CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

DIPLOMA THESIS

Bc. Filip Eckstein

Detecting methods of harmonic distortions in power generating system

Department of Microelectronics

Thesis supervisor: **Ing. Lubor Jirásek, Csc.**

PRAGUE 2015

Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Microelectronics

DIPLOMA PROJECT ASSIGNMENT

Student: **Bc. E C K S T E I N Filip**

Study programme: Communications, multimedia and electronics
Specialisation: Electronics

Title of Diploma Project: **Detecting methods of harmonic distortions in power generating system**

Guidelines:

1. Study available literature regarding to damaging of static power generators owing to non-linear load. Focus mainly on effects of third and fifth harmonic frequency.
2. Study and compare different harmonic detection algorithms.
3. Choose an appropriate platform to implement the chosen algorithms based on items 1) and 2). Take into consideration microprocessor's hardware requirements (Flash, RAM, uP computing time, IO, ADC and FPU).
4. Apply chosen algorithms.
5. Test the functionallity of the device and run an analysis of simulated and real data provided by ComAp a.s.
6. Evaluate the results of all implemented methods and their suitability for mentioned purpose.
7. Propose a technical solution for further usage.

Bibliography/Sources:

[1] Nikunj, S.: Harmonics in Power Systems. Siemens Industry, Inc., USA 2013. https://www.industry.usa.siemens.com/drives/us/en/electric-drives/ac-drives/Documents/DRV-WP-drive_harmonics_in_power_systems.pdf (20. 1. 2015)
[2] Eddie Jones, PE; Larry Ray, PE; Tim Shuter, PE: Generator Loading, Harmonics Monito ring and Mitigating Analysis in a Water Treatment Plant. Square D Engineering Services. http://www.schneider-electric.us/documents/solutions1/water-wastewater/generator-loading-harmonics.pdf (20. 1. 2015)

Diploma Project Supervisor: Ing. Lubor Jirásek, CSc.

Valid until: 31. 8. 2015

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Dean

Prague, January 21, 2015

České vysoké učení technické v Praze
Fakulta elektrotechnická

katedra mikroelektroniky

ZADÁNÍ DIPLOMOVÉ PRÁCE

Student: **Bc. E C K S T E I N Filip**

Studijní program: Komunikace, multimédia a elektronika
Obor: Elektronika

Název tématu: **Metody detekce harmonického zkreslení na výkonových generátorech**

Pokyny pro vypracování:

1. Prostudujte dostupnou literaturu týkající poškozování generátorů vlivem zatěžování generátorů měničovou technikou. Zaměřte se zejména na působení 3. a 5. harmonické.
2. Prostudujte a porovnejte možnosti použití různých algoritmů.
3. Vyberte vhodnou platformu pro aplikaci zvolených algoritmů podle bodů 1) a 2). Zohledněte při výběru požadavky na paměť Flash, RAM, strojový čas uP, požadavky na periferie (IO, ADC), další požadavky pro výběr uP (například FPU).
4. Zvolené algoritmy aplikujte.
5. Ověřte funkci zařízení. Proveďte analýzu simulovaných a reálných dat získaných od firmy ComAp a. s.
6. Vyhodnoťte výsledky způsobu implementace algoritmů a jejich vhodnost pro zmiňovaný účel.
7. Navrhněte možná řešení do budoucna.

Seznam odborné literatury:

[1] Nikunj, S.: Harmonics in Power Systems. Siemens Industry, Inc., USA 2013. https://www.industry.usa.siemens.com/drives/us/en/electric-drives/ac-drives/Documents/DRV-WP-drive_harmonics_in_power_systems.pdf (20. 1. 2015)
[2] Eddie Jones, PE; Larry Ray, PE; Tim Shuter, PE: Generator Loading, Harmonics Monito ring and Mitigating Analysis in a Water Treatment Plant. Square D Engineering Services. http://www.schneider-electric.us/documents/solutions1/water-wastewater/generator-loading-harmonics.pdf (20. 1. 2015)

Vedoucí: **Ing. Lubor Jirásek, CSc.**

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V Praze dne 21. 1. 2015

Statement

I hereby declare that I have completed this thesis independently and that I have used only the sources (literature, software, etc.) listed in the enclosed bibliography.
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In Prague on............................ ....

Acknowledgment

I would like to thank to my project supervisor Ing. Lubor Jirásek CSc. for his valuable thoughts and to Cegelec a.s and ComAp a.s. for enabling me to measure all necessary data on a real industrial aggregate. Great gratitude also goes to my family for calm and patient environment they provided me during the study.

Abstract

The increasing demands for uninterruptable and reliable power supply is a challenging issue in the industrial, commercial and safety critical applications such as in hospitals, data centers, shopping malls, banks or production plants. With increasing number of different types of electrical devices and automatization, cross equipment influences and safety of the power supply solution must also be taken into consideration. In this thesis, factors and effects resulting in unwanted harmonic distortion will be studied in order to find the best solution of selective harmonic detection in stationary power generating systems. Selected methods will be described, implemented and tested on the real embedded device. The data necessary for experiments will be measured on a real industrial aggregate in cooperation with ComAp a.s. Based on this thesis, a technical recommendations for the application on a real control device, will be summarized.

Abstrakt

S narůstajícími nároky na nepřetržitou dodávku elektrické energie i během případného výpadku dodávky energie od rozvodných závodů roste počet instalací, které jsou vybaveny záložním dieselovým, nebo plynovým motorgenerátorem. Tyto generátory se nejčastěji nacházejí v nemocnicích, datových centrech, obchodním domech, bankách anebo výrobních závodech. Důležitým faktorem je dále kvalita sítě, která je přímo ovlivňována připojenou nelineární zátěží. Tato práce se zabývá působením harmonického zkreslení na stacionární generátory elektrické energie a metodami vhodnými k jeho detekci. Metody selektivní detekce harmonického zkreselní - zejména pak třetí a páté harmonické - budou implementovány do reálného vestavného zařízení, kde budou otestovány na reálných průbězích signálu naměřených ve spolupráci s ComAp a.s. Na základě výsledků proběhnuvších experimentů bude doporučena vhodná metoda k implementaci do průmyslového řidicího systému.

Key words

harmonic distortion, harmonic spectrum, frequency, embedded device, Goertzel, FFT, RDFT, Fast Fourier Transformation, spectral leakage, triplen harmonics, third harmonic, fifth harmonic, convolutional windows, gen-set, odd harmonic, even harmonic

Key words

harmonické rušení, harmonické spektrum, frekvence, vestavný systém, Goertzel, FFT, RDFT, rychlá fourierova transformace, zkreslení spektra, liché harmonické, sudé harmonické, třetí harmonická, pátá harmonická, konvoluční okna, gen-set

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List of acronyms

μP Microprocessor. 3

AC Alternating Current. 1, 5, 6

ADC Analog/Digital Convertor. 3, 27, 44, 48

CPU Central Processing Unit. 21

DC Direct Current. 6, 21

DFT Discrete Fourier Transform. ii, 20–22, 24–27, 45

DSP Digital Signal Processing. 2, 20, 26, 29, 42

DTMF Dual-tone multi-frequency. 26

EMC Electromagnetic Compatibility. 17, 44, 48

EU European Union. 18

FFT Fast Fourier Transform. ii, iv, 20, 21, 24–27, 29, 42, 44–46, 48

FPU Floating Point Unit. 3, 29, 42, 48

I/O Inputs/Outputs. 2, 3

IIR Infinite Impulse Response. 26

PCC Point of Common Coupling. iv, 7

RAM Random Access Memory. 2, 3

RDFT Real-Time Discrete Fourier Transform. 20, 21, 27

RLC Resonant circuit. 8

RMS Root Mean Square. 17

SMPS Switch Mode Power Supply. 1, 18

SRAM Static Random Access Memory. 44, 45

TDD Total Demand Distortion. 7, 8

THD Total Harmonic Distortion. iv, 7, 8, 31, 46, 48

UPS Uninterruptible Power Supply. 1

VFD Variable Frequency Drives. 6

1 Introduction

In this chapter, the following issues will be discussed:

1. State of the art
2. Aim of the thesis
3. Structure of the thesis

1.1 State of the art

Nowadays, electricity and reliable sources of electrical power play an important role in the modern society. This need of uninterrupted electricity insists on efficiency, reliabiltiy, service life and economical factors of electrical power supplies. With increasing number of different types of electrical devices and automatization, cross equipment influences and safety of the power supply solution must also be taken into consideration.

The increasing demands for uninterruptable and reliable power supply is a challenging issue in the industrial, commercial and safety critical applications such as in hospitals, data centers, shopping malls, banks or production plants. Such installations must ensure the basic power supply in case of temporary power failure or a global blackout caused by e.g. a natural disaster. The most widespread solution to secure these basic power needs are covered with oil or gas fuelled[1] generator sets[2] in cooperation with the Uninterruptible Power Supply system. The main purpose of the UPS is to cover the energy supply during the short-break between the moment of the failure and the time when the generator set is loaded.

Installations[3] equipped with this solution are often the source of non-linear loads[4] which are caused by frequency converters, fluorescent tubes, AC motors with frequency converters, computers or automation devices.

Today, harmonics problems are common in various applications starting with industrial installation through commercial buildings to residential houses. Proliferating influence of upper harmonics to non-industrial applications is mainly caused due to new power conversion technologies such as the Switch Mode Power Supply[5]. This type of power supply is

[1] Requests for renewable natural resources also play an important role in recent years.
[2] Hereafter also referred to as gen-sets.
[3] Hospitals, data centers etc.
[4] The definition of the non-linear load will be described in chapter 2.2.
[5] The SMPS is an excellent power supply, but it is also a highly non-linear load.

integrated in virtually every today's power electronic device such as in computers, TV's, printers, banking machines, monitors etc. (see [1]).

