, because of their costs. These filters can be substitute by more effective and expensive active filters, using inverter to compensate harmonic currents. The other solution using electronic circuits is active front-end rectifier.

## 3.1 Topology solutions to mitigate harmonic currents effect

### 3.1.1 **Position of non-linear loads**

Harmonic currents cause voltage drop, which leads to THDU increase. It is clear, that the greater value of impedance, represented by short-circuit power $S_k$”, the greater the voltage drop. Therefore, in order to minimize THDU, it is suitable to install non-linear loads to the point with as great short-circuit power as possible. Such place can be near MV/LV transformer in the main switchgear.

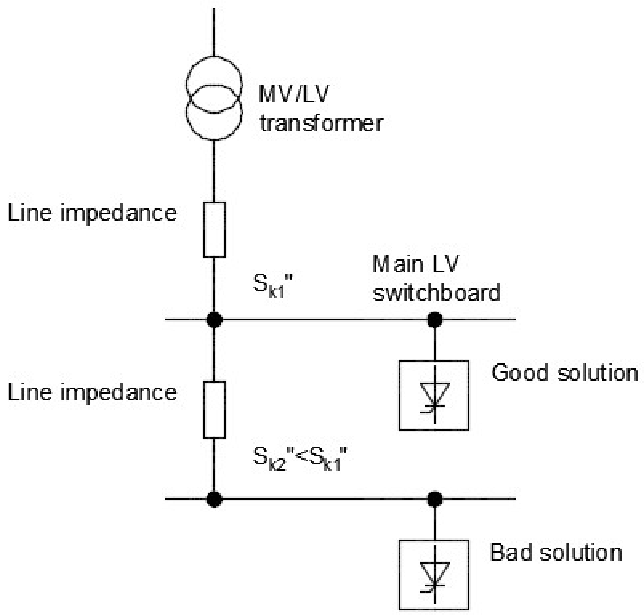



*Figure 3.1 – Recommended layout for non-linear loads, positioned as far upstream as possible*

### 3.1.2 **Non-linear loads within the separated group**

This solution consist in separating non-linear loads from other loads, which are sensitive to distorted voltage waveform. In this case, harmonic currents generated by non-linear loads basically do not affect voltage waveform in point, where other loads are connected, as the line impedance between MV/LV transformer and main LV switchgear is very small.

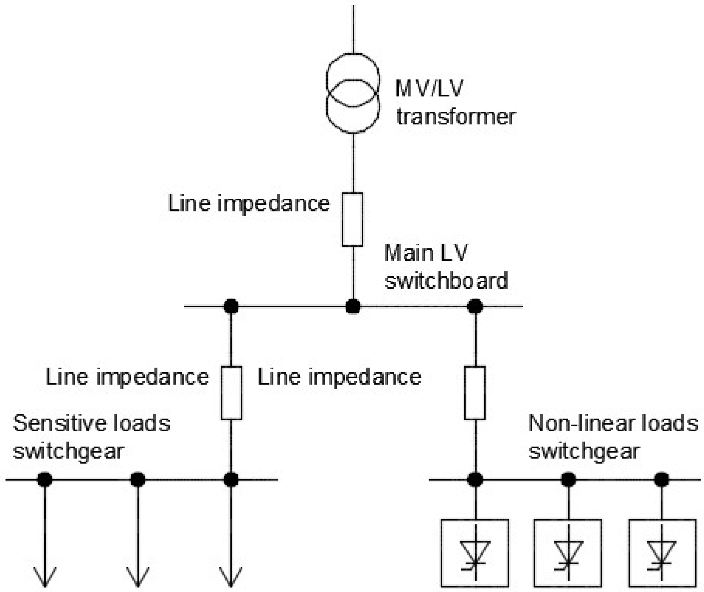



*Figure 3.2 - Separation (grouping) of non-linear loads*

### 3.1.3 **Separate sources**

The best scheme solution is to supply non-linear loads by separate transformer, as shown in figure 3.3. However, this method is very expensive, in comparison with previous two solutions.

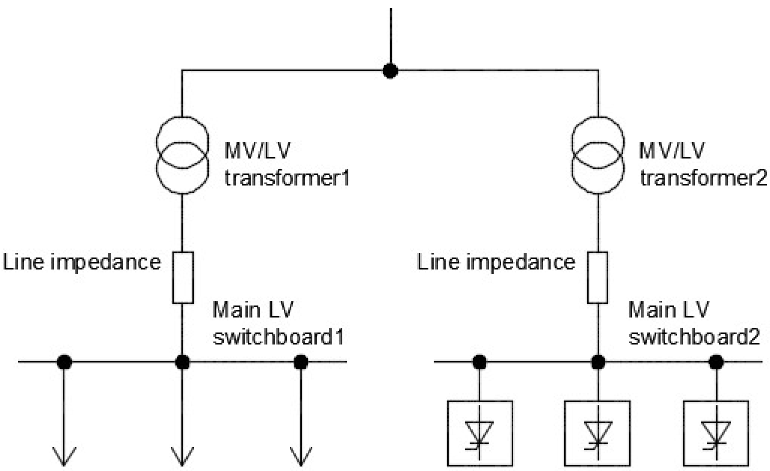



*Figure 3.3 - Using a separate transfomer to mitigate effects of harmonic currents*

## 3.2 Series reactors

Series reactors are usually used with VFDs. Inductance of reactor represents a harmonic currents attenuator – harmonic currents are limited because of its impedance. Reactor can be placed at input AC circuit or at output DC circuit. They can be combined as well. Look at the figure 3.4. There is absolutely the same model of six-pulse rectifier with the same parameters, as in the figure 2.17, but we will simulate it with input reactor and with input and DC reactor. Inductance of input reactor is 0,11 mH and inductance of DC reactor is 0,3 mH. Input currents are shown in figure 3.5. As we can see, current is smoother with input reactor. Effect is bigger when both of reactors are used. Spectral analysis is shown in figure 3.6. THDI decrease from value 78 % to value about 40 % with input reactor and to 30 % with input and DC reactor. Current peaks are reduced as well.

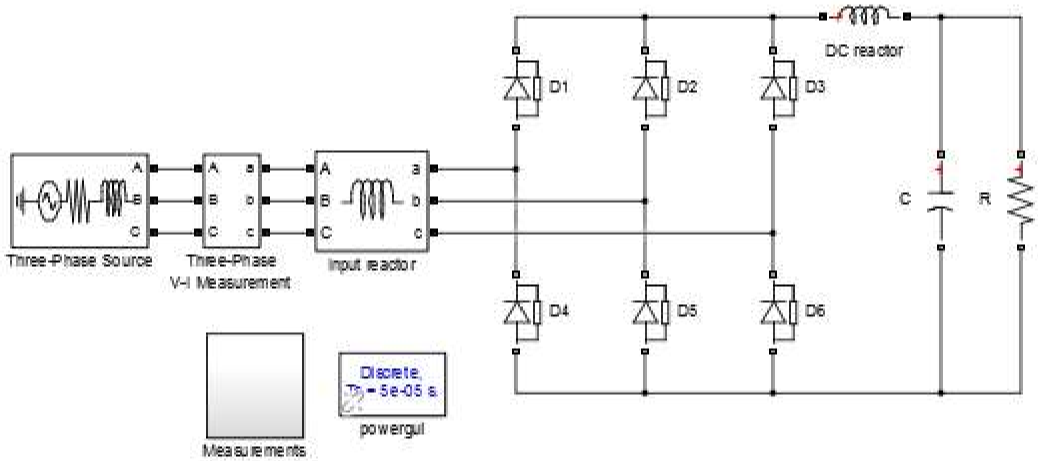



*Figure 3.4 - Six-pulse rectifier with input and DC reactor*

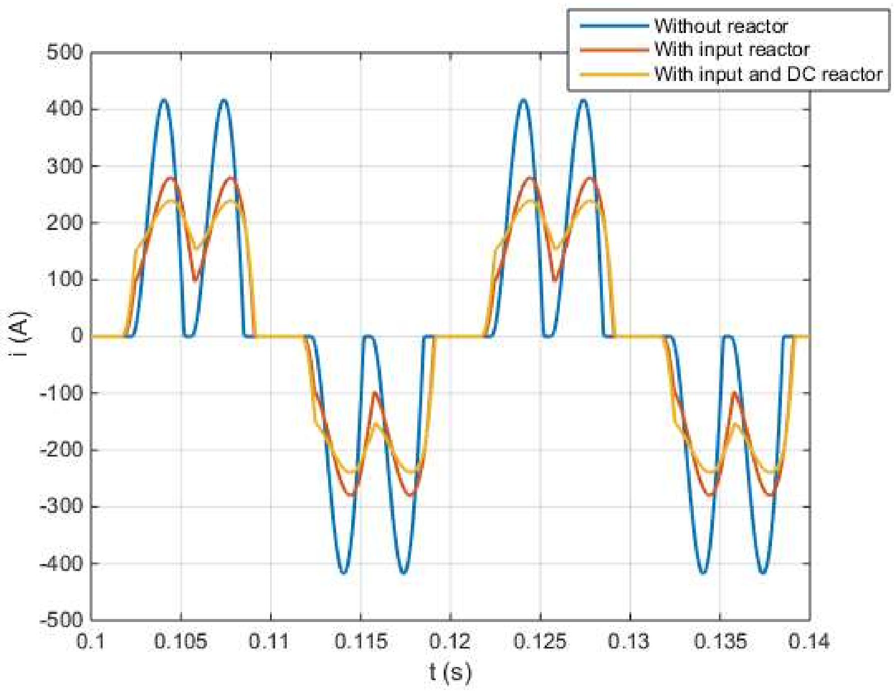



*Figure 3.5 - Input currents of six-pulse rectifier without reactors, with input reactor and with input and DC reactor*

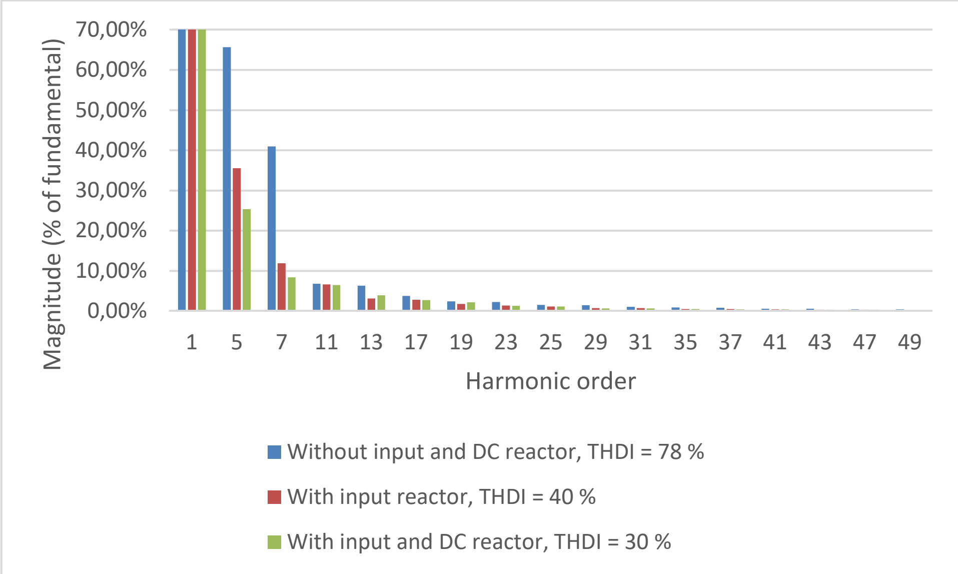



*Figure 3.6 - Harmonic spectrum of input currents in six-pulse rectifier, with and without reactor*

Series reactors are good and simple solution to reduce harmonic currents. Only one reactor is usually used, either input or DC reactor, their effect is practically the same. Using both of them is recommended in case of heavy distortion or large power VDFs. Nevertheless, effectiveness of series reactors may be insufficient. Disadvantage is also voltage drops because of series impedance.

## 3.3 Transformers with special connections

Some special transformer connections can eliminate harmonic currents. As said above, widely used are Y/y/d transformer. Tertiary winding connected in delta constitutes very low impedance circuit for zero sequence currents. As was shown in chapter 2.4, tripplen harmonic currents are zero sequence. Therefore, this kind of transformer does not allow tripplen harmonics to flow through it.

Widespread solution to mitigate harmonic currents is using multipulse rectifiers (multipulse VFDs). Twelve-pulse and eighteen-pulse drivers are used the most often. Twelve pulse driver contains two transformers (or one three winding transformer) and two bridge rectifiers, connected in parallel or in series. Primary winding connection is delta, secondary winding connection is delta and tertiary winding connection is star. Phase shift between output voltages is 30°. The most significant fifth and seventh harmonic currents cancel each other on input side (some other harmonics are cancelled out as well, see below). Secondary effect that helps reducing harmonics currents is due to transformer leakage inductance – it works as series reactor and reduces higher-order harmonic currents (drives are often equipped with input reactor as well).

Eighteen-pulse drive contains phase-shifting autotransformer and three bridge rectifiers. Phase shift between output voltages is 20°. This scheme eliminate all harmonic currents below the 17th and autotransformer leakage inductance reduces higher-order harmonic currents.

Models of 12-pulse and 18-pulse rectifiers with rectifiers connected in series are shown in figure 3.7 and 3.8. They are similar to six-pulse rectifier model shown in figure 2.17 with the same parameters, but two or three rectifier are used instead of one and also phase-shifting transformers are used. Output voltage of phase shifting transformers in the figure 3.7 and 3.8 was set so that output DC voltage, input reactive and active power were approximately the same. Power factor correction capacitor has to be used in our model of 18-pulse rectifier.

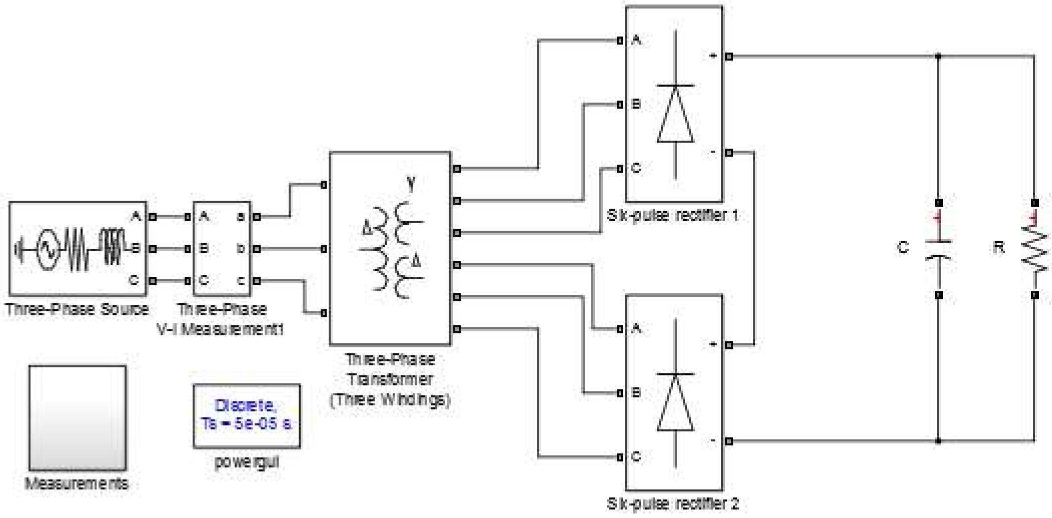



*Figure 3.7 - Twelve-pulse rectifier model*

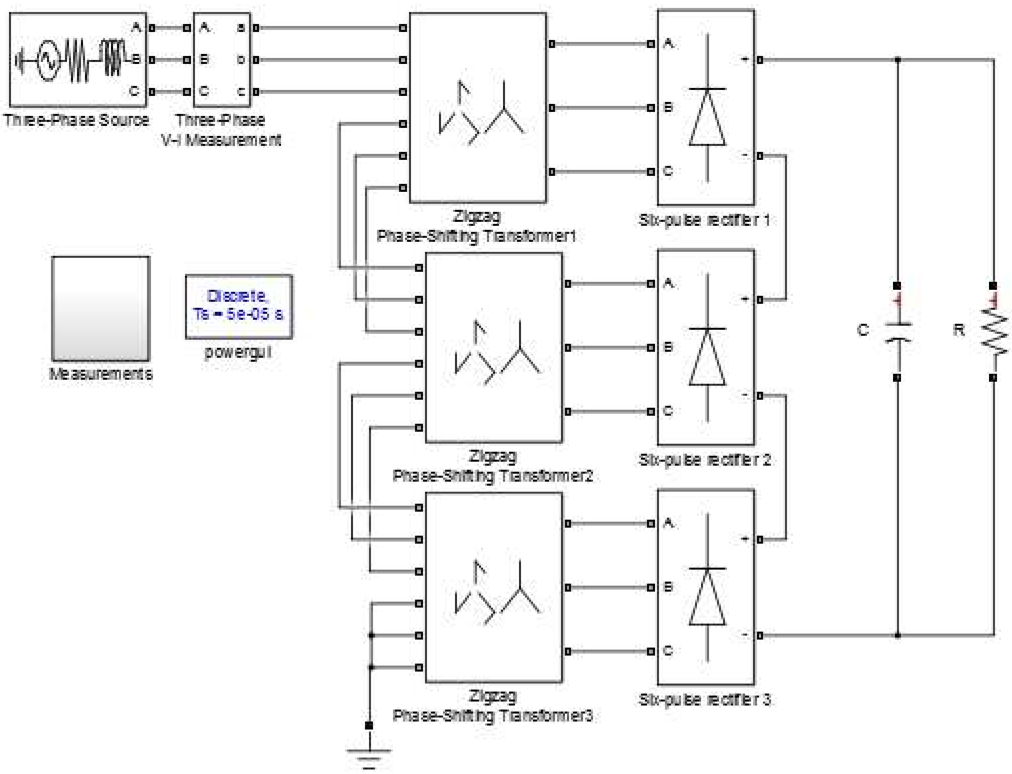



*Figure 3.8 - Eighteen-pulse rectifier model*

Parameters of models are as follows:

| | |
|---|---|
| Three-Phase Source | Un = 400 V; f = 50 Hz; Sk" = 10 MVA; X/R = 1 |
| C | C = 8 mF |
| R | R = 2,57 Ω ≈ 110 kW |
| Three Phase Transformer | S = 110 kVA; $U_1$ = 400 V; $U_2$ = 204,5 V; $U_3$ = 204,5 V; $u_k$ = 4 % |