Owing to upper harmonics, this kind of load may cause additional stress of the three phase generator set while operating in the island[6] operation. Skin effect evokes thermal stress and may irreversibly damage the gen-set current conductors. A directly earthed conductor[7] may be overloaded by the multiples of the third harmonic order. Other kinds of loads are responsible for mechanical stressing of the aggregate and can lead to supply voltage unbalance. With the increase in use of non-linear loads, detecting the upper harmonic frequencies is more important than ever as early detection can succeed in protecting the aggregate before the irreversible damage or even destruction.

One of the other negative consequences of current harmonic distortion is Flicker effect, which is responsible for unwanted light emission changes of incandescent lamps whereon the human eye is extremely sensitive [8]. According to [2], this phenomenon is usually associated with voltage fluctuations produced by load current changes (see [2]).

In the power applications, external measuring and control systems are used for purposes of harmonics detection. Some gen-sets are equipped with a multifunctional embedded controlling system that is able to measure three phase voltage/currents and calculate reactive power, active power, apparent power and power factor. These embedded systems are fitted with microcontroller unit (or Digital Signal Processing unit) able to calculate input signals samples in real time so the system can provide a fast feedback to control the aggregate properly. Unfortunately, today's microcontrollers (or microprocessors) have limited resources such as the size of a program's memory (flash), the size of data memory (Random Access Memory), number of Inputs/Outputs ports or lack of computing power. These constraints must be taken into consideration when choosing and implementing digital signal processing algorithms, as they might be unsuitable for embedded devices. In this thesis, all chosen algorithms for detecting harmonics will be compared and assessed in light of their use in low power microcontroller devices.

[6]Backup power supply is in the island mode if operates in isolation from the national or local electricity distribution network.

[7]Neutral wire.

[8]In the range between 0 and 30Hz[2].

1.2 Aim of the thesis

1. Study available literature regarding to damaging of static power generators owing to non-linear load. Focus mainly on effects of third and fifth harmonic frequency.
2. Study and compare different harmonic detection algorithms.
3. Choose an appropriate platform to implement the chosen algorithms based on items 1) and 2). Take into consideration microprocessor's hardware requirements (Flash, RAM, μP computing time, I/O, ADC and Floating Point Unit).
4. Apply chosen algorithm.
5. Test the functionallity of the device and run an analysis of simulated and real data provided by ComAp a.s.
6. Evaluate the results of all implemented methods and their suitability for mentioned purpose.
7. Propose a technical solution for further usage.

1.3 Structure of the thesis

In this thesis, several algorithms capable of detecting harmonics in the power generation system will be described and compared. The final results of this research are summarized in the chapters 4 and 5 which consists of detailed computer simulations and expertiments on the real embedded platform.
In the chapter 4, we will focus on the computer simulations of the chosen algoritms as will be described in the chapter3. The main purpose of evaluating computer simulations was to debug the results effectivelly prior to downloading the program into the target embedded platform. All results were then exported into the MATLAB framework for further research.
The chapter 5 summarizes the results of measurements on the embeddded platform chosen for purposes of this experiment.
The recommendations for application resulting from the research in this thesis are listed in chapter 6.

1.4 Chapter summary

The main conclusions drawn from this chapter can be summarized as follows:

Power supply demands

- reliability
- efficiency
- correct values
- life-cycle length
- no cross equipment influence

Upper harmonics sources

- power electronics equipment (switching converters, pulse/pulse-width modulated converters)
- power system elements (resonant interaction, overloaded transformer, generator construction, etc.)

Upper harmonics issues

- dissipation of heat due to additional losses
- Flicker effect
- life-cycle shortening
- system performance detention

2 Fundamentals of harmonics in power systems

In this chapter, the basic concepts of harmonics characteristics and formation in the context of power generating systems will be covered. In this thesis, AC circuts are considered. In this chapter, the following issues will be discussed:

1. Linear and non-linear load
2. Generation of harmonics
3. Negative effects of harmonic distortions
4. Harmonics in different three-phase configurations
5. EMC standards

2.1 Even and odd harmonics

In an electrical power distribution system, the two types of harmonics exists - even and odd. Both types relate to mathematical definitions of even[9] and odd[10] functions, where even is symmetrical to y-axis and odd is centrally symmetrical by the beginning of the coordinate system. From the electrical point of view, even harmonics are unnatural and in a power distribution nework occurs very rarely. However, they sometimes could be detected as a result of electrical device malfunction or if artificially injected into a power distribution network. In this thesis, an odd harmonics will be observed.

It is possible to visualize harmonic frequencies into a graph, which is called the harmonic spectrum. Such spectrum contains only frequency components which are multiplies of the fundamental frequency. According to Theorem 1), visualized harmonic spectrum has a degressive nature.

Theorem 1 *(High order harmonics frequencies law). The higher frequency is in the harmonic spectrum, the smaller amplitude the waveform of given harmonic has, unless the power source of this harmonic is greater than the power source of the fundamental frequency.*

[9] Unnatural.
[10] Natural.

2.2 Linear and non-linear load

As described in chapter 1.1, a so-called linear load connected to an electric power system is defined as a load which draws current from the supply and this current is proportional to the applied voltage. Examples of devices causing this type of load are fixed speed induction motors, heaters, light bulbs (resistive load) or incandescent lamps.

A load is considered non-linear if its impedance changes with the applied voltage. Changing impedance of the load causes the non-sinusoidal nature of the drawn current, even when connected to a sinusoidal voltage source. This can lead to the retroactive effect of load on a power source, whereon load is conected. The schematic of the configuration causes the retroactive effect owing to additional frequency sources is shown in Figure 1.

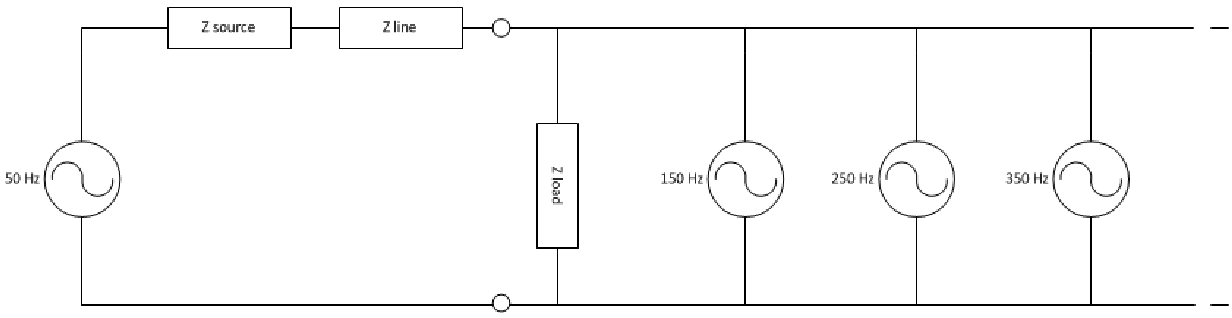


Figure 1: Schematic of a non-linear load connected to a power source.

Examples of devices causing the non-linear load are personal computers, VFD's, discharge lighting etc. Some of these devices are often equipped with the static power converters that are able to convert AC to DC, DC to DC, DC to AC and AC to AC. Such converters constitute the largest non-linear loads connected to electric power systems.[3]

2.3 Generation of harmonics

According to Fourier theorem, it is possible to decompose every signal to a series of sine waves with different characteristics (e.g. amplitude, frequency). Non-sinusoidal currents containing harmonic (multiples of a fundamental sine wave) currents are interacting with the impedance of the power distribution system and creating a voltage distortion. This distortion can affect both the distribution network equipment and the loads connected to it.[3]

As mentioned in chapter 2.2, devices causing the non-linear load are often equipped with static power converters which are responsible for the supply voltage distortion at the

PCC. The PCC is the point electrically nearest to a particular load, between the power distribution system network and the end user at which other loads are.[3] The PCC is illustrated in the following Figure.

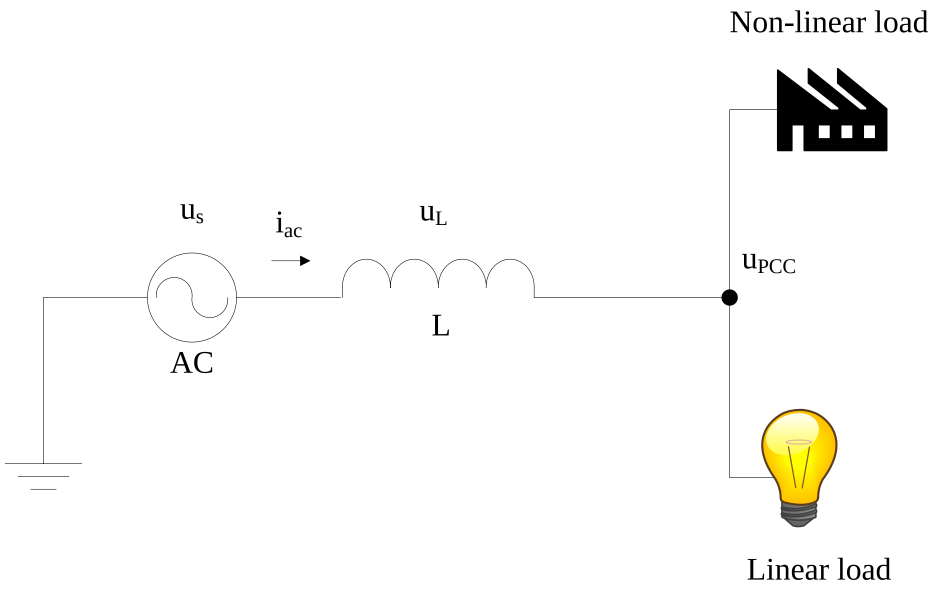


Figure 2: Illustration of the PCC.

2.4 Evaluation of harmonic distortion

In an effort to calculate the severity of harmonic distortion of a signal, THD[11] and TDD[12] factors were introduces. In order to calculate THD and TDD factors, Fourier analysis based decomposition of signal must be performed in advance. These factors belongs to important electric power quality indices. THD is calculated based on an actual load, whereas TDD calculates harmonic current distortion in a percentage of a maximum demand load current.

Total Harmonic Distortion of voltage THD_U is defined as follows:

$$THD_U = \frac{\sqrt{\sum_{\nu=2}^{\infty} U_\nu^2}}{U_1} 100 \qquad (\%). \tag{1}$$

[11] Total Harmonic Distortion
[12] Total Demand Distortion

Total Current Harmonic Distortion THD_I is defined as:

$$THD_I = \frac{\sqrt{\sum_{\nu=2}^{\infty} I_\nu^2}}{I_1} 100 \qquad (\%). \tag{2}$$

Total Current Demand Distortion (TDD) takes into consideration the circuit rating and it is defined as:

$$TDD_I = \frac{\sqrt{\sum_{\nu=2}^{\infty} I_\nu^2}}{I_{RMS}} 100 \qquad (\%), \tag{3}$$

where U_ν is a voltage of given frequency harmonic, U_1 is a voltage of a fundamental frequency, $I_1$is a current of a fundamental frequency, I_ν is a current of a given frequency harmonic and I_{RMS} is RMS current of a signal.

Measuring and calculating TDD and THD is essential to meet IEEE 519 standard, which is intended to limit the negative consequences of non-linear load effects.

2.5 Effects of harmonics

In this section, the most frequent problems caused by the harmonic voltages and currents will be listed. Exploration of facts resulting from Harmonics: Causes and Effects by David Chapman [4], where the basic consequences of harmonic contaminated current and harmonic contaminated voltage is described.

2.5.1 Effect of harmonics on impedance

The impedance of the RLC circuit is defined as

$$Z = \sqrt{R^2 + \left(\left(\frac{1}{2\pi f C}\right) - (2\pi f L)\right)^2}, \tag{4}$$

where R is resistance, f is frequency, C is capacitance and L is inductance.

As is shown in equation (5), the impedance of the RLC circuit is frequency dependent. Thus if frequency increses five times (e.g 5^{th} harmonic frequency occur), then the impedance of the circuit on given frequency is five times greater. This effect results in additional energy losses, which results in a temperature growth of an alternator. Permanent crossing of the temperature over the permitted values given by a manufacturer of an aggregate may significantly reduce the machine life-cycle.

2.5.2 Harmonic sequencing

Harmonics are divided into three types by their sequence - positive, negative and zero. Positive sequence harmonics rotate in the same direction as the fundamental frequency (forward direction). Positive harmonics, for example 4^{th}, 7^{th}, 10^{th} or 13^{th}, are classified. In a power distribution network, positive sequence harmonics are undesirable as they cause the overheating of transformers and conductors due to the addition of the waveforms.

Negative sequence harmonics rotate in the opposite direction, causing them to generate a reverse power in motors. This is especially true in induction motors, where the opposite phasor rotation weakens the required rotating magnetic field, resulting in less mechanical toruque produced. Negative sequence harmonics, for example 2^{nd}, 5^{th}, 8^{th} or 11^{th}, are classified. If the focus is on odd harmonics only, then negative sequence harmonics can be expressed as multiples of 5^{th} order.

The last set of harmonics have a zero rotational sequence, but they circulate between the phase and neutral line. This causes an unwanted current and/or voltage addition on the neutral line, which is responsible for an excessive heating. Among these so-called "triplen" harmonics, multiples of 3^{rd} order are classified.

The classification of first twelve harmonics can be seen in Table 1 located below. In the table, "+" means positive sequence, "-" means negative sequence and "/" means zero or no sequence. The illustration of harmonic sequencing is shown in Figure 3.

	Fund.	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**	**11th**	**12th**
Frequency [Hz]	50	100	150	200	250	300	350	400	450	500	550	600
Sequence	+	-	/	+	-	/	+	-	/	+	-	/

Table 1: Harmonic sequencing

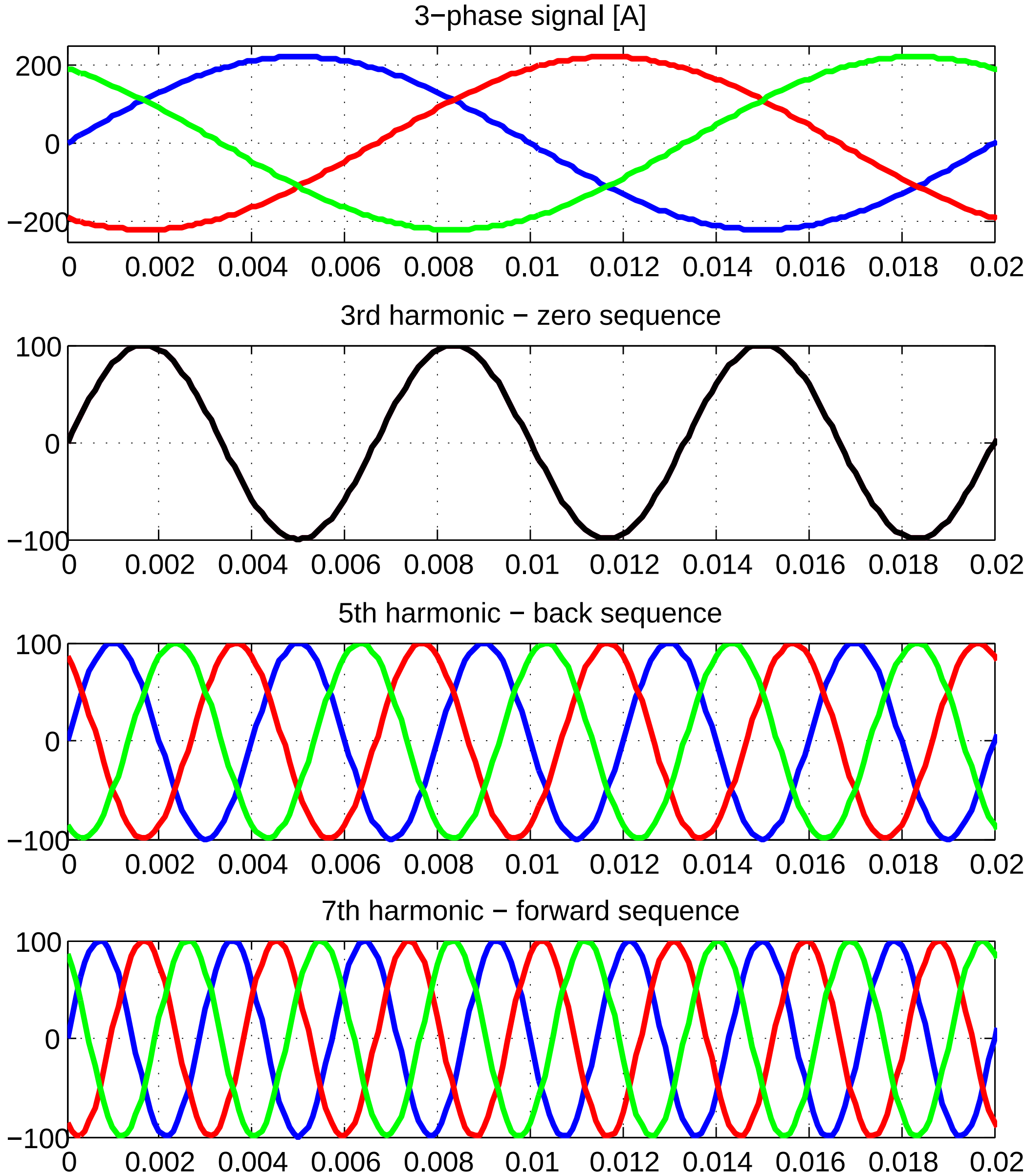


Figure 3: Illustration of harmonic sequencing.

2.5.3 Overheating of transformers

Influence of harmonics on transformers can be observed on energy losses caused by the eddy currents, effects of frequency dependent losses, magnetizing curve characteristics effect etc. These losses normally take normally around 10% of sum of all losses in the fully loaded convertor and they are raising with a square of harmonic order. This will lead to higher operational temperature and shorter life of a transformer. Overheating of transformers is one the most serious problems as 10 % of thermal overload reduces the transformer life-cycle to half.

2.5.4 Overloading of neutral line

In the four-wired symmetrical power network odd harmonics can cause the distortion of the current flowing through the neutral conductor as they cause that the vector sum of the phase currents at each phase leads to non-zero current in the neutral point. This is the result of unequally loaded phases, where odd hamonics at each line are in phase with each other (thus they are not shifted about 120°) and this effect results in unwanted addition on the neutral line as showing in Figure 4.

According to Chapman, on commercial building case studies can be shown that the current in the neutral conductor is in range of 150% to 210% of nominal phase current[13].

2.5.5 Overloading of compensation capacitors

The main purpose of compensation capacitors is to compensate the phase shift caused by the delayed current when induction load is connected. The impedance of the capacitor is descreasing with frequency (caused by upper harmonics) while the network impedance is increasing. This may result in damage of the capacitor as is parmanently loaded by upper harmonic components. These components may also cause the resonance of the capacity[14] which is responsible for sudden current or voltage peaks in the power disribution network.

2.5.6 Harmonic current flow to the other devices

Harmonic distortion of voltage causes harmonic current flow even to the other devices connected to the power distribution network (including the sources of linear load).

[13] Often in the half cross section designed neutral wires.

[14] Bank with the inductive elements in network.