*Table 3-1 - Parameters of model from figure 3.7*

| | |
|---|---|
| Three-Phase Source | Un = 400 V; f = 50 Hz; Sk" = 10 MVA; X/R = 1 |
| C | C = 8 mF |
| R | R = 2,57 Ω ≈ 110 kW |
| PFC capacitor | Un = 400 V; f = 50 Hz; Q = 50 kVAr |
| Zigzag Phase-Shifting Transformer 1 | S = 40 kVA; $U_1$ = 400 V; $U_2$ = 575 V; Phase shift = 0 degrees; $u_k$ = 4 % |
| Zigzag Phase-Shifting Transformer 1 | S = 40 kVA; $U_1$ = 400 V; $U_2$ = 575 V; Phase shift = 20 degrees; $u_k$ = 4 % |
| Zigzag Phase-Shifting Transformer 1 | S = 40 kVA; $U_1$ = 400 V; $U_2$ = 575 V; Phase shift = 40 degrees; $u_k$ = 4 % |

Input currents of six-pulse, twelve-pulse and eighteen-pulse rectifiers are shown in figure 3.9. As we can see, effect of 18-pulse rectifier is very considerable and input current waveform is practically sinusoidal.

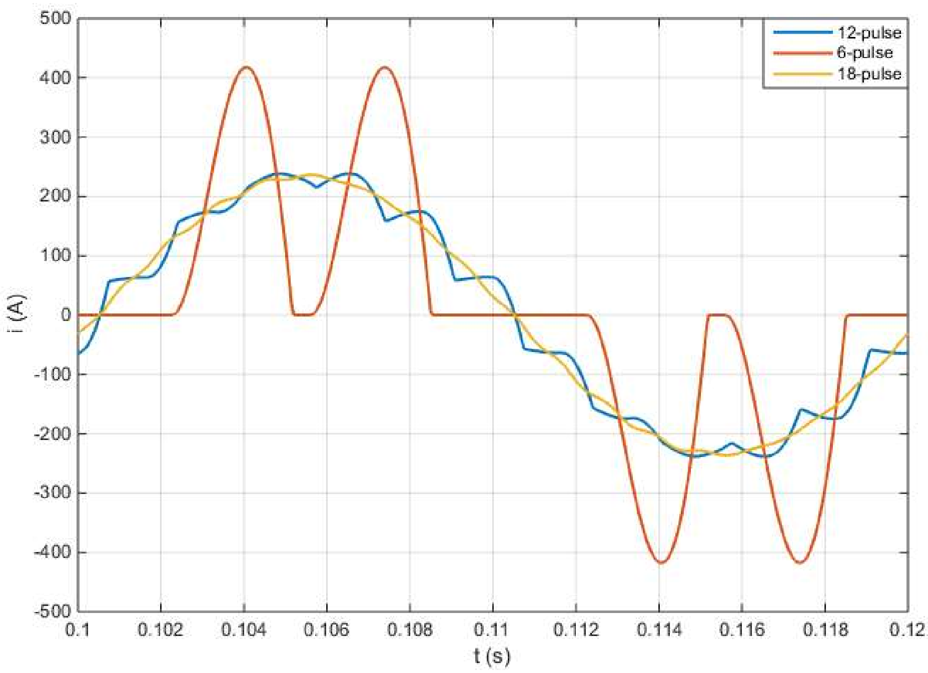



*Figure 3.9 - Input current of 6-pulse, 12-pulse and 18-pulse rectifier*

Spectrum analysis is shown in figure 3.10. As we can see, 6-pulse rectifier generates harmonics with order 6n ± 1, twelve-pulse rectifier generates harmonics with order 12n ± 1 and 18-pulse rectifier generates harmonics with order 18n ± 1. On the basis of these findings, we can write equation that defined harmonics order generated by p-pulse rectifier

$$h = pn \pm 1 \tag{2.1}$$

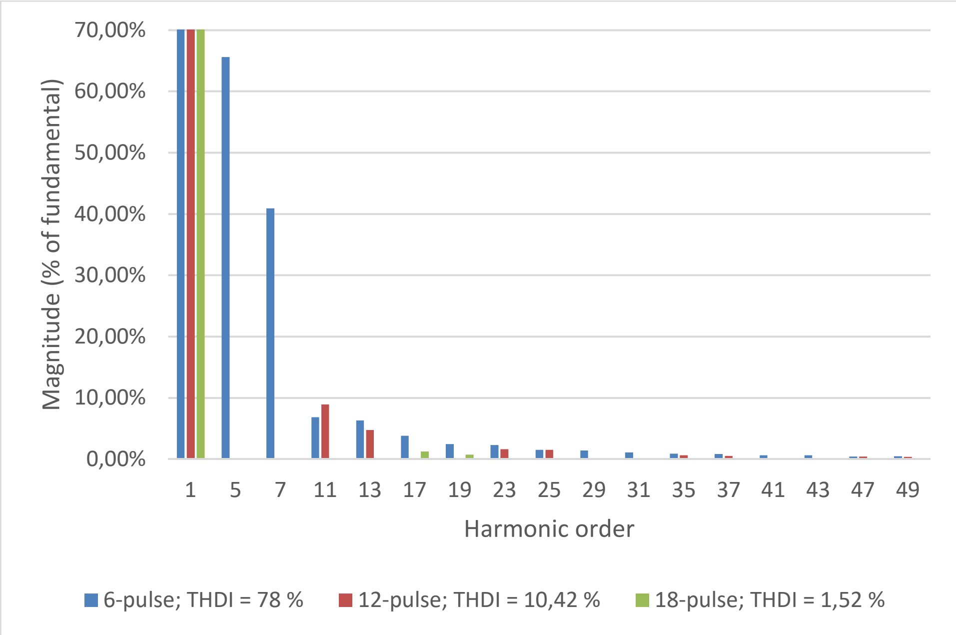



*Figure 3.10 - 6-pulse, 12-pulse and 18-pulse input current spectrum analysis*

THDI of twelve-pulse rectifier is still considerable. On the other hand, eighteen-pulse rectifier reduces harmonic currents sufficiently, as the THDI ranges usually from 1 % to 5 %. The main advantage of multipulse drives is easy application – no deep studies are needed, compared to passive filters. Other advantages are robustness and small costs for high power. Disadvantages are high cost for small power applications and impossibility to use this solution as a retrofit of existing devices. 110 kW 18-pulse drive of Eaton company is shown in figure 3.11

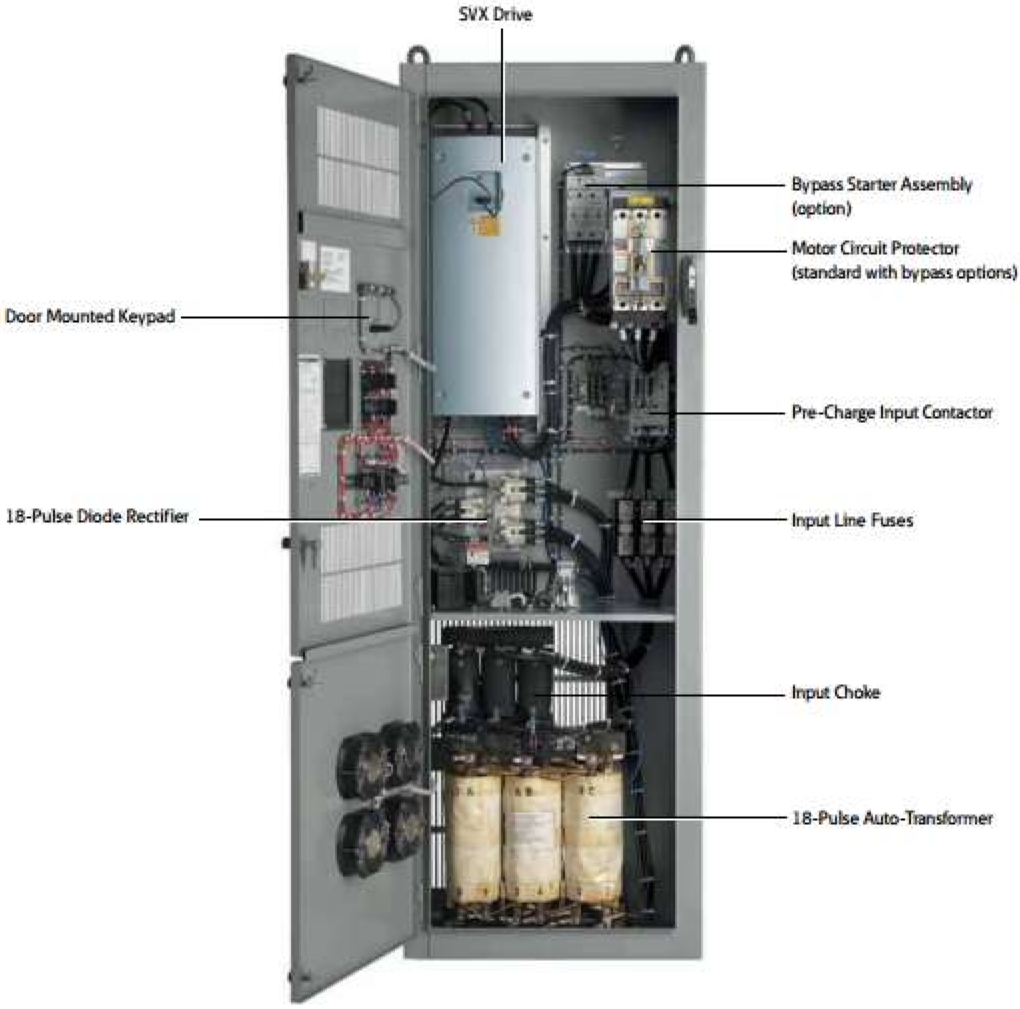



*Figure 3.11 - 18-pulse drive (150 hp ≈110 kW) [19]*

## 3.4 Passive filters

Passive filters are widely used solution for harmonic currents mitigation. Passive filters are divided into two categories – single tuned filters and high (band) pass filters.

### 3.4.1 Single-tuned filters

Single-tuned filter comprises of series connected capacitor and reactor. As every real reactor and capacitor have intrinsic resistance, single tuned filters in fact form series RLC circuit. Filters are connected in parallel with non-linear loads, as shown in figure 3.12. Filters provide low impedance path for harmonic currents $I_{h1}$, $I_{h2}$ and $I_{h3}$, so these harmonic currents generated by non-linear load flow through this filter and do not flow further to the grid.

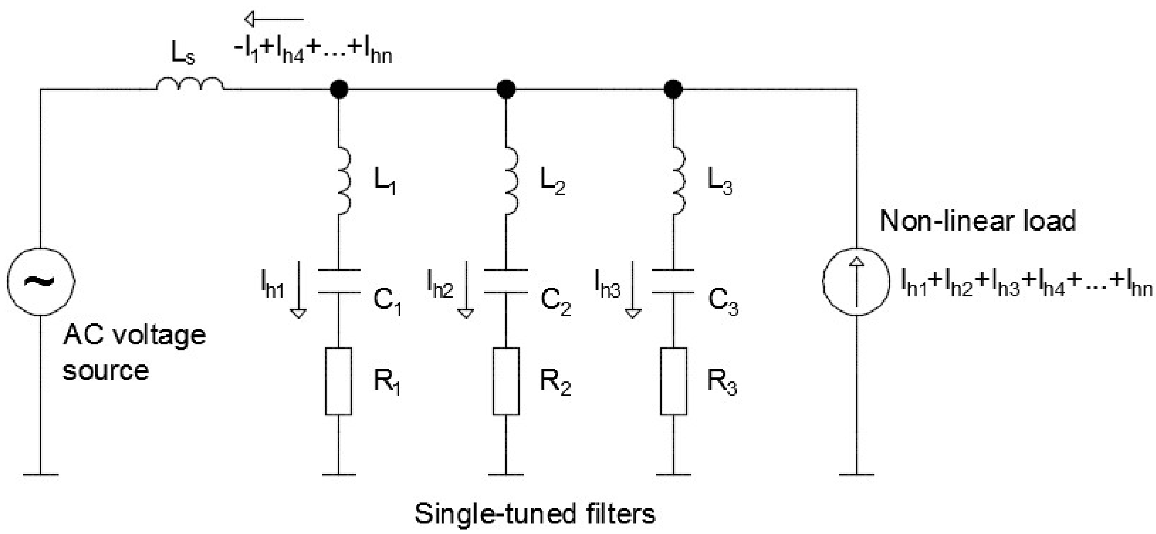



*Figure 3.12 - Single-tuned passive filters connected to the grid*

Passive filters, besides harmonic current filtering, provide power factor correction and thus they are usually used for both – harmonic reducing and power factor correction. Filters to a certain extent reduces other harmonic currents, whose frequency is close to tuning frequency.

#### *3.4.1.1 Single tuned filter design*

The steps to set up a single-tuned harmonic filter are as follows [3]:

1. Calculate the value of reactive power
2. Choose a reactor to tune the series capacitor to the desired harmonic frequency.
3. Calculate the peak voltage at the capacitor terminals and the rms reactor current.
4. Choose standard components for the filter and verify filter performance to assure that capacitor components will operate within IEEE-182 recommended limits.

As said above, passive filters provides in addition power factor correction. For this reason, the most used technique to calculate a reactive power $Q_c$ of filters is to calculate reactive power needed to improve displacement power factor from $\varphi_1$ to $\varphi_2$

$$Q_c = P\left(\tan\varphi_1 - \tan\varphi_2\right) \text{ [VAr]} \tag{2.2}$$

Where

P Active power

$\varphi_1$ Displacement factor of fundamental harmonic before compensation

$\varphi_2$ Displacement factor of fundamental harmonic after compensation (usually equals to 0,95)

However, this method is not universal, and does not suit for all kind of cases. When displacement factor $\varphi_1$ is close to value 0,95 (also, it may be even bigger), reactive power obtained from equation 3.2 is small, or it can not be determined. When choosing small reactive power, filter equipment, especially capacitor bank can be overloaded (see further in this chapter), because of harmonic currents. We can set the value $\cos\varphi_2$ slightly over the value 0,95, to 0,96-0,99 to obtain bigger reactive power, or we can follow an iteration process if capacitor is overloaded (choose greater reactive power and perform the calculation again). In addition, there is another method to determine filter reactive power – calculate non-active power N as

$$Q_c = N = \sqrt{S^2 - P^2} = \sqrt{\left(\frac{P}{TPF}\right)^2 - P^2} = P\sqrt{\frac{1}{TPF^2} - 1} \text{ [VAr]} \tag{2.3}$$

Where

S Apparent power

TPF Total power factor

If we calculate reactive power of filters using equation 3.3, possibility of overloading is low. On the contrary, filter will be probably oversized and power factor will be leading, so iteration process can be followed as well.

Filter branch impedance

$$\hat{Z} = R + j\left(\omega L - \frac{1}{\omega C}\right) \text{ [}\Omega\text{]} \tag{2.4}$$

Where

R Filter resistance

L Filter inductance

C Filter capacitance

Resonance condition for h-th harmonic frequency $\omega_h$

$$\left(\omega_h L - \frac{1}{\omega_h C}\right) = 0 \Rightarrow \omega_h = \frac{1}{\sqrt{LC}} \ [\mathrm{s}^{-1}] \tag{2.5}$$

Ration between the harmonic and fundamental frequency

$$h = \frac{\omega_h}{\omega_1} \ [-] \tag{2.6}$$

Inductive and capacitive reactances at harmonic frequency

$$X_{Lh} = h\omega_1 L \ [\Omega] \tag{2.7}$$

$$X_{ch} = \frac{1}{h\omega_1 C} \ [\Omega] \tag{2.8}$$

Resonance conditions can be also written as

$$X_{Ln} = X_{Cn} \Rightarrow h\omega_1 L = \frac{1}{h\omega_1 C} \Rightarrow L = \frac{1}{h^2 \omega_1^2 C} \ [\mathrm{H}] \tag{2.9}$$

and after modification

$$h = \sqrt{\frac{X_{C1}}{X_{L1}}} \Rightarrow X_{c1} = h^2 X_{L1} \ [\Omega] \tag{2.10}$$

The real reactive power at frequency $\omega_1$ changes because of inductive reactance. Using equation 3.10, we obtain (resistance is disregarded)

$$Q_c = \frac{U^2}{X_{c1} - X_{L1}} = \frac{U^2}{X_{c1} - \frac{X_{c1}}{h^2}} = \frac{U^2}{X_{c1}} \frac{h^2}{h^2 - 1} \ [\mathrm{VAr}] \tag{2.11}$$

Where

U Nominal phase-to-phase voltage (rms value)

Therefore, capacity is

$$C = \frac{Q_c}{U^2 \omega_1} \frac{h^2 - 1}{h^2} \text{ [F]} \tag{2.12}$$

Other important indicator of passive filter is quality factor, bandwidth and power losses. Regarding single-tuned harmonic filters, the quality factor relates the ability of a filter to dissipate the absorbed energy at the tuned frequency. [3] In series RLC circuit it is defined as

$$Q_f = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{X_{Lh}}{R} = \frac{X_{Ch}}{R} \tag{2.13}$$

Bandwidth is defined as

$$B = \frac{f_n}{Q_f} \tag{2.14}$$

Where
$f_n$ tuning frequency

Losses at fundamental frequency can be calculated as (using equation 3.11 and 3.13)

$$\begin{aligned} P_{losses} &= 3RI_1^2 = R\frac{U^2}{\left(X_{c1} - X_{L1}\right)^2} = R\frac{U^2}{X_{c1}}\frac{h^2}{h^2-1}\frac{1}{X_{c1}}\frac{h^2}{h^2-1} = RQ_c\frac{h^2}{h^2-1} = \\ &= \frac{X_{c1}Q_c}{hQ_f}\frac{h^2}{h^2-1} = \frac{Q_c}{Q_f}\frac{h}{h^2-1} \text{ [W]} \end{aligned} \tag{2.15}$$

Where
$I_1$ Fundamental current rms value

If standards components are chosen, we have to verify, if its parameters are within limits. We will assume, that only fundamental current and harmonic current at tuning frequency flow through the filter branch and that other harmonic currents flow through the remaining filter branches.

The rms and peak voltage of the capacitor

$$U_{Crms} = \sqrt{U_{C1}^2 + U_{Ch}^2} \tag{2.16}$$

$$U_{Cpeak} = \sqrt{2} U_{Crms} \tag{2.17}$$

Voltage through the capacitor at fundamental frequency

$$U_{C1} = I_{C1} X_{C1} \tag{2.18}$$

Fundamental frequency current through the capacitor

$$I_{C1} = 1{,}05 \frac{U_{L-N}}{X_{L1} - X_{C1}} \tag{2.19}$$

Voltage through the capacitor at tuning frequency

$$V_{Ch} = I_{Ch} X_{Ch} \tag{2.20}$$

The rms current through the capacitor bank

$$I_{Crms} = \sqrt{I_{C1}^2 + I_{Cn}^2} \tag{2.21}$$

Capacitor power

$$Q_C = I_{Crms} U_{Crms} \tag{2.22}$$

Recommended limits for continuous operation of shunt capacitors by IEEE-182:

$$U_{Crms} \le 1{,}1 U_{Crms\_rated}$$

$$U_{Cpeak} \le 1{,}2 U_{Cpeak\_rated}$$

$$I_{Crms} \le 1{,}35 I_{Crms\_rated}$$

$$Q_c \le 1{,}35 Q_{Crated}$$

Once the filter parameters have been selected, it is important to verify that nonresonant conditions are presented between the capacitor bank of the filter and the inductive reactance of the system. To carry out this task rigorously, a harmonic analysis program is needed to determine the frequency response of the system and to assess whether the desired reduction in harmonic distortion levels is achieved. [6]

### 3.4.2 **High-pass filters**

High pass filters are used to filter high-order harmonics and cover a wide range of frequencies. The other advantages of high-pass filters are lesser sensitivity to temperature variation, frequency deviation, component manufacturing tolerances, loss of capacitor elements etc. [20] Disadvantages are greater losses and different sizing of filter elements (requires elements with higher VA rating). Four types of high-pass filters are shown in figure 3.13.

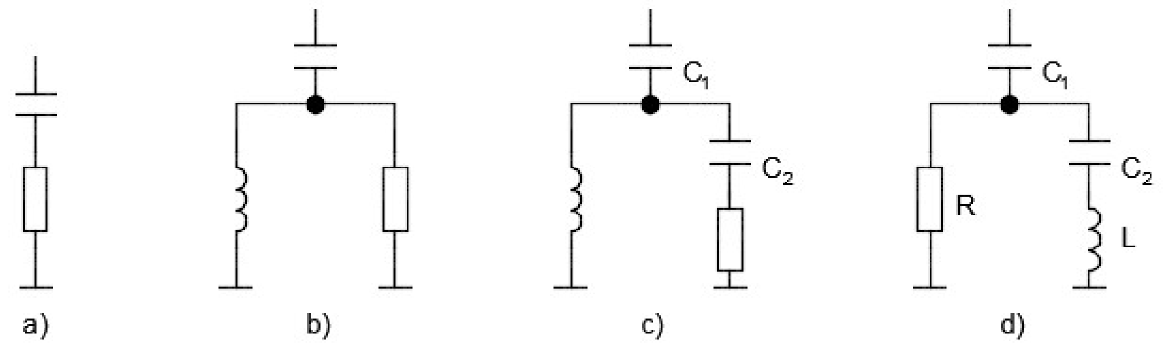



*Figure 3.13 - Types of high-pass filters; a) first order; b) second order; c) third order; d) C-type [20]*

The first-order filter is not normally used, as it requires a large capacitor and has excessive loss at the fundamental frequency. The second-order type provides the best filtering performance, but has higher fundamental frequency losses as compared with the third-order filters. The main advantage of the third-order type over the second-order type is a substantial loss reduction at the fundamental frequency, owing to the increased impedance at that frequency caused by the presence of the capacitor $C_2$. Moreover,the rating of $C_2$ is very small compared with $C_1$. The filtering performance of the C-type filter lies in between those of thesecond- and third-order types. Its main advantage is a considerable reduction in fundamental frequency loss, since $C_2$ and $L$ are series tuned at that frequency. However, this filter is more susceptible to fundamental frequency deviations and component value drifts. [20]

The most used is second order high-pass filter. Its impedance is

$$Z = \frac{j\omega LR}{j\omega L + R} + \frac{1}{\omega C} \tag{2.23}$$

According to [20], behaviour of damped filters has been described by Ainsworth with the help of two parameters, $f_0$ and m

$$f_0 = \frac{1}{2\pi CR} \tag{2.24}$$

$$m = \frac{L}{R^2 C} \tag{2.25}$$

Typical values of m lie between 0,5 – 2.

### 3.4.3 **Example: Passive harmonic filter design in industrial plant with linear loads and six-pulse drives**

We demonstrate passive filter design on simple model in Simulink. Model scheme is shown in figure 3.15. Model represents simplified industrial plant and consists of 22 kV MV grid, MV/LV transformer, line impedance, two linear loads and two non-linear loads (six-pulse rectifier from chapter 2.15). Parameters of each component of model are shown in table 3-1.

| | |
|---|---|
| MV Grid | Un = 22 kV rms, Sk“ = 500 MVA, X/R = 7 |
| Transformer T1 | $U_1$ = 22 kV; $U_2$ = 0,4 kV; uk = 6 %; Dyn1 |
| Line impedance | R = 5e-3 Ω; $X_L$ = 5e-3 Ω |
| Load1, Load2 | RL load<br>P = 110 kW; Q = 112 kVAr; cos φ = 0,7 |
| Load3, Load 4 | C1 = 8 mF; R = 1,145 Ω ≈ 250 kW |

*Table 3-2 - Passive harmonic filter model parameters*

We consider, that loading is 100 %, i.e. P = 720 kW so THDI = TDD. We measure THDU and THDI at point PCC and IPC. Measured data are shown in table 3-2.

| **Point** | **THDU (%)** | **THDI (%)** |
|---|---|---|
| PCC | 0,22 | 24,41 |
| IPC | 7,11 | 24,41 |

*Table 3-3 - Measured voltage and current distortions at PCC and IPC points*

THDU at IPC point is within limit defined by IEC 61000-2-4 for class 2 (see appendix A), because

$$THDU_{IPC} > THDU_{IPC\_permitted}$$
$$7{,}11\% > 8\%$$

We do not have to mitigate harmonic currents in order to decrease THDU. However, as this value is very close to limit 8 %, it is highly recommended. Note, that THDU at point PCC at primary side of transformer is virtually negligible.

Now, we will examine, if voltage and current distortion is within the limits defined by IEEE 519-2. We have to calculate short circuit ratio (SCR) at point PCC at transformer primary side as first:

$$SCR_{PCC} = \frac{I_{SC\_PCC}}{I_{L\_PCC}} = \frac{\frac{S''_{k\_g}}{\sqrt{3} \cdot U_g}}{\frac{P_{\max}}{\sqrt{3} \cdot U_{tr\_p}}} = \frac{S''_{k\_g}}{P_{\max}} = \frac{500 \cdot 10^6}{720 \cdot 10^3} = 694$$

Where

| | |
|---|---|
| $I_{SC\_PCC}$ | Short circuit current at point PCC |
| $I_{L\_PCC}$ | Max. demand load current at point PCC |
| $S''_{k\_g}$ | Short circuit power at grid |
| $U_g$ | MV grid voltage |
| $U_{tr\_p}$ | Transformer primary/secondary voltage |

As said in appendix A PCC point is in this case on the primary side of utility MV/LV transformer, as shown in figure 3.15. SCR at this point is 694, so current TDD should not exceed 15 % at PCC point (see table A-3), which is not met (15 % < 24,41 %). THDU at this point should be lower than 5 % (see table A-4), which is met, because THDU at primary side is only 0,3 %.

We will design passive single-tuned filter consisting of 4 branches, tuned to 5th, 7th, 11th and 13th harmonic frequencies. We will follow steps, showed in chapter 3.4.1.1. Firstly, we have to calculate reactive power and capacitance needed to improve power factor. We choose displacement factor cosφ2 = 0,985. Measured displacement factor $\cos\varphi_1 = 0,905$.

Required reactive power

$$Q_C = \left| P\left(\tan\left(\arccos\left(\varphi_2\right)\right) - \tan\left(\arccos\left(\varphi_1\right)\right)\right)\right| =$$

$$= \left|720 \cdot 10^3 \cdot \left(\tan\left(\arccos\left(0,985\right)\right) - \tan\left(\arccos\left(0,905\right)\right)\right)\right| =$$

$$\doteq 210 \text{ kVAr}$$

As low order harmonic currents have higher magnitude than high order ones, we divide reactive power and capacitance unevenly, in the ratio 5:3:2:1. For 5th harmonic filter branch we get

$$Q_c(5) = \frac{5}{5+3+2+1} \cdot Q_c = \frac{5}{5+3+2+1} \cdot 210\ 000 = 95\ 455 \text{ VAr}$$

Analogously we obtain reactive power for other filter branches

$$Q_c(7) = 57\ 273 \text{ VAr}$$
$$Q_c(11) = 38\ 181 \text{ VAr}$$
$$Q_c(13) = 19\ 091 \text{ VAr}$$

Phase to phase voltage U = 400 V. We neglect voltage drops. Capacitance for each branch can be calculated by equation 3.12

$$C(h) = \frac{Q_c(h)}{U^2 \omega_1} \frac{h^2 - 1}{h^2} \text{ [F]}$$

Capacitance for fifth harmonic filter branch

$$C(5) = \frac{5}{5+3+2+1} \cdot \frac{57\ 401}{400^2 \cdot 2 \cdot \pi \cdot 50} \frac{5^2 - 1}{5^2} = 1{,}82 \text{ mF}$$

Analogously we obtain capacitances for other filter branches

$$C(7) = 1{,}11 \text{ mF}$$
$$C(11) = 0{,}75 \text{ mF}$$
$$C(13) = 0{,}37 \text{ mF}$$

Inductance for each branch can be calculated from equation 2.45.

$$L(h) = \frac{1}{h^2 \omega_1^2 C(h)}$$

For 5th order filter we get

$$L(5) = \frac{1}{5^2 \omega_1^2 C(5)} = \frac{1}{5^2 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 1{,}82} = 0{,}22 \text{ mH}$$

Inductance for other single tuned filters

$$L(7) = 0{,}18 \text{ mH}$$
$$L(11) = 0{,}11 \text{ mH}$$
$$L(13) = 0{,}15 \text{ mH}$$

Resistivity of single tuned filter can be calculated using equation 2.47.

$$Q_f = \frac{X_L(h)}{R(h)} \Rightarrow R(h) = \frac{X_L(h)}{Q_f}$$

For fifth order and considering $Q_f = 40$ we get

$$R(5) = \frac{X_L(5)}{Q_f} = \frac{h\omega_1 L(5)}{Q_f} = \frac{5 \cdot 2 \cdot \pi \cdot 50 \cdot 0{,}31}{50} = 8{,}7 \text{ m}\Omega$$

And for other branches

$$R(7) = 10 \text{ m}\Omega$$
$$R(11) = 9{,}6 \text{ m}\Omega$$
$$R(13) = 16{,}21 \text{ m}\Omega$$

| Filter type | R (mΩ) | L (mH) | C (mF) |
|---|---|---|---|
| **5th single tuned** | 8,7 | 0,22 | 1,82 |
| **7th single tuned** | 10 | 0,18 | 1,11 |
| **11th single tuned** | 9,6 | 0,11 | 0,75 |
| **13th single tuned** | 16,21 | 0,15 | 0,37 |

*Table 3-4 - Calculated filters parameters*

Filter impedance vs. frequency and phase vs. frequency is shown in figure 3.14. As we can see, impedance minimums are at frequencies 250, 350, 550 and 650 Hz, as expected. Filter phase at 50 Hz is -90°, which means, that filter is source of capacitive reactive power at 50 Hz. From the first graph, we can read capacitive reactance at 50 Hz (Xc ≈ 0,761 Ω). Capacitive reactive power at 50 Hz can be then calculated

$$Q_c = \frac{U^2}{Xc} = \frac{400^2}{0{,}76} \doteq 210 \text{ kVAr}$$

Which corresponds to calculated reactive power.