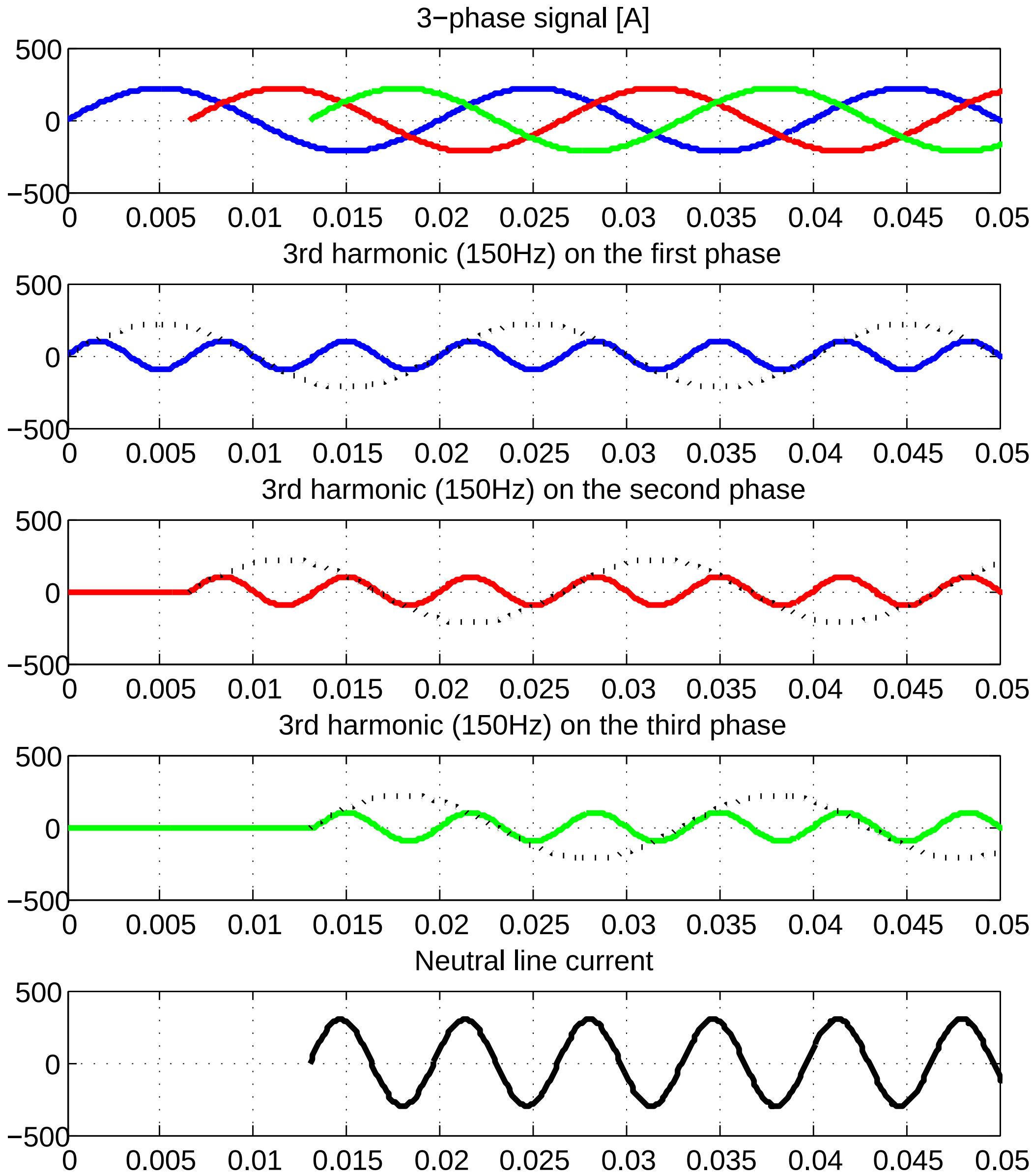


Figure 4: Illustration of influence of 3^{rd} harmonic on neutral line.

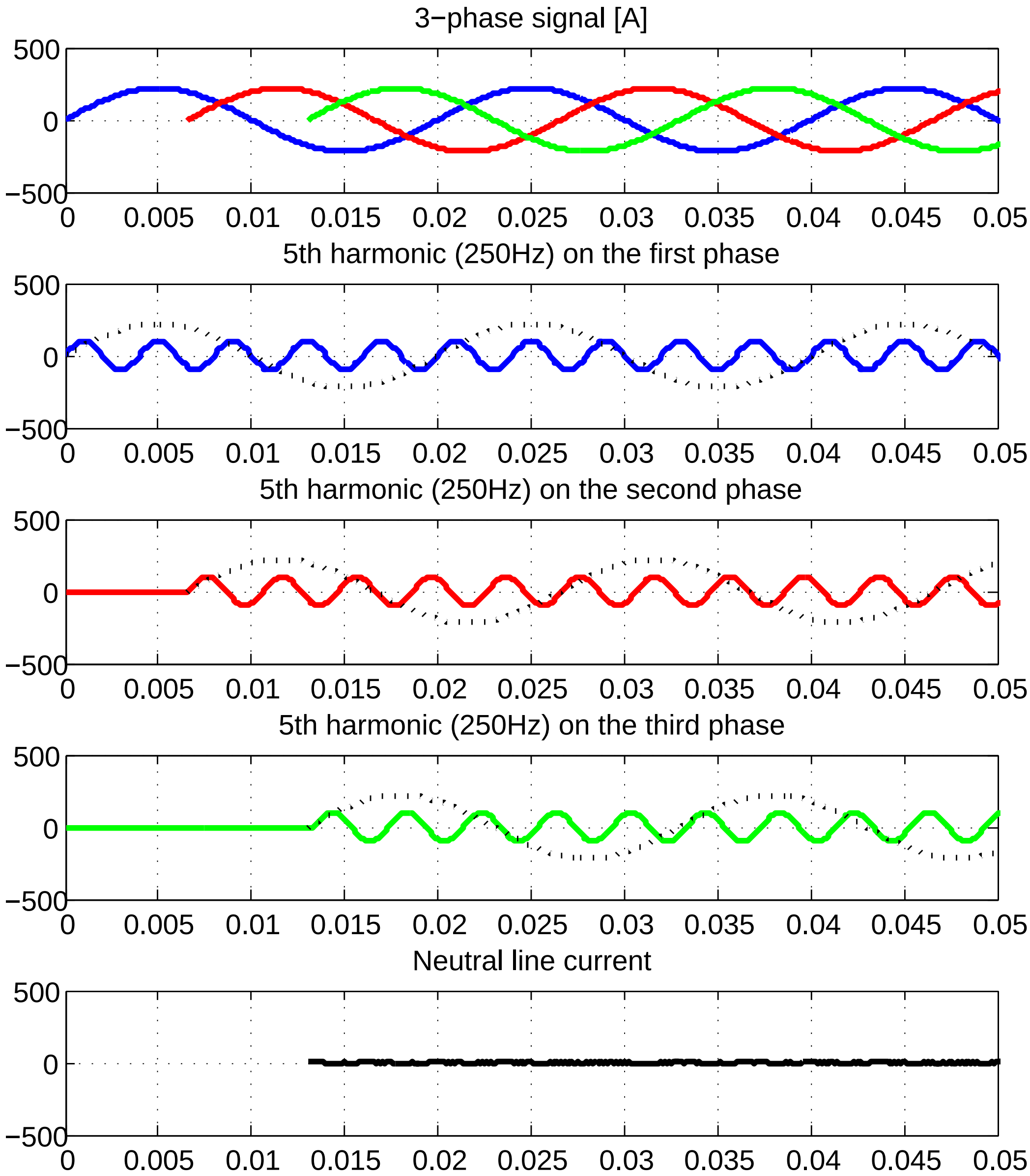


Figure 5: Illustration of influence of 5^{th} harmonic on neutral line.

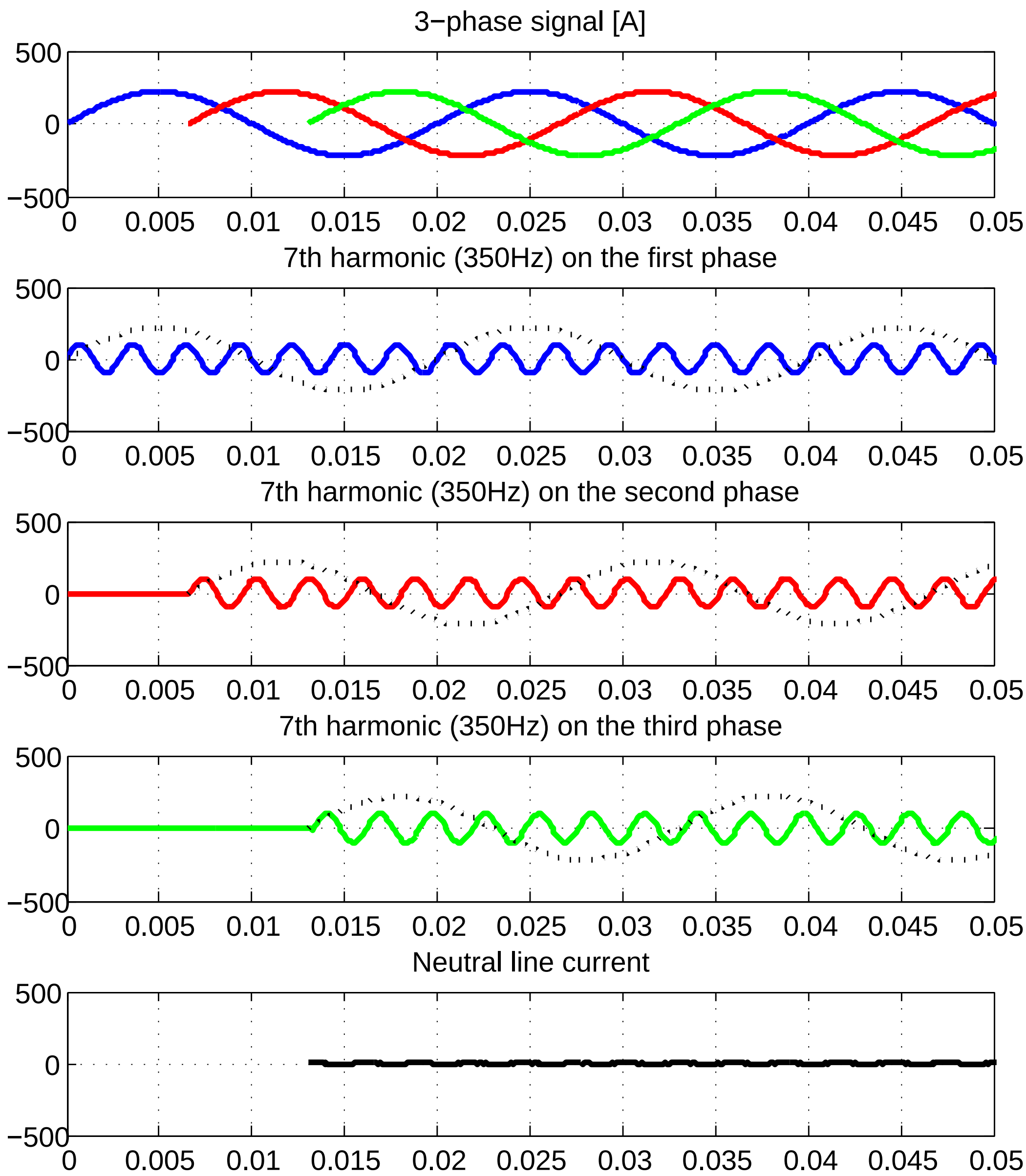


Figure 6: Illustration of influence of 7^{th} harmonic on neutral line.