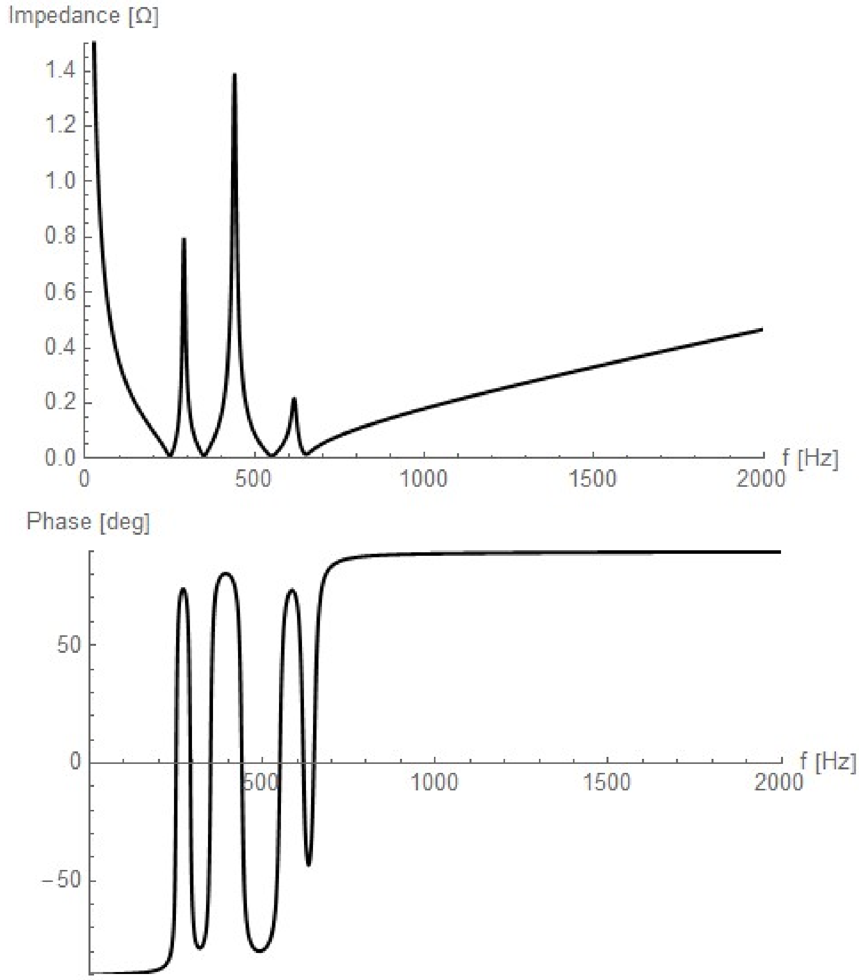



*Figure 3.14 - Impedance vs. frequency and phase vs. frequency of calculated filter*

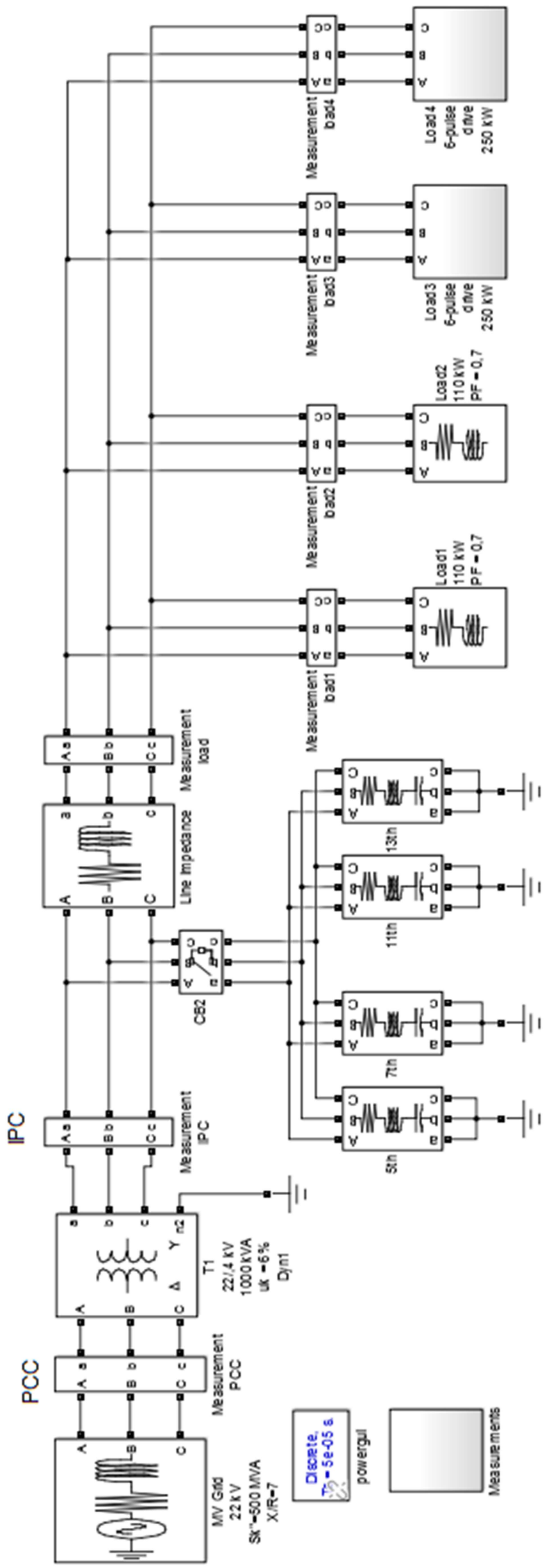



*Figure 3.15 – Model of simple industrial grid with linear and nonlinear loads and passive filters*

We switch filters on to the grid in time 0,4 s. Current waveform is shown in figure 3.16. As we can see, after transient state, distortion of current waveform is much smaller with filters switched on.

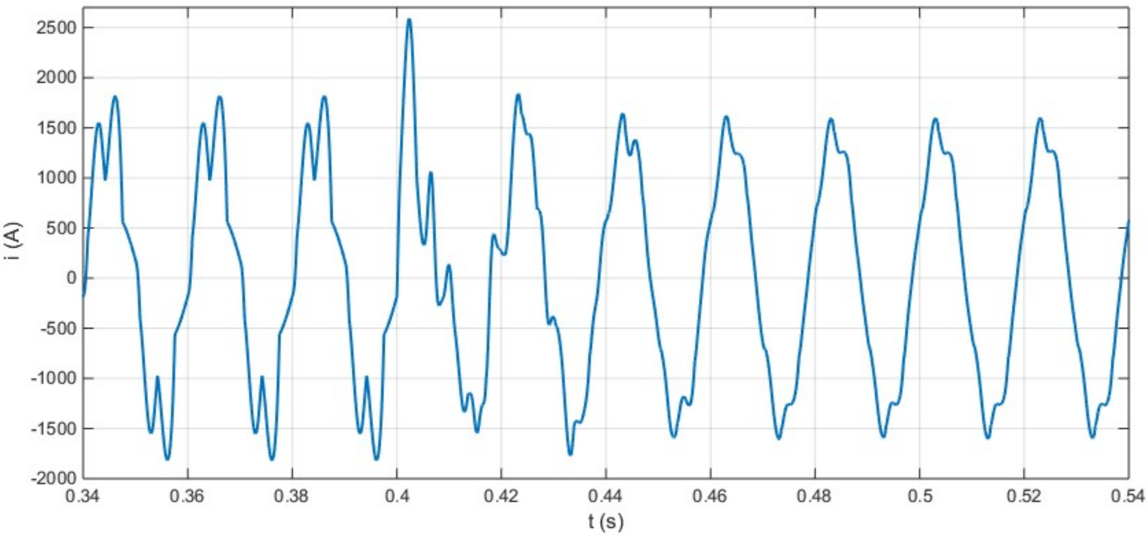


*Figure 3.16 - Current waveform at IPC point*

Spectral analysis of harmonic currents before and after compensation up to 50th order is shown in figure 3.17. As we can see, THDI is improved to value 8,71 %, which is enough, limits of standard IEEE 519-2 is 15 %. THDU at IPC point is improved to value 2,33 %, which is safely away from value 8 % defined by IEC 61000-2-4. At this graph we may notice, that harmonics with order higher than 13th are reduced as well. We should take this into consideration when verifying filters performance to avoid overloading of filter components, especially capacitor.

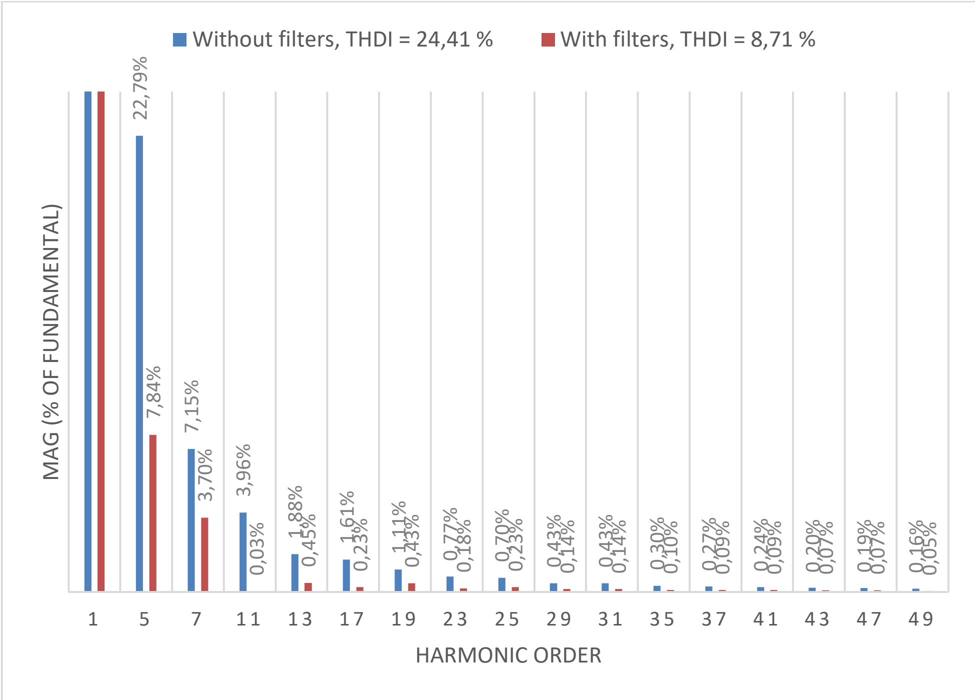



*Figure 3.17 - Comparison of harmonic currents and voltages before and after compensation*

Total power factor before and after compensation is

$$TPF_1 = DPF_1 \cdot \cos\varphi_1 = \frac{1}{\sqrt{1+\left(\frac{THDI_1}{100}\right)^2}} \cdot \cos\varphi_1 = \frac{1}{\sqrt{1+\left(\frac{24,41}{100}\right)^2}} \cdot 0,905 = 0,88$$

$$TPF_2 = DPF_2 \cdot \cos\varphi_2 = \frac{1}{\sqrt{1+\left(\frac{THDI_2}{100}\right)^2}} \cdot \cos\varphi_2 = \frac{1}{\sqrt{1+\left(\frac{8,71}{100}\right)^2}} \cdot 0,985 = 0,981$$

Where

| | |
|---|---|
| $DPF_1, DPF_2$ | Distortion power factor before and after compensation |
| $THDI_1, THDI_2$ | Total harmonic distortion before and after compensation |

As each filter has resistance R in resonant condition, not whole harmonic current flows throug it, but it divides in proportion to grid and filter impedance. We can see, that each branch drain some part of harmonic current from the grid, that varies between 50-90 %. For example, 7th harmonic current is reduced only to 50 %, while 11th harmonic current is reduced to 99 %.

Relationship between harmonic current flowing through the filter and total harmonic current is called filter effectivenes, it can be written as

$$\eta_{filter}(h) = \frac{I_{filter}(h)}{I_{filter}(h) + I_{grid}(h)} = \frac{Z_{grid}(h)}{Z_{filter}(h) + Z_{\mathrm{grid}}(h)} \tag{2.26}$$

Where

| | |
|---|---|
| $I_{filter}(h)$ | h-th order harmonic current flowing through the filter |
| $I_{grid}(h)$ | h-th order harmonic current flowing through the grid |
| $Z_{filter}(h)$ | h-th order filter impedance in resonant conditions |
| $Z_{grid}(h)$ | Grid impedance at frequency $f = h.f_1$ |

We will calculate effectiveness for all demonstrated filters. If we modify equation 3.23 using equation 2.13, we obtain

$$\eta_{filter} = \frac{\sum_h I_{filter}(h)}{\sum_h I_{filter}(h) + I_{\mathrm{grid}}(h)} = \frac{\frac{THDI_1}{100} - \frac{THDI_2}{100}}{\frac{THDI_1}{100}} = 1 - \frac{THDI_2}{THDI_1} \tag{2.27}$$

If we substitute values from table 3-4 in equation 3.24, we get

$$\eta_{filter} = 1 - \frac{THDI_2}{THDI_1} = 1 - \frac{8,71}{24,41} = 0,65$$

Values of filter effectiveness in practice are about 0,6-0,9. If effectiveness of calculated filter is low, we could increase quality factor, which leads to smaller filter impedance. However, we can not increase quality factor so much, as filter parameters will be very sensitive and it can be detuned. After calculation of filter parameters, we should choose standard components for the filter and verify filter performance to assure that capacitor components will operate within IEEE-812 recommended limits, but we will not do that in this demonstration, as we only wanted to show steps for design of passive filters. In addition, we should check out, if there is a risk of resonance between grid and filters, but as no harmonic current with order lower than 5th is present, there is not necessity of doing it.

Advantage of passive filters is their costs – it is one of the cheapest way to reduce harmonic distortion. The other advantage is double use, for power factor correction and mitigation of harmonics. Nevertheless, there are also disadvantages. The biggest is probably inability to adapt of passive filters to varying load. For example, if we switched off one of the non-linear load in our model, capacitive reactive power would exceed inductive reactive power and power factor would be leading and it would decrease. Other disadvantages are possibility of resonance effect and possibility of detuning as a consequence of changing of filter components parameters.

### 3.5 Active harmonic filters

Big disadvantage of passive filters is inability to provide effective harmonic correction for varying loads. When non-linear loads power considerably and incessantly vary, it is more advantageous to use active harmonic filter. Two types of active filters are used – shunt and series filter. Active filters may be used for harmonic, power factor and flicker correction, compensation of unbalanced current and voltage, voltage and frequency control.

Shunt active filter block diagram is shown in figure 3.18. It works this way - control system in active filter determines amplitude and phase of harmonic currents at the grid ($I_{source}$), fundamental reactive current and flicker value. Active filter evaluates this data and generate proper pulses for PWM inverter with capacitor at DC side. PWM inverter injects harmonic currents to the grid ($I_{AHF}$) with the same amplitude and opposite phase in relation to harmonic currents from non-linear loads ($I_{load}$). Thus, harmonic currents at the grid are cancelled by harmonic currents from active filter.

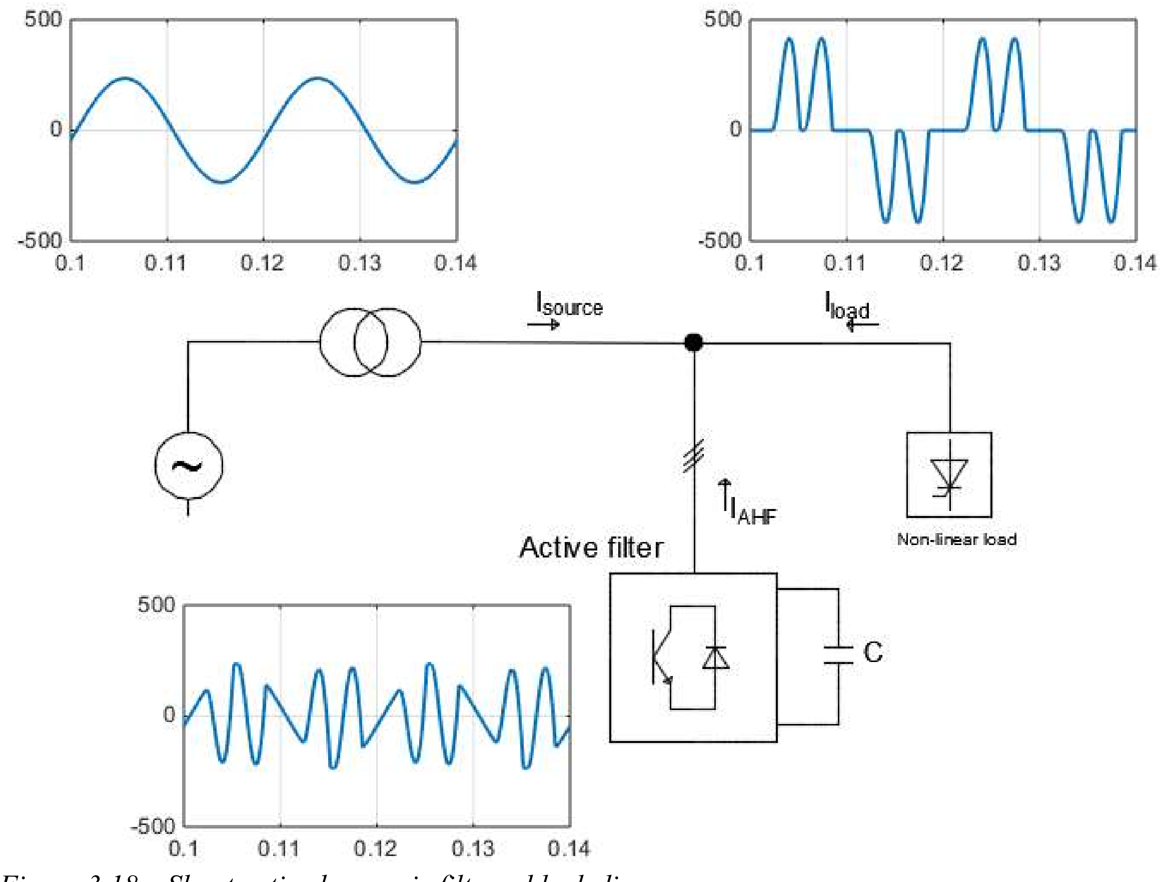



*Figure 3.18 – Shunt active harmonic filter – block diagram*

The series active filter is connected in series with the grid and loads, as shown in figure 3.19. It works on the similar principle as shunt filter, but it does not inject current, but voltage, through the matching transformer. Series filter can control voltage amplitude, reduce harmonic voltages and maintain voltage symmetry.