2.5.7 Skin effect

Skin effect is the phenomenon whereat alternating current flows through the edge of the wire. This effect is frequency driven so it can be observed on higher frequencies. Significance of skin effet increases over 350 Hz (7^{th} harmonic order) as it is causing the additional losses and heat in wires.

2.5.8 Zero cross errors

The measurement tools which are based on a zero cross detection don't work properly when signal is contaminated by the upper harmonics. Distorted signal causes multiple zero crossing which will lead to the measuring error. Also, many types of electronic controllers are based on zero-cross voltage detection to determine the moment when the load went off. Switching off the load during the voltage zero crossing is beneficial as is possible to avoid the transient effects and aging of the switches.. If signal is contaminated, zero-cross based control loops becomes instable.

2.6 Harmonics in different configurations

In this section, the main principles of occurence of upper harmonics (mainly 3^{rd} harmonic) in different topologies of three-phase power systems will be described. However, only a brief description of each type of connection will be mentioned. A thorough study of discussed problems can be seen in [5]. There are two general ways three-phase power systems can be connected that shall be considered - 2.6.1 Star configuration and 2.6.2 Delta configuration.

2.6.1 Star configuration (Y)

The star connection is formed of the three windings that are connected together in the same point which is generally called the neutral.

Any star-connected system of lines could be connected in two different forms. In the first option we can use the four-wire connection (it means L1, L2, L3 and neutral wire). For every even order harmonic frequency, the 3-phase 4-wire system is still balanced as all even harmonics are not in phase so they are canceled. This is valid for all even harmonics.

If we examine an odd order harmonics, we will find out that the third-harmonic[15] waves at each conductor are in phase with each other. If there is even harmonic distortion, the

[15] And consequently fifth, seventh, etc.

current still cancels out in the neutral wire, but if there is odd harmonic current distortion it adds instead. This could produce a very large current on the neutral wire.

The second form of the star system consists of a three-wire connection, which is specific as a neutral wire is not present or is unearthed. Consequently, in a symmetrical three-wire star-connected power system third harmonics currents cannot exist. However, if we focus on the third-harmonic voltage, it can exist in each phase but only from line to ground. They cannot appear in the line-to-line voltage.

2.6.2 Delta configuration (Δ)

The main difference of the delta configuration in comparison with the star configuration is the absence of the neutral point; the opposite ends of each of the three windings are connected together such that the end of each winding is connected with the beginning of another winding. Thus, the third-harmonic is not able to flow to any neutral wire. It was shown by Franklin[5] that: "In a symmetrical three-phase delta-connected system third-harmonic voltages tending to occur in each phase would be spaced 360° apart, and so would be in phase with each other and act in the closed delta circuit as a single-phase voltage of third-harmonic frequency. Such a voltage could not actually exist in a closed delta system, so that third-harmonic currents circulate round the delta without appearing in the lines and the third-harmonic voltages are suppressed." However, the third harmonic current still heats the winding of an aggregate.

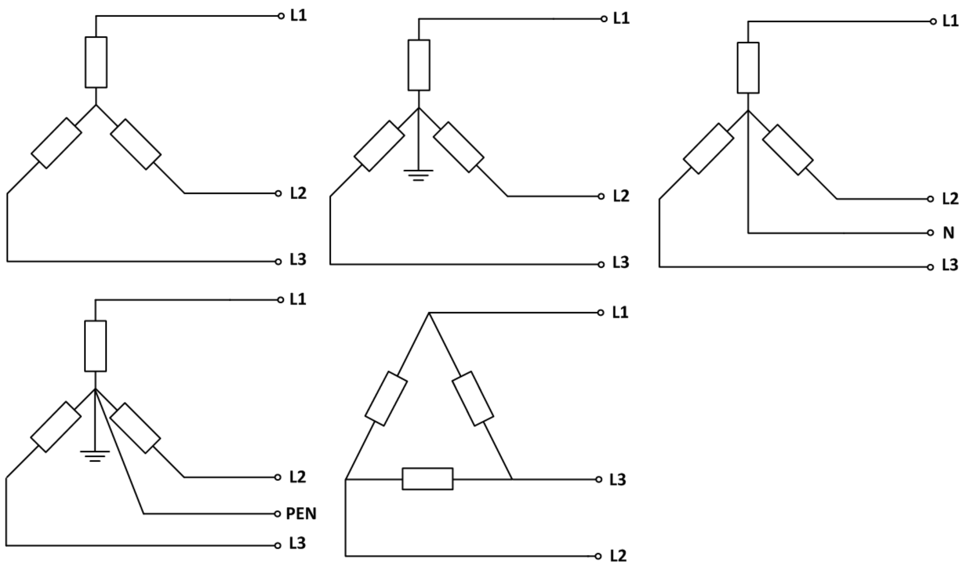


Figure 7: Illustration of various topologies of a 3-phase systems.

2.6.3 Summary of consequences of odd harmonics in different 3-phase configurations

As is shown in Franklin[5]:

	Star (3 wire)	**Star (4 wire)**	**Delta (3 wire)**
Odd harmonic currents	Cannot exist.	Exist between the phases and between phases and neutral.	Completely suppressed.
Odd harmonic voltages	May exist between lines and neutral. Not between lines.	Exist between the phases and between phases and neutral.	Exist, but they flow round the closed delta configuration, not in the phases itself.

Table 2: Consequences of odd harmonics in different configurations.

2.7 EMC standards

Every electronic device, radio device or electromagnetic based aggregate must follow all electrotechnical standards and regulations valid in the country, where the device is operating. These standards are described in documents, which can differ depending on the country of origin. If the device is designated for a worldwide export, then the certification for multiple standards must be fullfiled in order to assure the electromagnetic compatibility (EMC).

According to EN 50160[16], 95 % of ten-minute RMS values in any week period must not exceed given ratio of harmonic contribution. Percentage ratio of allowed harmonic contribution is given for odd multiples of three up to 21^{st} harmonic frequency - thus for 3^{rd}, 9^{th}, 15^{th} and 21^{st} term. For odd non-multiples of three, tolerable harmonic contribution ratio up to 25^{th} harmonic are defined. Harmonic frequencies over 25^{th} harmonic order are not mentioned in the standard. However, total harmonic distortion, that includes all harmonic frequencies (odd and even) up to 40^{th} order, must not exceed 8% limit.

[16]This standard is valid in the European Union as well as in the Czech Republic.

The list of other important standards describing the EMC and harmonic regulations is shown below this paragraph:

- EN 50160
- Harmonic Standard ER G5/4 (UK)
- IEC 61000-4-30 EMC
- IEC 1000-3-6 EMC

To satisfy Czech and EU standards, *the detection of* 3^{rd} *and* 5^{th} *harmonic frequency only - as subjeted to exploration in this thesis - is insufficient as total harmonic distortion (THD) measurement must be performed up to* 40^{th} *harmonic order*. This must also include all even components. Further research within this thesis will consider this finding.

As was already mentioned in section 2.4, THD is defined as follows:

$$THD_U = \frac{\sqrt{\sum_{\nu=2}^{\infty} U_\nu^2}}{U_1} 100 \qquad (\%). \tag{5}$$

2.8 Chapter summary

The main conclusions drawn from this chapter can be summarized as follows:

Generation of harmonics:

- Power electronics - power convertors, SMPS
- Lighting - fluorescent tubes and electronics
- Technology

Effects of high harmonics:

- Effects on impedance
- Back sequence harmonics in rotating machines
- Overheating of transformers
- Overloading of neutral line

- Overloading of compensation capacitors
- Skin effect
- Harmonic current flow to the other devices
- Zero cross errors

Harmonics in different configurations:

- Harmonics effects in star configuration
- Harmonics effects in delta configuration

EMC standards

- European IEEE standards
- Calculation of Total Harmonic Distortion

3 Harmonics detection algorithms

In this chapter, the following issues will be discussed:

1. The comparison of the characteristics of chosen methods
2. Fourier analysis fundamentals
3. The description of each chosen algorithm

3.1 Chosen algorithms

The digital signal processing theory covers a vast scientific area including the basics of harmonic distortion detection in periodic signals. This thesis does not cover all existing methods as it would be difficult and time-consuming to do such extensive research. Among other things, some methods could be excluded as they are inappropriate to use in an embedded low performance device. Notwithstanding, the simple[17] Discrete Fourier Transform[18] method was implemented and tested in the embedded device to demonstrate its ineffectiveness in comparison with DSP optimized detection methods which will be described in detail further in this chapter. In summary, five harmonic detection methods were implemented and observed on the DSP microprocessor device:

- Discrete Fourier Transform (DFT)
- Optimized Discrete Fourier Transform (DFT)
- Fast Fourier Transformation (FFT)
- Goerzel algorithm
- Sliding Real-time Discrete Fourier Transform (RDFT)

In this chapter, all theoretical fundamentals of chosen algorithms will be described.

[17] Brute force.
[18] Hereafter referred to as DFT.

3.2 Comparison of chosen methods characteristics

In the following table (3), the basic characteristics of all chosen algorithms were compared. There were several criteria which were respected such as computational complexity, ability of algorithm to count only selected frequencies or the need of N to be a power of 2. The ability of the algorithm to be used for 1-phase applications was also taken into consideration. Details and important remarks for the summary are described below the table.