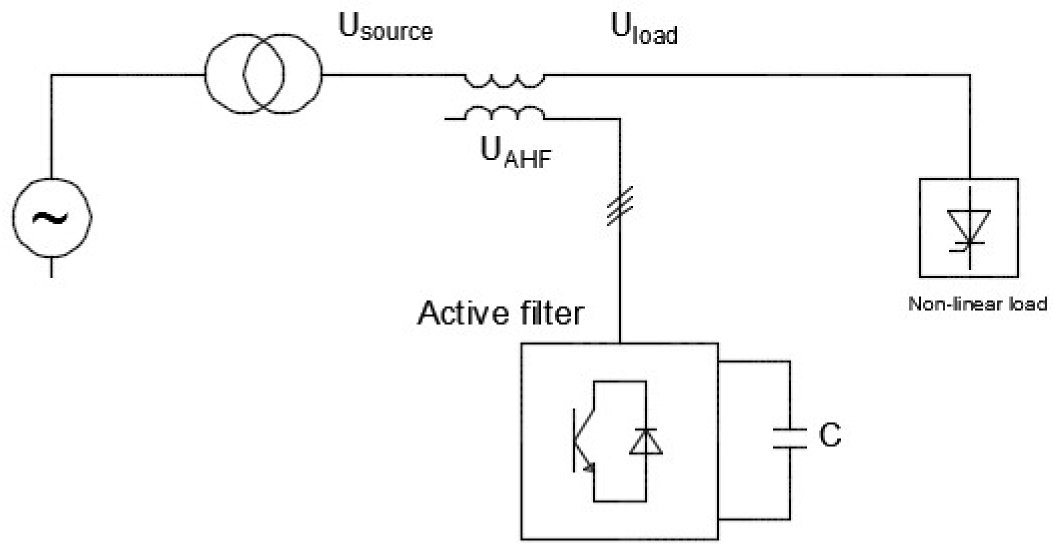



*Figure 3.19 - Series active harmonic filter*

We can combine both types of filter. Such a system provides voltage control and harmonic currents correction at the same time. In order to reduce costs, active filter are often used with passive RLC filters – such systems are called hybrid filters. For example, lower order harmonic currents, such 5th and 7th of the most significant loads can be reduced by cheaper passive filters, and higher order harmonics can are reduced by active filter in this case. This allows using active filter with smaller power rating. Active shunt filter + passive shunt filter scheme is shown in figure 3.20.

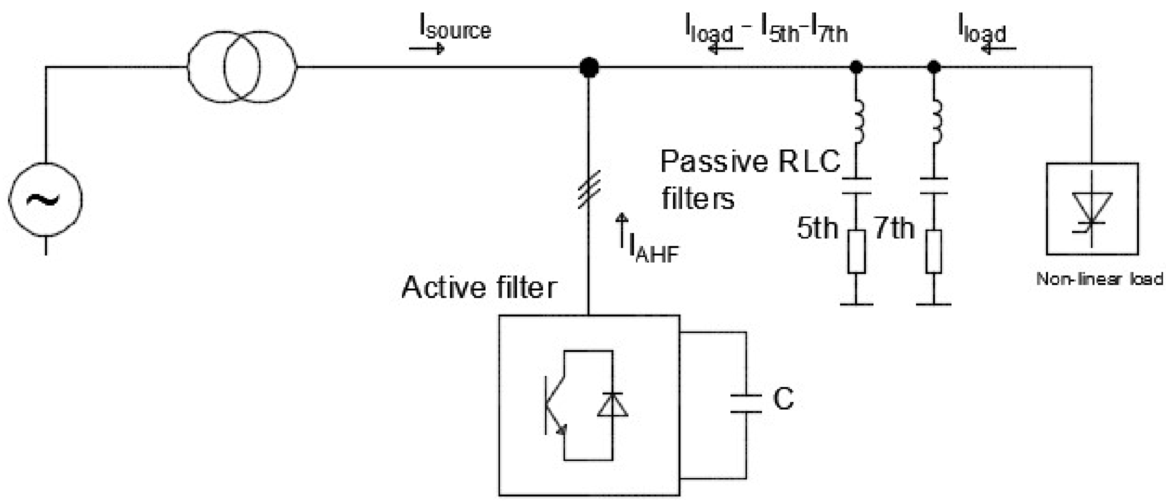



*Figure 3.20 - Active shunt harmonic filter + passive shunt filter*

Active filters can usually reduce THDI up to 5 %. As said above, their main advantage is ability to mitigate harmonic currents under varying load. Also they can improve other parameters as power factor, voltage and current unbalance etc. Other advantages are scalable design – they can be connected in parallel to increase their power rating, simple retrofit, easy design – no deep studies are needed, in comparison with passive filters and no risk of resonance. Otherwise, big disadvantage outweighing all advantages is big costs.

## 3.6 Active front-end drives (AFE drives)

AFE drive contain bridge rectifier composed of IGBT transistors instead of conventional diodes, as shown in figure 3.21. Current harmonics can be controlled through the switching action of the IGBTs. [21] Total harmonic current distortion can be lower than 5 %, as manufacturers state. Input currents of conventional rectifier without any harmonic correction devices and AFE rectifier are shown in figure 3.22. As we can see, AFE drive drawn sinusoidal current with big part of high order harmonics.

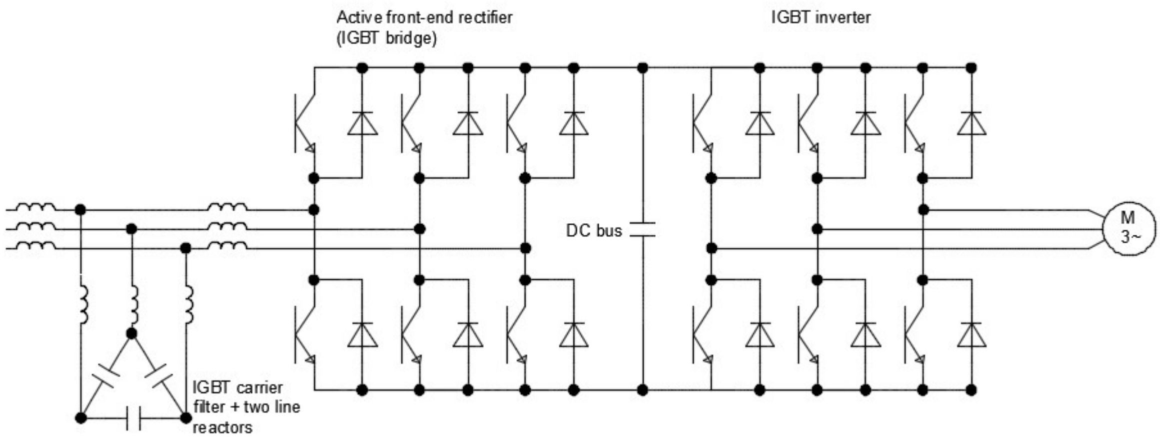



*Figure 3.21 - Active front-end drive power circuit*

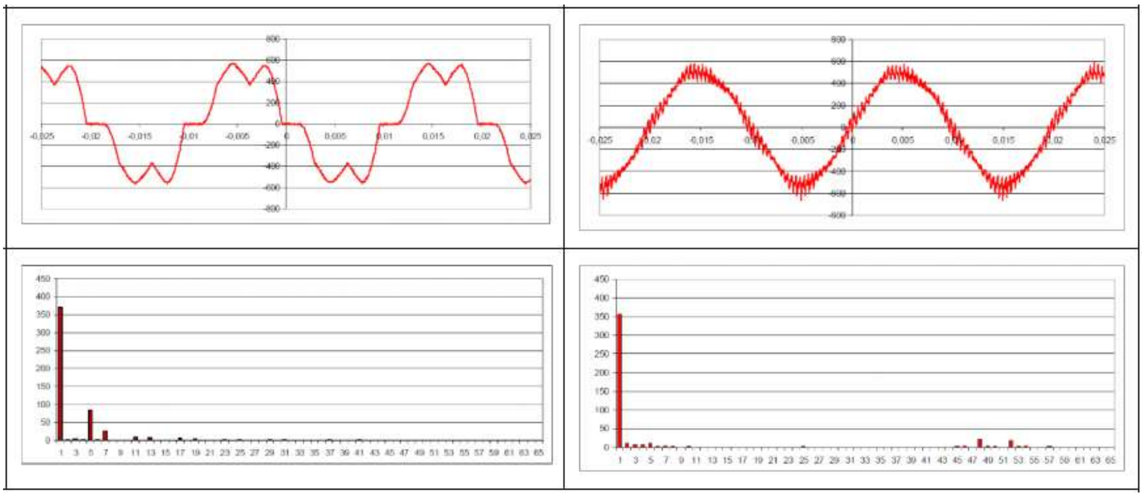
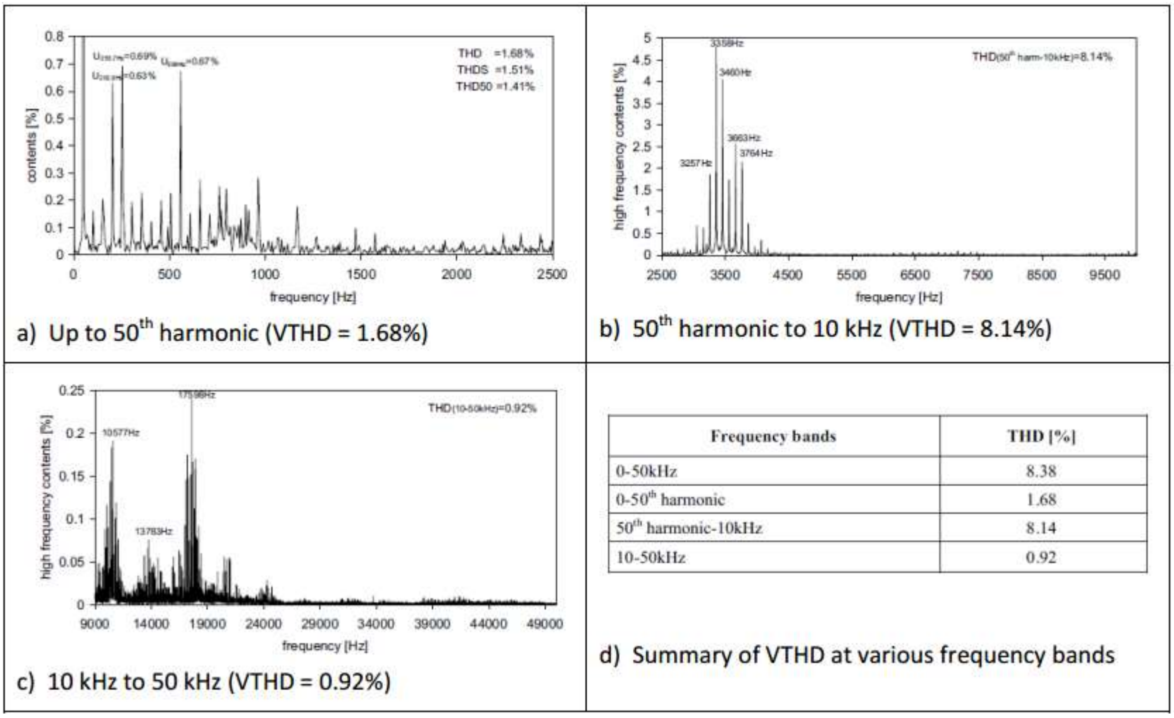


*Figure 3.22 - Input currents and spectral analysis of conventional rectifier (left) and AFE rectifier(right) [21]*

High order harmonic generation (about 50th order) due to IGBTs switching is the big disadvantage of AFE drives. Total harmonic distortion stated by manufacturers do not usually contain harmonic components with order greater than 50th, thus real THDI is actually greater than stated. It can be very difficult in practice to determine these high order harmonics, because many of measurement devices shows spectrum up to 40th, 50th harmonic. These fact is demonstrated in figure 3.23. There are spectral analysis for frequency band 0-2500 Hz (50th order), 2500 Hz-10 kHz and 10 kHz to 50 kHz. Total harmonic distortion is 8,38 %. If we considered only harmonic components to 50th order, we would measure THDU only 1,68 %.




| Frequency bands | THD [%] |
|---|---|
| 0-50kHz | 8.38 |
| 0-50th harmonic | 1.68 |
| 50th harmonic-10kHz | 8.14 |
| 10-50kHz | 0.92 |

*Figure 3.23 - Voltage spectrum analysis of AFE drive for different frequency bands [21]*

This is not the only disadvantage of AFE drives. Ripple in voltage from the AFE drive can cause overvoltages in the other 6-pulse drives installed in the same switchboard. AFE drive still requires input passive filter to reduce high order switching harmonics, although its efficiency is usually very small. In addition, these input filters are more likely to resonate with the power system at rectifier harmonic frequencies (5th, 7th etc.). Other disadvantages are greater ground leakage currents and big losses. [21] Also, we have to mention, that AFE drive is the most expensive solution to harmonic mitigation.

## 3.7 Overview of harmonic currents mitigation techniques

| Technique | Use | Advantages | Disadvantages |
|---|---|---|---|
| **Topology solution – positioning of non-linear loads** | General use, concerning whole installation | Simple design, low costs | Reduce only THDU, does not affect THDI |
| **Topology solution – separating of non-linear loads** | General use, concerning whole installation | Simple design, low costs | Reduce only THDU, does not affect THDI |
| **Topology solution – separating of sources** | General use, concerning whole installation | Simple design, reduce THDU considerably | Big costs, does not affect THDI |
| **Series reactor** | With variable frequency drives | Low costs, simple design, can be installed in existing devices | Small effectiveness, voltage drops |
| **12-pulse rectifier** | With variable frequency drives | Relatively small costs, simple design, good effectiveness | Can not be used as retrofit of existing devices, mitigation may be insufficient in some cases |
| **18-pulse rectifier** | With variable frequency drives | Very good effectiveness, simple design, small costs for large power applications | Can not be used as retrofit of existing devices, big costs for small power applications |
| **Passive filter** | In whole installation or with large power non-linear loads, or with group of non-linear loads | Good effectiveness, small costs, can be used for power factor correction as well, can be installed in existing installation | Not suitable for varying loads, risk of resonance effect, big losses, risk of leading power factor, deep studies are needed |
| **Active filter** | In whole installation or with large power non-linear loads, or with group of non-linear loads | Good effectiveness, can improve other paramters as well (flicker etc.), simple design, can be installed in existing installation, suitable for varying loads | Very big costs, relatively big power losses |
| **AFE rectifier** | With variable frequency drives | Good effectiveness (if good passive filter is used), simple design | Very big costs, relatively big power losses, often used with low quality input filter – presence of high order harmonics, can not be used as retrofit of existing devices |

*Table 3-5 - Overview of harmonic currents mitigation techniques*

## 4 Investigation of harmonic distortion in Eaton European Innovation Centre

### 4.1 Basic information and problem description

Eaton European Innovation Centre (hereinafter referred to as EEIC) is research centre of Eaton Company focusing on development of new technologies and devices. Scheme of electrical grid at EEIC is shown in figure 4.1. Building is powered by two MV/LV transformers T1 and T2. Their LV output is connected to main switchgears RH1 and RH2. Important loads are backed up by generator, alternatively by UPS. LV/LV transformer T3 supplies motors with nominal voltage 690 V. 500 kVAr and 250 kVAr capacitors are used to power factor correction. Main part of EEIC building occupies administrative part with large number of computer technology and fluorescent lamps. In addition, there are research laboratories with considerable amount of variable frequency drives. These nonlinear loads causes harmonic distortion. The biggest problem caused by harmonic distortion here is resonance occurring at some harmonic frequency between PFC capacitors and grid. Resonance leads to increase in harmonic voltages, which causes destruction and burning of equipment in PF correction switchgear, like capacitors or contactors. Our task in this chapter will be investigation, whether IEC 61000-2-4 and IEEE-519 standards are met and, alternatively, design a suitable solution, that will lead to meeting the standards and elimination of resonance and therefore, destruction of PF correction equipment.