	DFT	**RDFT**	**FFT**	**Goertzel**	**Optimized DFT**
Selective harmonic calculation	Yes	No	No	Yes	Yes
1-ph / 3-ph applications	1ph + 3ph	1ph + 3ph	1ph + 3ph	1ph + 3ph	1ph + 3ph
Computational complexity	N^2	N^2	$Nlog_2N$	NM	N^2
Need of N to be power of 2	No	No	Yes	No	No

Table 3: Comparison of algorithms.

If we focus on RDFT, it can be shown that the computational complexity for each subsequent sample is $O(N)$ for RDFT in comparison with $O(N^2)$ for DFT or $O(Nlog_2N)$ for FFT. However, if RDFT is always computed for new N samples, then the complexity is the same as for the DFT algorithm.

Goertzel algorithm is able to calculate selected bins of the frequency spectrum. Then the computational complexity can be qualified as M applications (based on the number of bins) of Goertzel algorithm on a data set with N samples.

If we take a closer look at DFT and the optimized DFT, the computational complexity (N^2) and the main principle of both algorithms are identical. However, in the case of optimized DFT, a look-up table (for trigonometric coefficients) was implented so the time for computation was significantly decreased but the demands for CPU memory increased.

3.3 Fourier analysis fundamentals

Harmonic analysis is based on calculating independent terms of Fourier series coming from the Fourier theorem.

The Fourier series of a discrete periodic signal is defined as

$$x[n] = \frac{A_0}{2} + \sum_{k=1}^{K} A_k \cos kn + \sum_{k=1}^{K} B_k \sin kn, \tag{6}$$

where A_0 is the DC component, which is defined as

$$A_0 = \frac{2}{N} \sum_{n=1}^{N} x[n]. \tag{7}$$

The coefficients A_k and B_k can be written as

$$A_k = \frac{2}{N} \sum_{n=1}^{N} x[n] \cos n\alpha_n, \tag{8}$$

$$B_k = \frac{2}{N} \sum_{n=1}^{N} x[n] \sin n\alpha_n, \tag{9}$$

where α_k is a partial angle of the signal period as shown in Figure 10:

$$\Delta\alpha = \frac{2\pi}{N}. \tag{10}$$

This will lead to the final identification of selected harmonic frequencies by calculating the magnitude and phase:

$$X[k] = \sqrt{A_k^2 + B_k^2}, \tag{11}$$

$$\psi[k] = \arctan \frac{B_k}{A_k}. \tag{12}$$

3.4 Discrete Fourier transformation

The discrete Fourier transform (DFT) belongs to the family of mathematical techniques based on decomposing signals into sinusoids which is called Fourier analysis. Fourier analysis was first described by Jean Baptiste Joseph Fourier in 1807 in a paper containing the controversial claim that every signal can be represented as a sum of sine functions. The DFT belongs to a branch of the Fourier family algorithms, where digitized signals can be analyzed.[6]

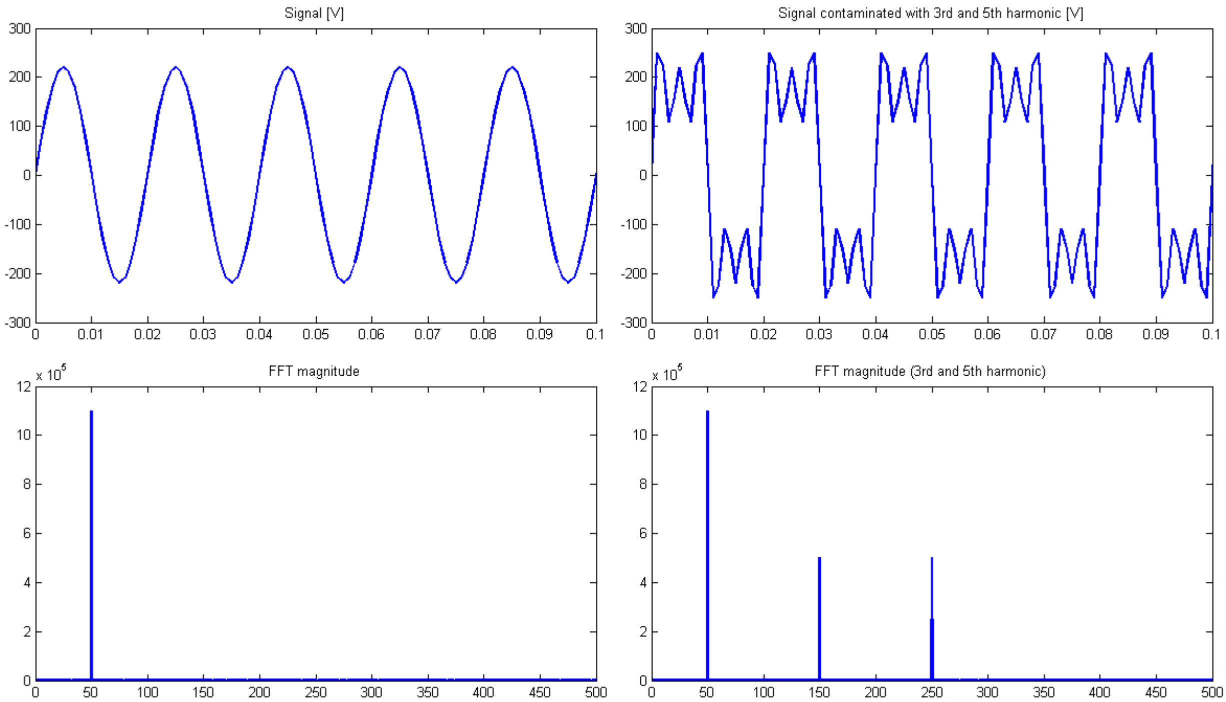


Figure 8: Demonstration of signal contaminated with 3^{rd} and 5^{th} harmonic frequency and the equivalent FFT spectra.

3.4.1 Mathematical background

The implemented algorithm is based on a discrete calculation of the real and the imaginary part of the discrete Fourier transform, which is mathematically described in the following equation:

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-\frac{jkn2\pi}{N}}, \tag{13}$$

where

$$x[n] = 0, 1, 2, ..., N-1, \tag{14}$$

and according to De Moivre's Theorem (15), finally decomposed into the summation (16) of the real and the imaginary parts

$$e^{j\theta} = \cos\theta + j\sin\theta, \tag{15}$$

$$X[k] = X_{re}[k] + jX_{im}[k], \tag{16}$$

where imaginary part is expressed as

$$X_{im}[k] = \sum_{n=0}^{N-1} x[n] \sin(\frac{jkn2\pi}{N}) \tag{17}$$

and the real part is

$$X_{re}[k] = \sum_{n=0}^{N-1} x[n] \cos(\frac{jkn2\pi}{N}). \tag{18}$$

Therefore the algorithm was implemented as a cyclic calculation and summation of the real and imaginary part for each signal sample. The process of summation was repeated for each harmonic order.

3.4.2 Optimized DFT

As the so-called "Brute force DFT" algorithm is ineffective and improper for use in an embedded systems applications, the optimized version of algorithm was implemented. Mentioned inefficiency of the DFT computation lies on the time-intesive calls of the trigonometric operations as mentioned in equations (17) and (18) above. The coefficients for each sample are same for each data array of N samples. This fact can be used in order to optimize the algorithm for use in an embedded microprocessor by precalculating the trigonometric coefficients into the look-up-table. Furthermore, in the real implementation only one table for both coefficients is enough if clever array indexing is used[19]. However, if the number of samples is other than N, then the coefficients must be recalculated. This type of optimization represents a compromise between the computation complexity and requirements for the static memory.

3.5 Fast Fourier Transformation

The Fast Fourier Transform[20] was first described in 1965 be J.W. Cooley and J.W Turkey[21] in their paper: "An algorithm for the machine calculation of complex Fourier

[19] With advantage, we can prosper from the periodic character of sine and cosine functions.
[20] Hereafter reffered to as FFT.
[21] The FFT is also known as the Cooley-Turkey algorithm.

Series," Mathematics Computation, Vol. 19, 1965, pp 297-301. The basic principle of FFT algortihm coming out from the complex DFT as the use of complex numbers play an essential role in this spectrum calculation method. As the FFT belong to notorius methods of signal spectrum analysis, only fundamental principle will be described within this thesis. However, detailed study can be perfomed reading Cooley-Turkey's paper or book: "The Scientist and Engineer's Guide to Digital Signal Processing," by Steven W. Smith, Ph.D.[6]

3.5.1 Process of FFT calculation

The FFT converts a time domain singal to a frequency domain data. The process of calculation consists of three main stages. In the first stage, N (samples) time domain signal is decomposed into N signals each containing a single point. This is performed by effective bit reversal data sorting. By performing this step we will also find (the second stage) the frequency spectra of the 1 point time domain signals as the frequency spectrum of a 1 point signal is equal to itself. Finally, the last (and the most complicated part) of the calculation is to combine the "N frequency spectra in the exact reverse order that the time domain decomposition took place."[6] As it is not possible to apply the bit reversal shortcut for the frequency domain decomposition, the calculation must be performed step by step. The basic element of this is generally known as "The FFT butterfly".[6]

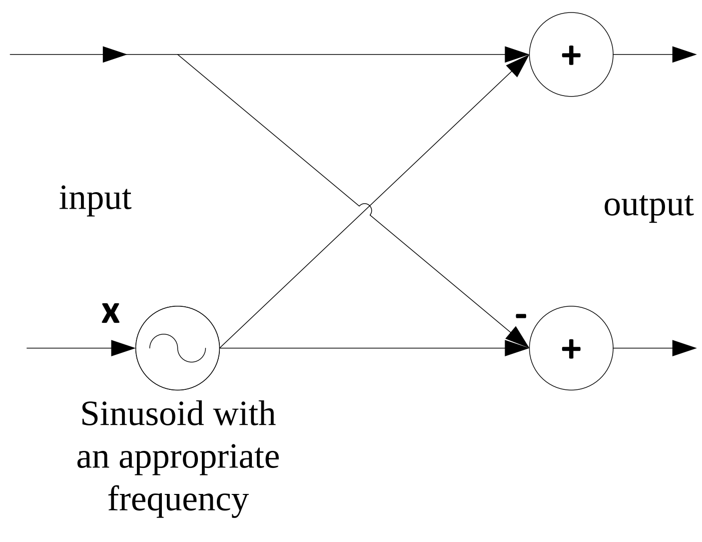


Figure 9: Illustation of FFT 2-radix elementary block. This element is generally known as "The FFT butterfly".

3.6 Goertzel algorithm

The Goertzel algorithm was first described in 1958 by Gerald Goertzel. Today, this Digital Signal Processing technique is used in a wide spectrum of practical applications such as telecommunication systems where the DTMF tones produced by keypad buttons are recognized as a single harmonic frequencies in the signal spectrum. However, this method can also be used for call progress decoding or frequency response measurements (if applied on a wide range of frequencies) and other mobile telephone applications.[7]

The Goertzel algorithm is based on the effective calculation of selected discrete sinusoids such as in the DFT based methods. The analysis of individual frequencies is the most frequent way of Goertzel application as the full spectrum analysis has higher order of complexity in comparison with the FFT. However, if only the presence of very specific frequencies only is desired, using of the FFT is not efficient because most of the calculated results are ignored.

3.6.1 Mathematical background

The transfer function of the Goertzel 2^{nd} order IIR filter is given by the following equation:

$$H_{f_i}(z) = \frac{1 - e^{\frac{2\pi f_i}{f_s}} z^{-1}}{1 - 2\cos\frac{2\pi f_i}{f_s} z^{-1} + z^{-2}}, \tag{19}$$

where f_i is the desired frequency to be detected and f_s is the sampling frequency. The schematic of this 2^{nd} order filter can be seen in Figure 10. In practice, we still need to have the information about actual frequency of the fundamental harmonic otherwise the final signal spectrum might become blured or inaccurate.

3.7 Sliding Real-time Discrete Fourier Transform

The Sliding Real-Time Discrete Fourier Transform belongs to the family of algorithms based on the Fourier analysis. This real-time approach to the Discrete Fourier Transform[22] is well designed for the use in an embedded systems applications.
As was already mentioned in the beginning of this chapter, the trivial implementation

[22] Also known as the Sliding DFT.

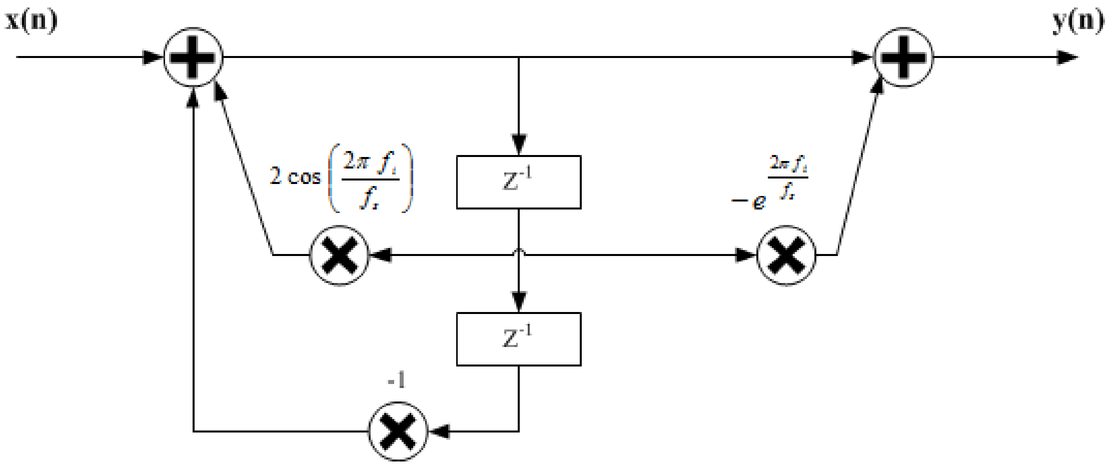


Figure 10: Schematic of the Goertzel filter.

of the DFT is known to be quite complex both in program design and computational complexity, which equals $O(N^2)$ (for non-optimized DFT). The main advantage of the real-time approach of the RDFT algorithm is that the computing speed does not depend on the number of samples (N), but only on the number of desired harmonic frequencies. Also, the spectrum analysis is executed after each new data sample that comes from the ADC so the difference between the oldest and the most recent values only is considered. This comes out from the fact that the algorithm uses a windowing First In First Out data queue which accepts N data values and a circual index pointer that selects the current data.
According to [8]: "If the algorithm was exploited as a non-sliding DFT, the complexity $O(N)$ can be estimated to $k_{max}N$, representing a performance that is comparable to the one delivered by the Goertzel algorithm. If $k_{max}N < \log_2 N$, the algorithm is even faster than the FFT. "

From a practical point of view, implementation of the RDFT algorithm is not complicated in comparison with the FFT which is not trivial to write from scratch.

3.7.1 Mathematical background

The RDFT algorithm uses recursive equations to compute the Fourier coeeficients a'_k and b'_k at any time of the sampling procedure:

$$a'_k = a_k + (y'_i - y_i)\frac{\cos(ki\frac{2\pi}{N})}{N}, \tag{20}$$

$$b'_k = b_k + (y'_i - y_i)\frac{\sin(ki\frac{2\pi}{N})}{N}, \tag{21}$$

where a'_k and b'_k are the current coefficients and a_k and b_k are the previous coeeficients. Variables y'_i and y_i represents the most recent data value and the oldest value. Trigonometric coefficients calculation were optimized by using the look up table, which saves some of the complex mathematical operations but costs more of static memory.

4 Computer simulations

In this chapter, the following issues will be studied:

1. Synthetized data experiments
2. Real data experiments
3. Simplification of three-phase circuits analysis (Clarke transformation)
4. Windowing

As was already mentioned at the beginning of this thesis, the experiments are divided into two key parts: computer simulations and experiments on the real embedded platform. In this chapter, we will focus mainly on the computer simulations of all implemented algorithms. The main purpose of evaluating computer simulations was to debug the results prior to downloading the program into the target embedded platform. This approach makes it possible to work with the implementation and the experiments' results effectivelly. In addition, the outputs are then easy to observe when exported into the MATLAB framework. This was achieved by the automatic generation of M-file scripts after each experiment. The implementation was performed in C language[23].
The experiments were executed using synthesised as well as real data. This thesis is mainly focused on floating point data as today's technology enables to work with floats effectivelly if FPU is integrated[24].

4.1 Synthesised data experiments

The main purpose of this experiment is to verify the competence of implemented methods to detect the third and fifth harmonic frequency. As a reference, the MATLAB implementation of FFT was chosen.

In Figure 11, the resulting spectrum of the synthesised signal distorted with the third (20 %) and fifth harmonic (50 %) can be seen. The total harmonic distortion of the synthesised signal is 0.47. The numerical output of each implemented algorithm is different. However, the ratio of harmonic contributions compared with the fundamental frequency are the same, with non-significant error variables as shown in the following table (4).

[23] In C89 standard.

[24] The majority of today's DSP and hybrid DSP instruction set processors provides an integrated FPU. As it's becoming a matter of course, the price per such unit is still decreasing.

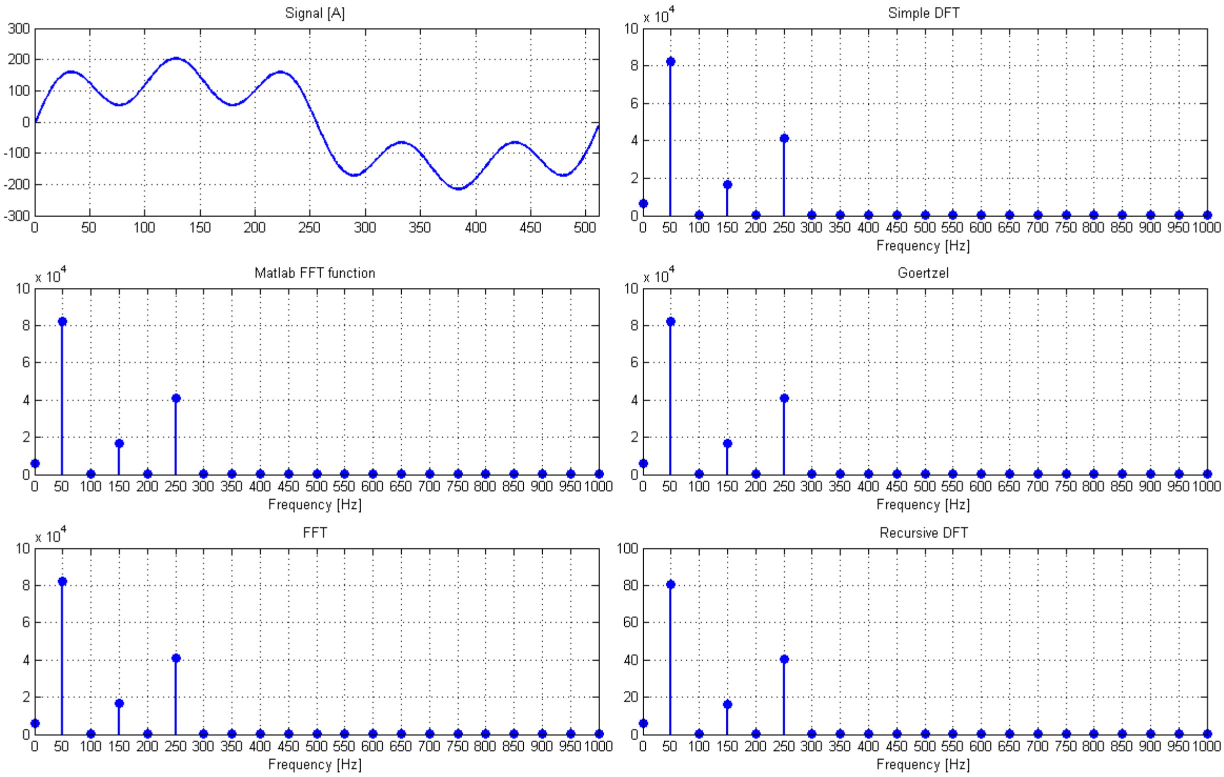


Figure 11: Synthesised signal of 1024 samples contaminated with the third and fifth harmonic. $THD = 0.47$

	DC component	2^{nd} **harmonic**	3^{nd} **harmonic**	4^{nd} **harmonic**	5^{nd} **harmonic**
DFT	7.5350	0.0193	19.9936	0.0503	50.0488
MATLAB FFT	7.5350	0.0193	19.9937	0.0503	50.0488
Goertzel	7.5241	0.0193	20.0009	0.0503	50.0629
Embedded FFT	7.5350	0.0193	19.9937	0.0503	50.0488
RDFT	7.5350	0.0193	19.9936	0.0503	50.0488

Table 4: The ratio of harmonic contributions compared with the fundamental frequency - results for all employed algorithms.