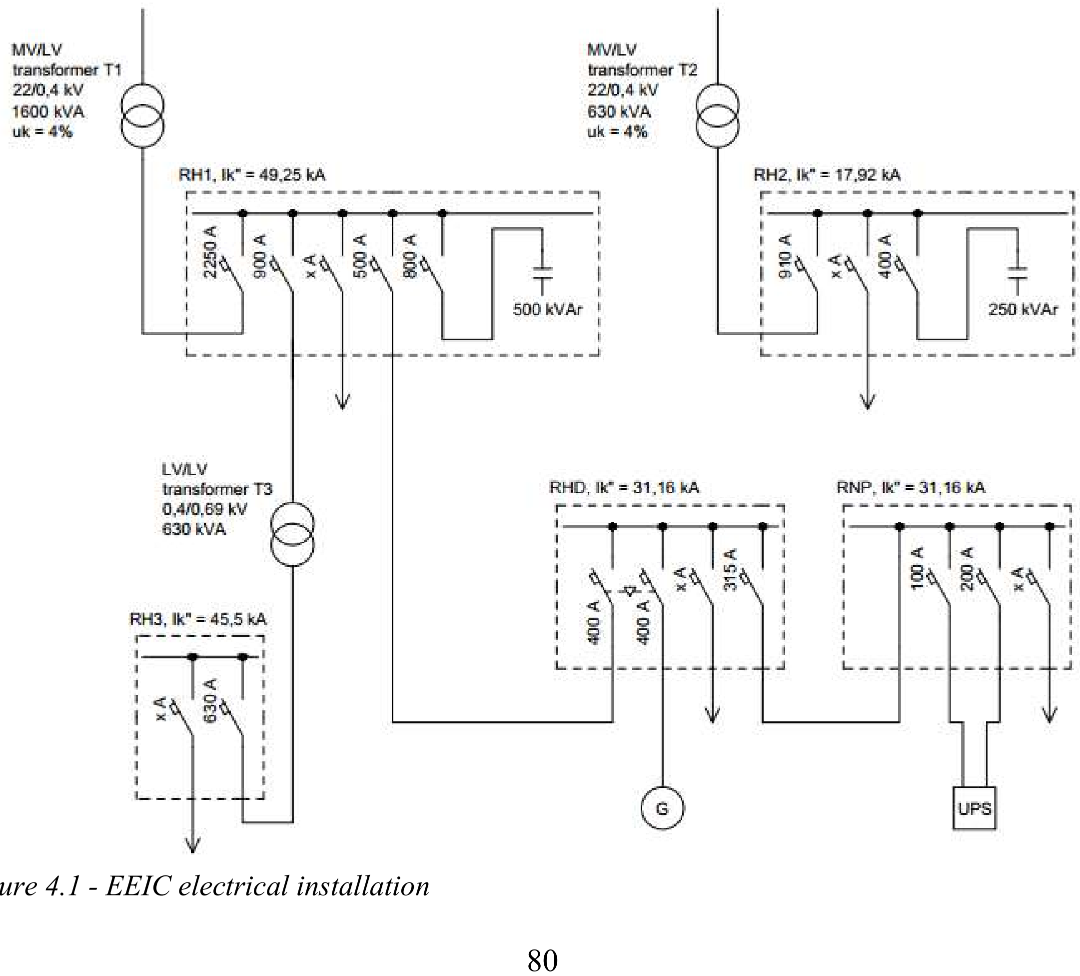



*Figure 4.1 - EEIC electrical installation*

Total capacitive reactive power at RH1 is divided into 12 steps, in ratio 9x50:25:12,5:12,5 kVAr. Total capacitive reactive power at RH2 is divided in a similar way, in ratio 4x50:25:12,5:12,5 kVAr. Individual steps are switched-on depending on reactive power and power factor. We described resonance phenomenon in chapter 2.10.1.2. As said in this chapter, PFC capacitors at low voltage side of transformer with grid represents parallel resonance circuit. The higher the capacitive reactive power, the lower the resonance frequency (see equation 2.31). As magnitude of low order harmonic currents is higher, resonance effects will be more dangerous at lower frequencies. Resonance frequency depending on capacitive reactive power for both switchgears is shown in figure 4.2. As we can see, risk of resonance is high in both switchgears. The worst conditions at RH1 will arise, if capacitive reactive power 275 kVAr will be switched-on. Resonance frequency order in this case will be 11,1. As VFDs generate 11-th order harmonic current, resonance may occur. The worst conditions at RH2 will occur, if all steps will be switched-on. Order of resonance frequency will be 7. Light loads and computers generate odd harmonics, so there is risk of resonance as well.

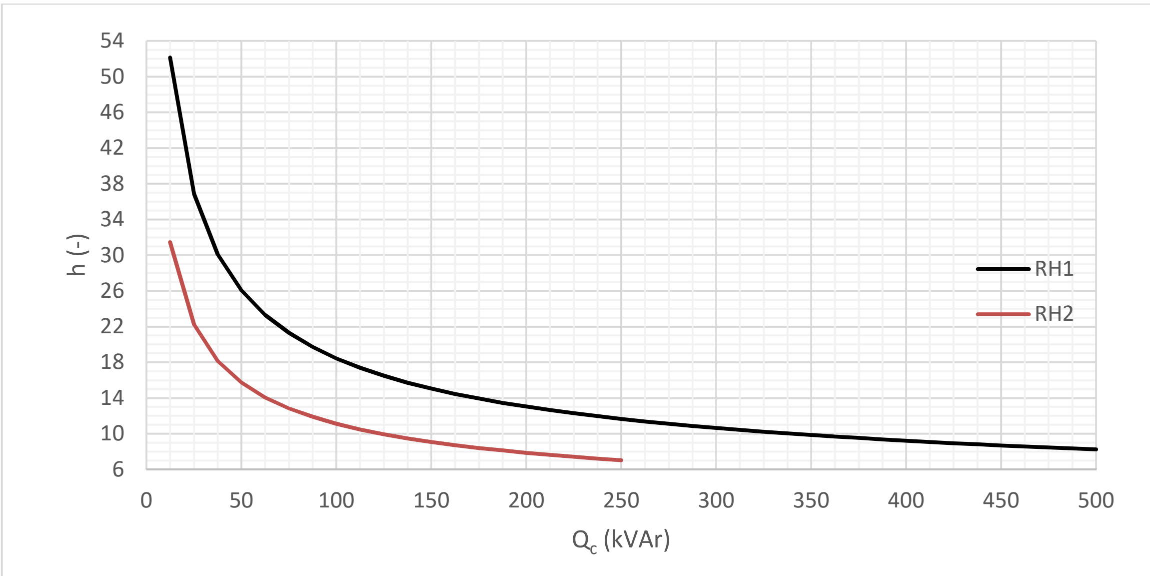



*Figure 4.2 – Orders of resonance frequency depending on capacitive reactive power at RH1 and RH2*

## 4.2 Measured data

Measuring was carried out from 25.4.2016 15:41 to 29.4.2016 13:26 at switchgear RH1 and from 20.4.2016 13:14 to 25.4.2016 14:59 at switchgear RH2. Data was measured and recorded in 5 minute intervals. All of common electrical parameters were measured, like current, voltage, power factor, active, reactive and apparent power, THDU, THDI etc. Current, THDU and THDI maximum values are the most important for us. THDU and TDD courses at RH1 and RH2 are shown in figure 4.2-4.4.

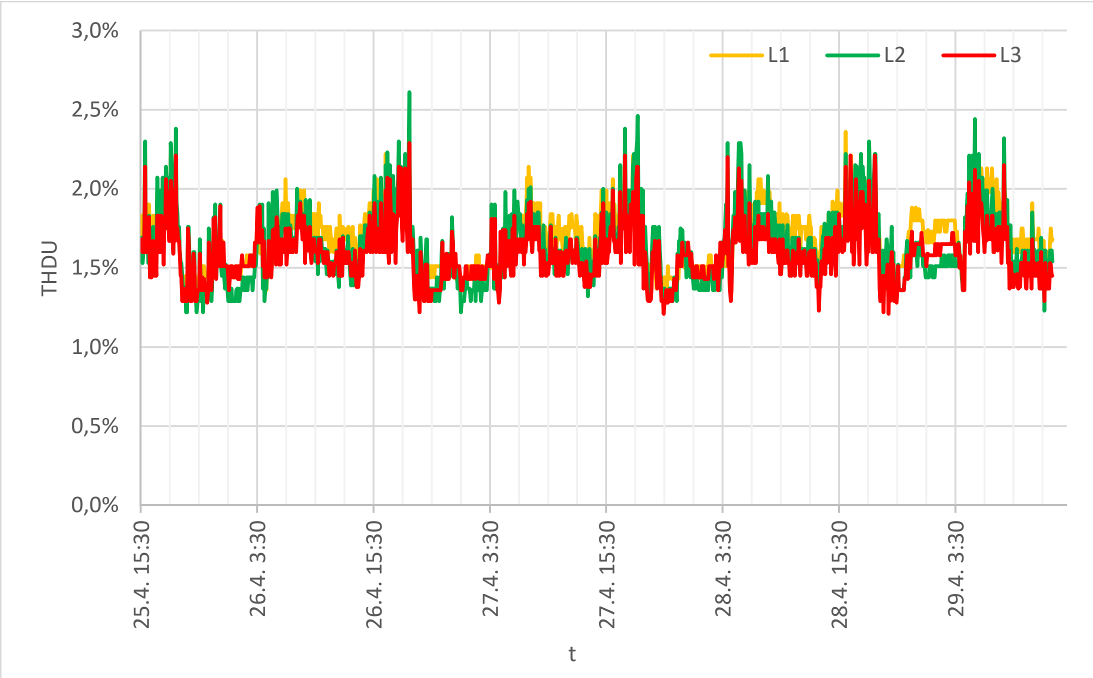



*Figure 4.3 - THDU at switchgear RH1*

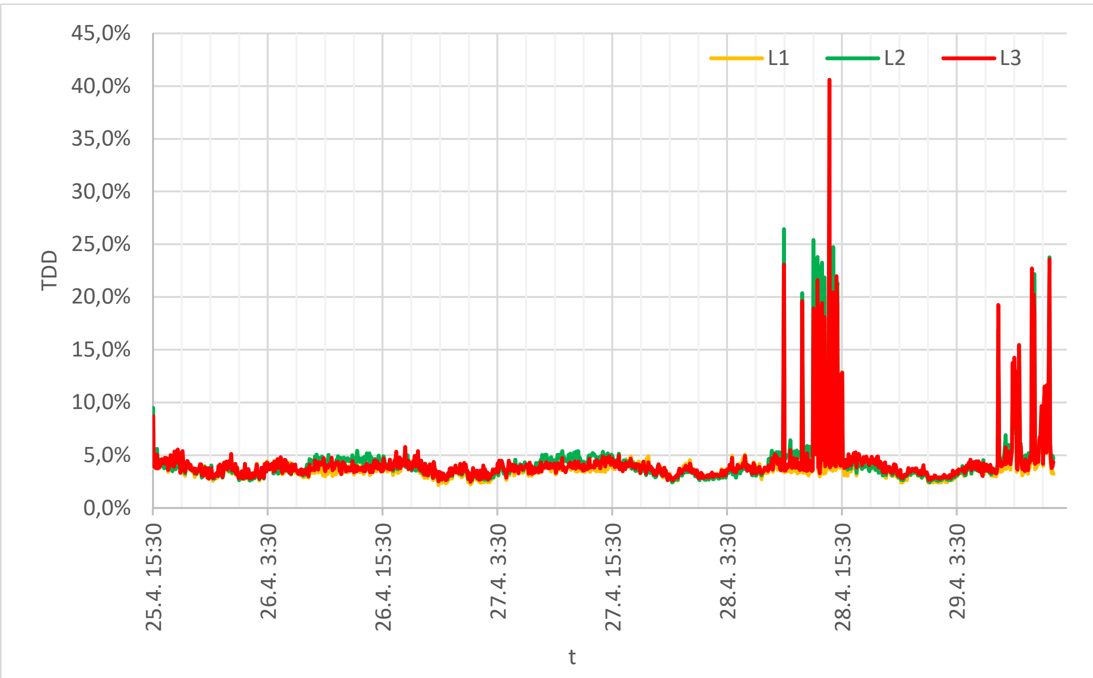



*Figure 4.4- TDD at switchgear RH1*

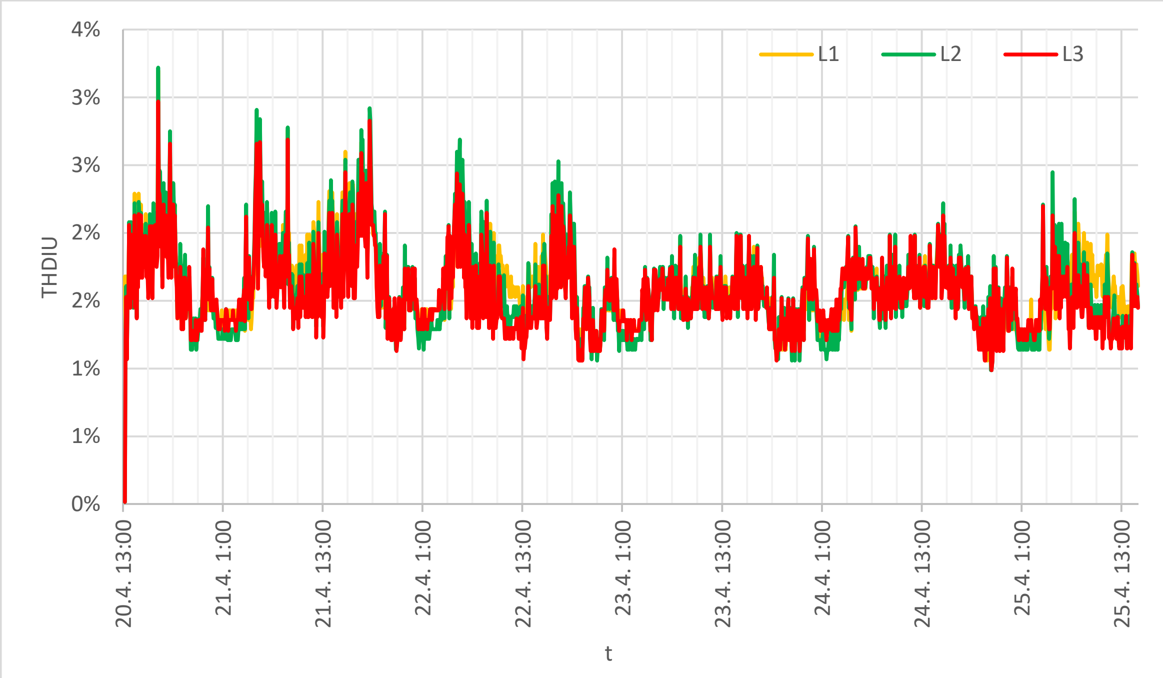



*Figure 4.5 - THDU at switchgear RH2*

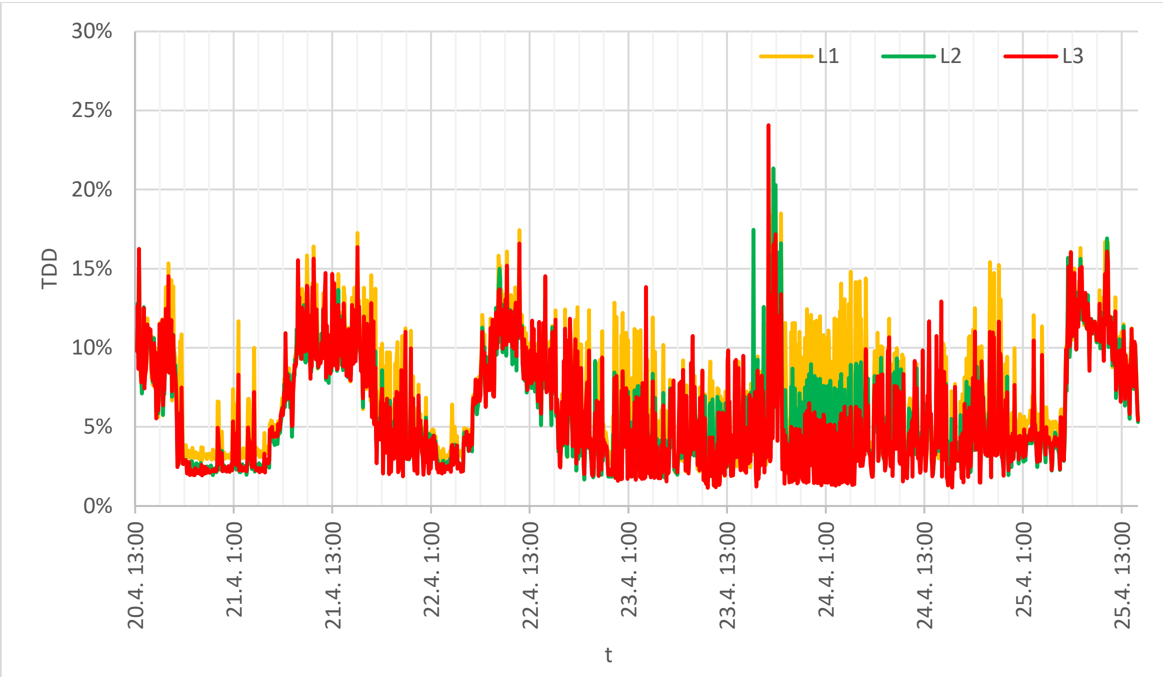



*Figure 4.6 - TDD at switchgear RH2*

Measured maximum demand load currents, used for computing TDD (see appendix A, equation A1)

$$I_{L1,RH1} = 289 \text{ A}; I_{L2,RH1} = 313 \text{ A}; I_{L3,RH1} = 342 \text{ A};$$

$$I_{L1,RH2} = 228 \text{ A}; I_{L2,RH2} = 230 \text{ A}; I_{L3,RH2} = 230 \text{ A};$$

As we can see, maximum measured demand load currents are small in comparison with nominal currents (2250 A in RH1 and 910 in TH2).

If we compare figure and 4.3 and 4.5, we can see, that courses are very different. TDD at switchgear RH1 is practically constant all the time and rarely exceeds 5 %, with the exception of short-term conditions, when TDD considerably increase, for example, at time 28.4. 14:00 (see figure 4.3). TDD at this time increase to 40 %. Such sudden leaps are caused by frequency drives with asynchronous motors. Situation at switchgear RH2 is totally different. As we can see in figure 4.5, TDD varies a lot between values 2 % and 15 %. It reaches even value 24% at time 23.4. 18:00. Such course of TDD is caused mainly by fluorescent lamps and computers.

## 4.3 Compliance with standards

Firstly, we have to check, if limits, defined by IEC standards are met. As we can see in figure 4.2 and 4.4, maximum THDU at switchgear RH1 is $THDU_{RH1}$ = 2,61 %. Maximum THDU at switchgear RH2 is $THDU_{RH2}$ = 3,5 %. Switchgears RH1 and RH2 represents points IPC1 and IPC2. Maximum THDU stipulated for IPC point by standard IEC 61000-2-4 is 8 %, if consider class 2 (see appendix A). Thus, THDU values for both IPC points are within the limits. We met this standard even considering class 1 with more severe limits. However, we have to observe, that this THDU is measured under light load conditions. We would have to perform measurements under full load conditions to unequivocally determine, whether THDU limits are met.

Evaluation, if standard IEEE 519 is met will be more difficult, because we do not know value TDD at point PCC, which is at medium voltage side of transformers T1 and T2. THDU is within the limits, as limit is 5 % (see appendix A, table A-4) and THDU at LV side is max 3,5 %. As THDU at primary side of utility transformer is always less than THDU at secondary side, it is clear, that THDU at primary side is within the limits. However, as said above, we cant determine it unequivocally. We can use a model in Matlab Simulink to obtain approximate values of TDD at PCC point. We will assume worst conditions that may arise according to figures 4.4 and 4.6. So, we consider conditions at LV side of T1 and T2 as listed below:

- T1: TDD = 24 %; $I_1$ = 225 A; cos $\varphi_1$ = 0,98
- T2: TDD = 40 %; $I_1$ = 286 A; cos $\varphi_1$ = 0,86

We had to made some assumptions when creating model, because of lack of data. Unfortunately, we do not know spectral analysis of current and we do not have exact specification of loads. We can only estimate, in what ratio are light, computer loads and VFDs. PFC capacitors are not included in this model, as well as line impedances, which are neglected. Diode bridges (simulate light loads and computer loads),VFDs with DC reactors and linear load are connected to LV side of transformer T1. Power of VFDs is much bigger than power of diode bridges (see table 4.1). Only diode bridges and linear load are connected to LV side of transformer T2. Transformer T2 does not supply laboratories, so VFDs are not connected to T2. Linear loads are used to adjust required value of current and power factor. We measure voltage and current at MV side (PCC) and also at LV sides of T1 and T2 (Measurement PCC, Measurement T1, Measurement T2). Block Measurement serves to process measured data. Model scheme is shown in figure 4.7.

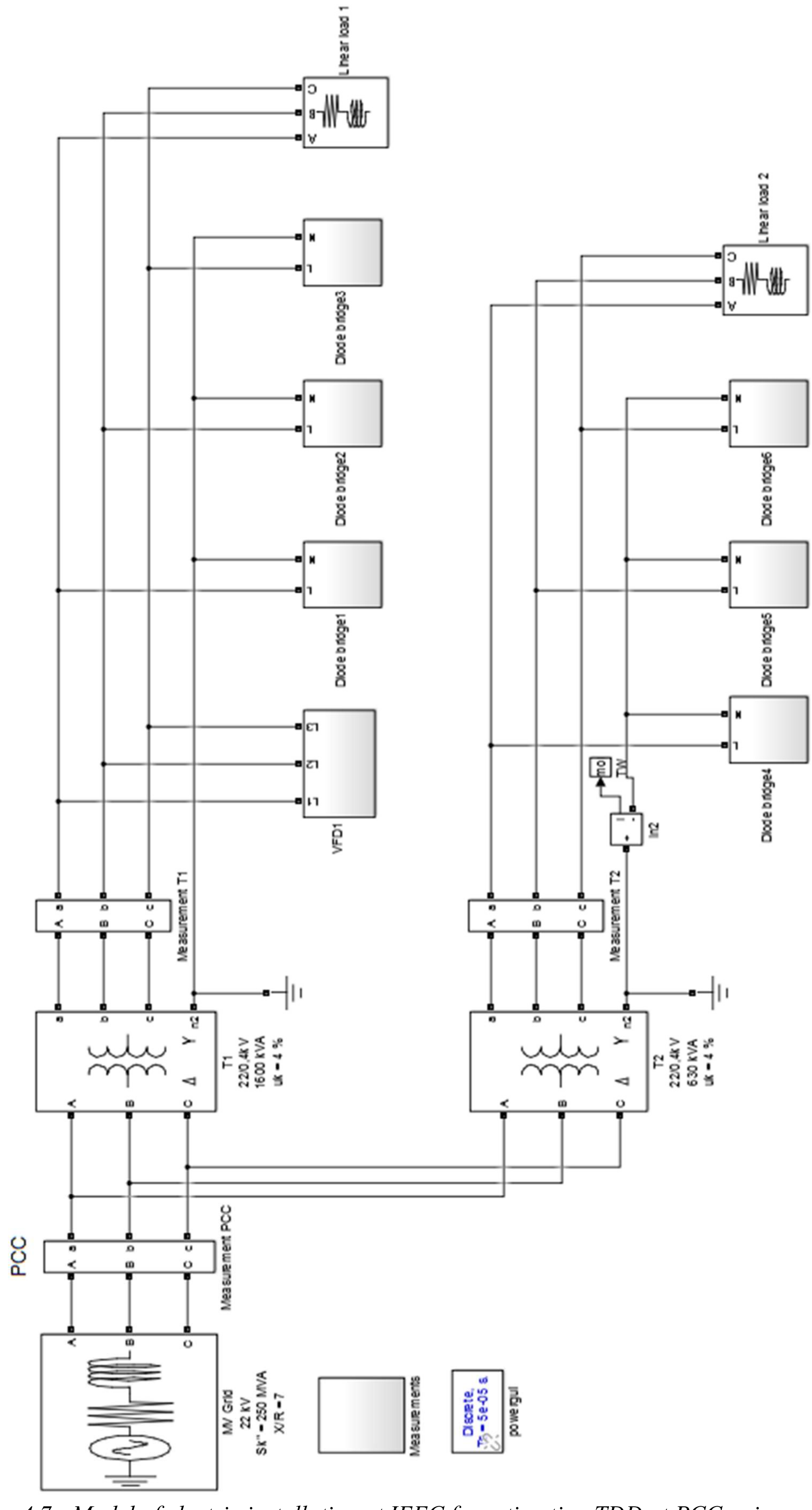



*Figure 4.7 - Model of electric installation at IEEC for estimating TDD at PCC poin*

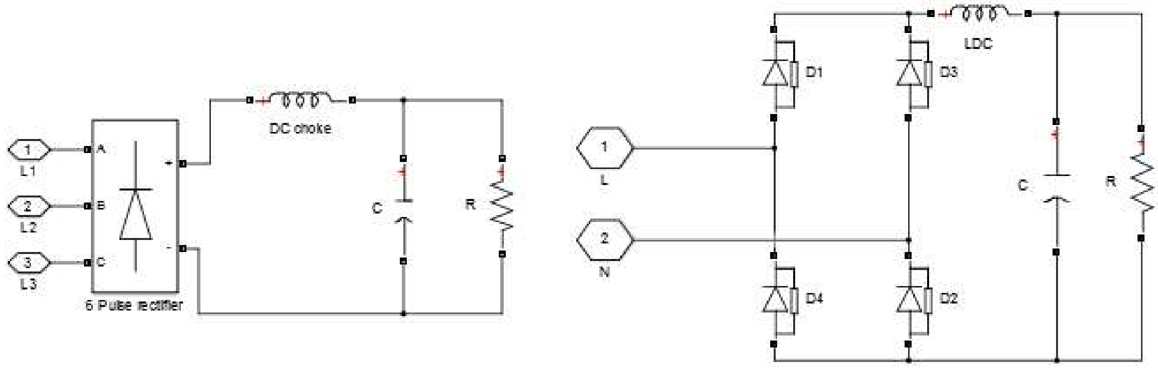



*Figure 4.8 - VFD and Diode Bridge block*

| | |
|---|---|
| MV Grid | 22 kV rms, Sk“ = 250 MVA, X/R = 7 |
| Transformer T1 | 22/0,4 kV; S = 1600 kVA; uk = 4 %; Dyn1 |
| Transformer T2 | 22/0,4 kV; S = 630 kVA; uk = 4 %; Dyn1 |
| VFD1 | Six-pulse rectifier with resistive DC load<br>U = 400 V; P ≈ 105 kW; C = 5 mF;<br>DC choke: 0,115 mH; R = 2,75 Ω |
| Diode bridge 1, 2, 3 | Diode bridge rectifier with resistive<br>DC load<br>U = 230 V; P ≈ 12 kW; C = 150 μF;<br>LDC: 100 mH; R = 3,55 Ω |
| Linear load 1 | 3 Phase RL load<br>U = 400 V; P = 30 kW;<br>Q (inductive) = 75 kVAr |
| Diode bridge 4, 5, 6 | Diode bridge rectifier with resistive<br>DC load<br>U = 230 V; P ≈ 27,3 kW; C = 150 μF;<br>LDC: 100 mH; R = 1,55 Ω |
| Linear load 2 | 3 Phase RL load<br>U = 400 V; P = 71,5 kW;<br>Q (inductive) = 20 kVAr |

*Table 4-1 - Parameters of model in figure 4.7*

Current waveforms are shown in figure 4.9. Current rms values are 286,6 A at LV side of T1 and 225,5 A at LV side of T2. Spectral analysis of currents is shown in figure 4.9. As we can see, TDD (at this case THDI = TDD) is approximately 40 % at LV side of T1 and 24 % at LV side of T2, which corresponds with the real data. TDD at PCC point is only 21,84 %. This is caused by absence of third order harmonics at MV side, which are eliminated by delta winding at primary side of transformers T1 and T2.

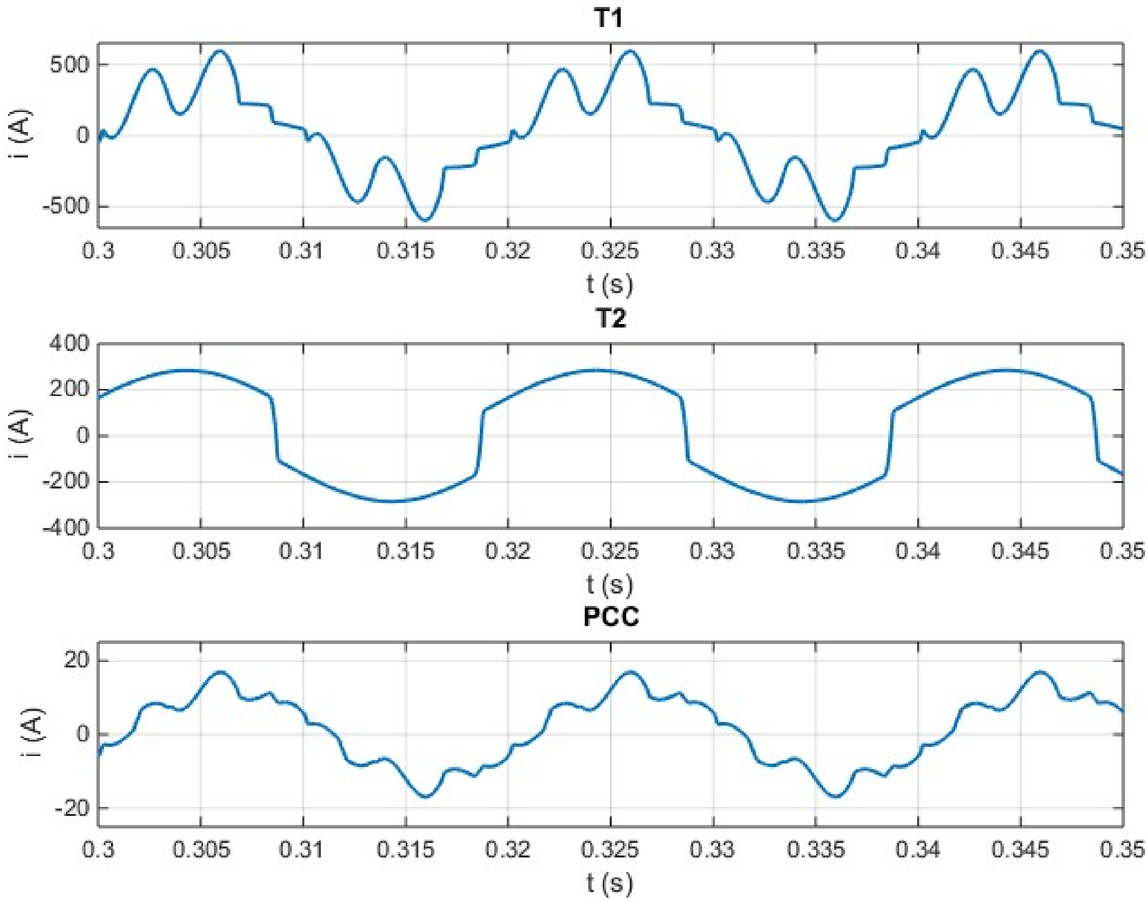



*Figure 4.9 - Current waveforms at LV side of T1 and T2 and at PCC point*

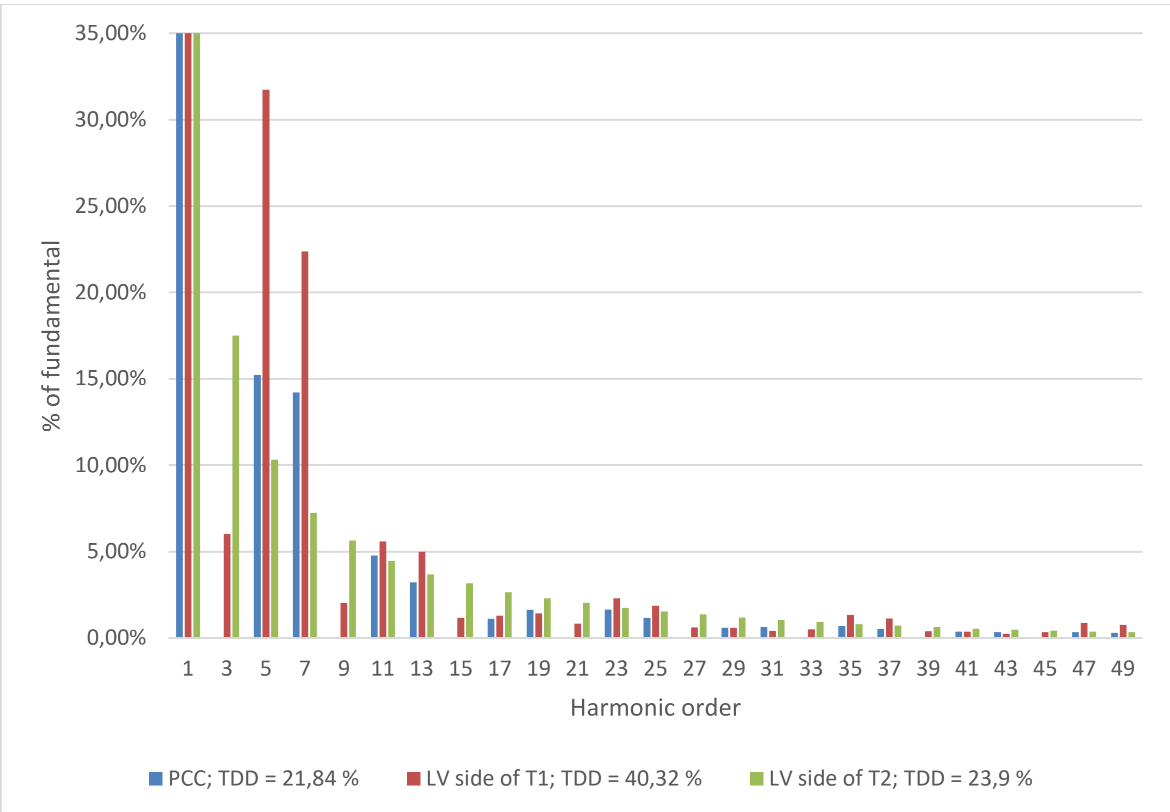



*Figure 4.10 - Spectral analysis of current at LV side of T1 and T2 and at PCC point*

Short circuit current ratio at PCC is

$$SCR_{PCC} = \frac{I_{SC\_PCC}}{I_{L\_PCC}} = \frac{\frac{S''_{k\_g}}{\sqrt{3} \cdot U_g}}{I_{L\_PCC}} = \frac{\frac{250 \cdot 10^6}{\sqrt{3} \cdot 22 \cdot 10^3}}{9{,}33} \doteq 703$$

Where

| | |
|---|---|
| $I_{L\_PCC}$ | Max. demand load current at point PCC |
| $S''_{k\_g}$ | Short circuit power at grid |
| $U_g$ | MV grid voltage |

Maximum TDD value according to IEEE-519 (see appendix A, table A-3) is 15 %, which is not met. Installation devices reducing harmonic currents is necessary to meet the standard IEEE-519.

## 4.4 Solutions

In this chapter, we will discuss solutions eliminating problems with resonance. This is the most serious problem that has to be solved for sure. Concerning harmonic distortion, we do not need to reduce harmonic distortion, as standard IEC 61000-2-4, which has to be met, is met. However, as said in previous chapter, standard IEEE-519 is not met. Although we do not have to comply with this standard, as it is not in force at Czech republic, non-complying with this standard means, that distortion is not insignificant and we should reduce harmonic currents. Thus, we will try to find solution, that will solve problems with resonance and, at the same time, ensure meeting the standard IEEE-519.

**a) Equip PFC switchgears with detuned reactors**

As said in chapter 2.10.1.2, this solution is based on detuning of resonance circuit (PFC capacitors + grid), so that resonance frequency is below the frequency of the lowest order harmonic current generated by nonlinear loads. Such detuning is done by means of inductor, connected in series with PFC capacitor. In our case, the lowest frequency presented in system is 150 Hz (3rd harmonic). We have to use reactors with relative impedance 14 %, that decrease resonance frequency to 134 Hz. Advantages and disadvantages of this solution are:

| | |
|---|---|
| + | Low costs |
| + | Inductors in series with capacitors operates as high pass filter, so they reduce TDD to some extent |
| + | Simple installation, no deep studies are needed, availability of detuned inductors |
| - | Altough they reduce TDD, reducing could not be sufficient to meeting the standards IEEE 519 in our case |
| - | Increasing in capacitor voltage, generates large amount of heat (nesessity of ventilation) |

**b) Equip PFC switchgears with detuned reactors + equip VFDs with DC chokes or input reactors**

At this solution, we will use detuned reactors in PFC switchgears as in previous solutions, but, in addition, we will install DC reactors to VFDs. VFDs already equipped with DC reactors can be equipped with input reactors. This will lead to considerable reduction of TDD, so that standard IEEE will be met (see chapter 3.2 how input reactor and DC reactor can reduce harmonic currents). Advantages and disadvantages of this solution are:

| | |
|---|---|
| + | Slightly higher, but still acceptable costs |
| + | Simple installation, no deep studies are needed, availability of detuned inductors, DC and input reactors |
| + | Meeting the IEEE 519 limits (in our case) – see further |
| - | Increasing of capacitor voltage, generate large amount of heat (necessity of ventilation) |
| - | Reduction of TDD is sufficient, but TDD can still remain significant |

**a) Active harmonic filters**

Using an the active harmonic filters (see chapter 3.5) is suitable in this case because of strongly varying load. This solution reduce TDD to very small value, which will lead to elimination of resonance problems as well. This solution is very good, however, costs are too high. Advantages and disadvantages of this solution are:

+ Low TDD, Meeting the IEEE 519 limits
+ Can be used for improving PF and other electric parameters as well
+ Simple design and installation

- Costs (as far the highest from all presented solutions)

It follows from above mentioned, that the best solution is using detuned reactors in PFC switchgear and DC/input reactors in VFDs. First solution is acceptable, but we do not recommend it, as it does not solve the problem with harmonic distortion. Solution with active filter is good, but expensive. We can determine, how TDD will be improved by adding an input reactor in matlab. We added an input reactor (figure 4.12) to VFD1. We choose inductance 0,3 mH. We switch-on inductor at time 0,4 s. As we can see in figure 4.13 and 4.14, TDD is improved to value 9,82 %, which is enough to meet the IEEE-519 limits.

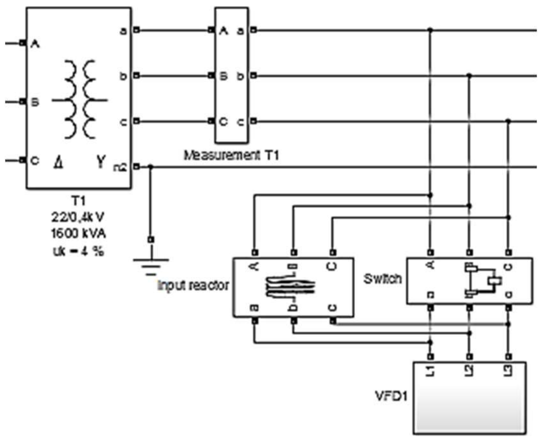
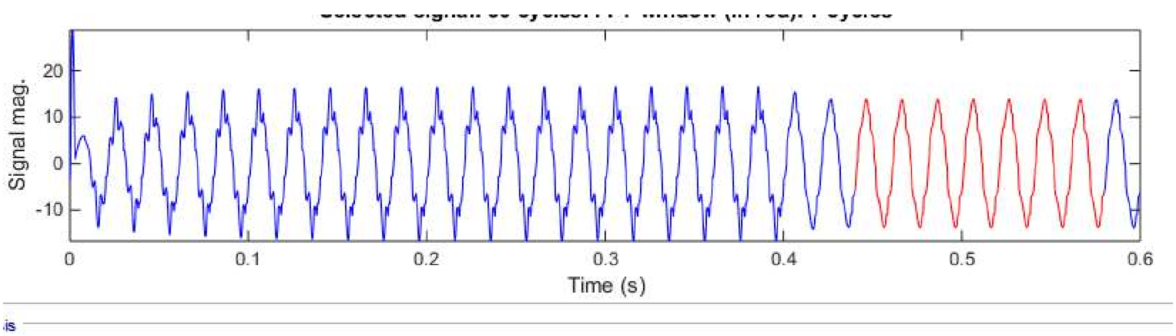



*Figure 4.11 - VFD with input reactor*




```
Sampling time      = 5e-05 s
Samples per cycle = 400
DC component       = 0.0004233
Fundamental        = 13.01 peak (9.197 rms)
THD                = 9.82%
```

*Figure 4.12 - Current waveform at PCC point with and without input reactor*

# 5 Conclusion

Aim of this thesis was performing investigation of harmonic distortion in Eaton European Innovation Center (EEIC) and design a suitable solution. Before performing such investigation, we described necessary theory. At first, we briefly presented electrical installations in industrial plant. We specified topology of such installations and also equipments occurring there and their parameters. Next we studied basics of harmonic currents theory and named the most common electrical equipments generating harmonic currents. Negative effects of harmonic currents were characterized with focus on resonance phenomenon. Standard solutions for mitigation of harmonic currents were discussed. We demonstrated in detail, how to design a passive filter used for power factor correction and filtering of harmonic currents. We explored harmonic distortion limits defined by standards IEC 61000-4-2 and IEEE-519. On the basis of this knowledge, we performed an investigation of harmonic distortion in EEIC, that deals with harmonic currents occurence and resonance phenomenon causing destruction of PFC equipment. We assessed measured data and proposed several solutions, which can be used. Presented solutions were using only detuned reactors in PFC Switchgear, using detuned reactors and also input or DC reactors in VFDs or using an active filter. We realised, that the best solution is using detuned reactors in PFC switchgears and fitting VFDs up with input or DC reactors. Such solution is effordable, suppresses resonance effect in PFC Switchgear and reduces TDD so that it is within the limits defined by IEEE 519.

## Appendix A

Standard IEC 61000-2-4: Compatibility levels in industrial plants for low-frequency conducted disturbances stipulate limits for harmonic voltages in industrial plants (among other parameters, as voltage deviations, voltage dips, voltage unbalance etc.). This standard defines 3 class of electromagnetic environment classes[22]:

- Class 1 – Its compatibility levels is lower than these for public electrical grids. It concerns very sensitive devices, laboratory equipment, some type of computers etc.
- Class 2 – It generally concerns IPC[1] and PCC[2] points in industrial plants. Compatibility levels of this class are the same as these for public electrical grids, defined in IEC 61000-2-2 and EN 51600 as well.
- Class 3 – It concerns only IPC points in industrial plants. Its compatibility levels are higher than these for public electrical grids. It may be considered, when:
    - major of loads are powered from converters
    - welding machines are connected
    - large power motors are switched on often
    - power load frequently varies

Compatibility levels for these three classes are shown in tables A-1 and A-2

| ***Harmonic voltage limits, odd harmonics except for multiplies of three*** | | | |
|---|---|---|---|
| **Order h** | **Class 1 $U_h$ (%)** | **Class 2 $U_h$ (%)** | **Class 3 $U_h$ (%)** |
| **5** | 3 | 6 | 8 |
| **7** | 3 | 5 | 7 |
| **11** | 3 | 3,5 | 5 |
| **13** | 3 | 3 | 4,5 |
| **17** | 2 | 2 | 4 |
| **17<h≤49** | 2,27x(17/h)-0,27 | 2,27x(17/h)-0,27 | 4,5x(17/h)-0,5 |
| ***Harmonic voltage limits, odd harmonics that are multiplies of three*** | | | |
| **Order h** | **Class 1 $U_h$ (%)** | **Class 2 $U_h$ (%)** | **Class 3 $U_h$ (%)** |
| **3** | 3 | 5 | 6 |
| **9** | 1,5 | 1,5 | 2,5 |
| **15** | 0,3 | 0,4 | 2 |
| **21** | 0,2 | 0,3 | 1,75 |
| **21<h≤45** | 0,2 | 0,2 | 1 |
| ***Harmonic voltage limits, even harmonics*** | | | |
| **Order h** | **Class 1 $U_h$ (%)** | **Class 2 $U_h$ (%)** | **Class 3 $U_h$ (%)** |
| **2** | 2 | 2 | 3 |
| **4** | 1 | 1 | 1,5 |
| **6** | 0,5 | 0,5 | 1 |
| **8** | 0,5 | 0,5 | 1 |
| **10** | 0,5 | 0,5 | 1 |
| **10<h≤50** | 0,25x(10/h)+0,25 | 0,25x(10/h)+0,25 | 1 |

*A - 1 - Compatible levels of harmonic voltages by IEC 61000-2-4 [22]*

[1] IPC (in plant point of coupling) - point on a network inside a system or an installation, electrically nearest to a particular load, at which other loads are, or could be, connected

[2] PCC (point of common coupling) - point in an electric power system, electrically nearest to a particular load, at which other loads are, or may be, connected

| | Class 1 | Class 2 | Class 3 |
|---|---|---|---|
| **Total harmonic distortion (TDHU)** | 5% | 8% | 10% |

*A - 2 - Compatible levels for total harmonic distortion by IEC 61000-2-4 [22]*

As said, standards IEC does not stipulate limits for current distortion in industrial plants and public electrical grids. To meet the standards related to harmonic distortion, it is enough to meet limits for harmonic voltages shown above. It means, that in practice it may arise situation, when voltage distortion is relatively small and under limits, but current distortion may be considerable. Such conditions are undesirable, because harmonic currents cause many problems (see chapter 2.10). For this reason, it is suitable to keep current distortion under limits. Limits for current distortion are defined in American standard IEEE-519-92: Recommended practices and requirements for harmonic control in electrical power systems. Limits are shown in table A – 3. Note, that this table deals with total demand distortion, not total harmonic distortion. Total demand distortion is calculated current harmonic distortion (THDI) against full load. It can be calculated as

$$TDD = THDI \frac{P_{actual}}{P_{full}} = THDI \frac{Actual\_power(\%)}{100\%} \quad [\%] \qquad \text{(A1)}$$

Where

$P_{actual}$ Actual power of load

$P_{full}$ Power at full load

Actual_power (%) Actual power of appliance in percentage of full power

| Individual harmonic order (odd harmonics) | | | | | | |
|---|---|---|---|---|---|---|
| **$I_{sc}/I_L$** | **<11** | **11≤h<17** | **17≤h<23** | **23≤h<35** | **35≤h** | **TDD (%)** |
| **<20** | 4 | 2 | 1,5 | 0,6 | 0,3 | 5 |
| **20<50** | 7 | 3,5 | 2,5 | 1 | 0,5 | 8 |
| **50<100** | 10 | 4,5 | 4 | 1,5 | 0,7 | 12 |
| **100<1000** | 12 | 5,5 | 5 | 2 | 1 | 15 |
| **>1000** | 15 | 7 | 6 | 2,5 | 1,4 | 20 |
| Note 1: Even harmonics are limited to 25% of the odd harmonic limits above<br>Note 2: Current distortion that results in a DC offset, e.g., half-wave converters, are not allowed. | | | | | | |

*A - 3 - Current distortion limits for general distribution systems (120 V - 69 000 V) by IEEE 519-92 [23]*

Where

$I_{sc}$ maximum short-circuit current at PCC

$I_L$ maximum demand load current (fundamental frequency component) at PCC

Voltage distortion limits are shown in tables A-4. Note, that limits are severer than these defined by IEC. Low voltage systems may be divided into three applications with different limits, as shown in table A-5. Notice, that standard IEEE defines also limits for commutation notches, occurring due to commutation processes in power converters.

| Bus voltage a PCC | Individual voltage distortion (%) | THDU (%) |
|---|---|---|
| 69 kV and below | 3 | 5 |
| 69001 through 161 kV | 1,5 | 2,5 |
| 161000 kV and above | 1 | 1,5 |

*A - 4 - Voltage distortion limits by IEEE-519-92 [23]*

| | Special applications | General systems | Dedicated system |
|---|---|---|---|
| **THDU (%)** | 3 | 5 | 10 |
| **Notch depth (%)** | 10 | 20 | 50 |
| **Notch area $A_N$ (μs.V)** | 16400 | 22800 | 36500 |
| Note 1: The value $A_N$ for other than 480 V systems should me multiplied by U/480 | | | |
| Note 2: Special applications include hospitals and airports | | | |
| Note 3: A dedicated system is exclusively dedicated to the converter load | | | |

*A - 5 - Low voltage system classification and distortion limits by IEEE-519-92 [23]*

It should be noted, that IEEE standard stipulates limits at point PCC. Nevertheless, explanation of PCC point is slightly different from explanation in standard IEC. Explanation of PCC point in standard IEEE 519-92 is:

A point of metering, or any point as long as both the utility and the consumer can either access the point for direct measurement of the harmonic indices meaningful to both or can estimate the harmonic indices at point of interference (POI). Within an industrial plant, the PCC is the point between the nonlinear load and the other loads.[24]

However, IEEE 519 working group presently defined PCC differently:

The Point of Common Coupling (PCC) with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The ownership of any apparatus such as a transformer that the utility might provide in the customer's system is immaterial to the definition of the PCC.[24].

That definition is very close to definition in IEC standard above. In practice it means, that by original definition, PCC point in industrial plants is secondary side of MV/LV transformer (alternatively HV/MV transformer). According to new explanation, PCC point in industrial plant would be primary side of utility transformer.

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