4.2 Real data experiments

The real data used in this thesis comes out from the measurements on the DC traction equipment for traction vehicels with DC drive such as trolley-cars. The measuring of harmonic distorted AC currents on the DC traction equipment for the purpouses of this thesis was enabled by Cegelec a.s.

The measurements on the real device was performed for accelerating[25] (increasing torque), steady state (constant torque) and braking[26] (descreasing torque). Especially during transient effects (accelerating and braking), occurence of upper harmonic frequencies was possible to observe. In order to test all algorithms on the real samples, several experiments were made. To illustrate the real situation within this thesis, the signal as shown in Figure 13 a) was chosen.

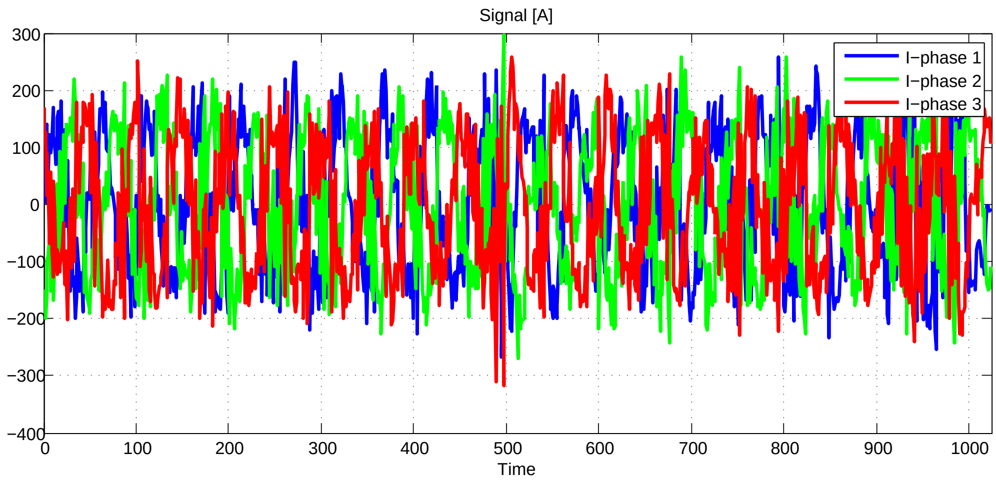
The signal was recorded during power increase of the 50Hz converter. In order to increase the spectral resolution, 5^{th} order signal decimation was applied as led to sampling frequency of 2.56 kHz. The harmonic analysis of signal spectrum is done for 1024 samples, where the distance between two bins is 2.5 Hz so the maximum detected frequency is 1.28 kHz. The resulting spectrum on each phase for harmonics up to 11^{th} order is shown in Figure 13 b). In the mentioned graph, significant odd harmonic additions can be observed, especially 5^{th}, 7^{th} and 11^{th}, which belongs to high harmonics.

The examples of a different signals measured on the real device (power converter VinCeG 2010) can be found in Appendix of this thesis.

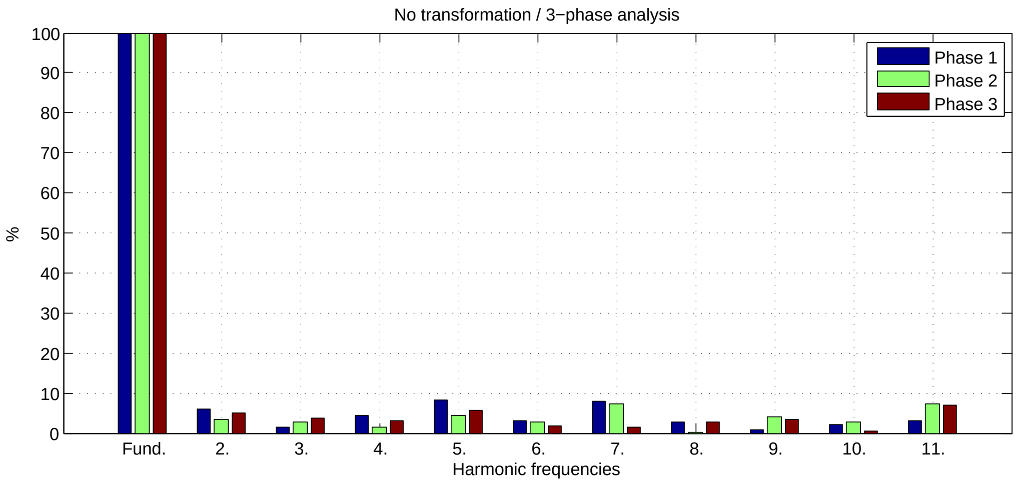
(a) (b)

Figure 12: Power converter VinCeG 2010 whereon measurement was performed.

[25]Motoric mode, in which power is consumed.
[26]Braking mode, in which power is delivered.



(a)



(b)

Figure 13: Harmonic analysis of the real signal using implemented algorithms.

4.3 Simplification of three-phase circuits

In order to simplify the analysis of the three-phase circuits, Clarke transformation was implemented.

4.3.1 Clarke transformation

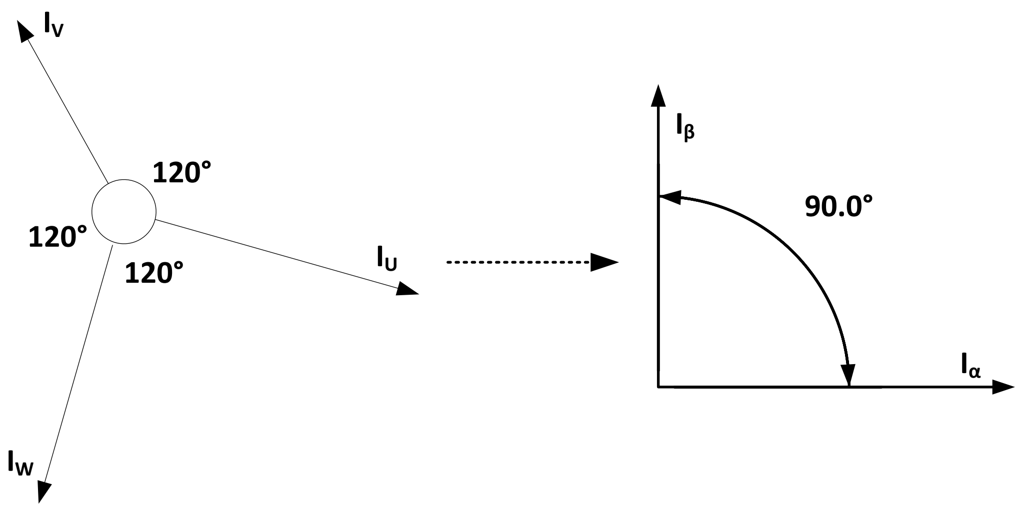


Figure 14: Clarke transformation.

Clarke transformation[27] is a mathematical transformation method employed to reduce the computational complexity of the three-phase circuits analysis. It translates the three-phase signal from the basic three-phase reference frame into the two-axis orthogonal and stationary reference frame. Due to this simplification, the spectrum analysis of the three phase system requires only two signal harmonic decompositions. Clarke transformation is the most beneficial if full spectrum analysis is required. The transformation is defined as follows:

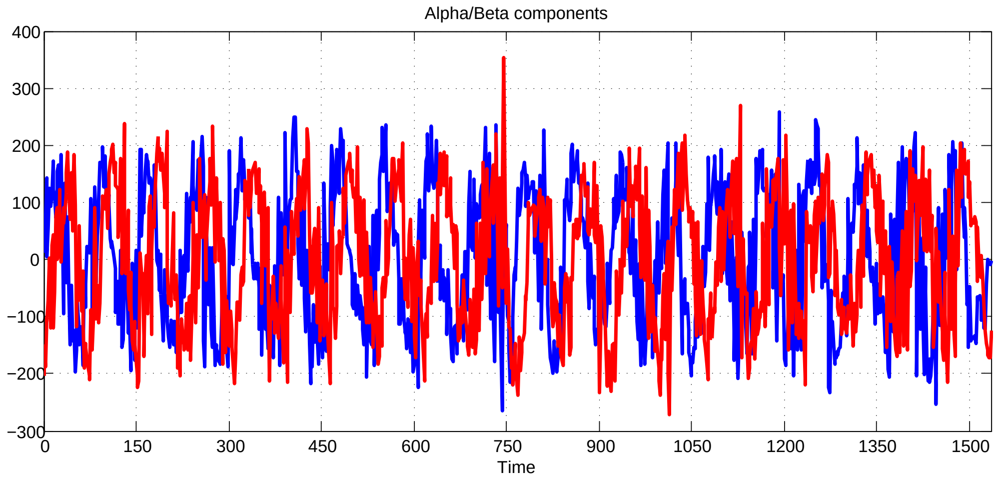
$$I_\alpha = \frac{2}{3} I_U - \frac{1}{3}(I_V + I_W), \tag{22}$$

where I_U, I_V and I_W are the phase currents of the three-phase power system. For the β plane, the following transformation is defined:

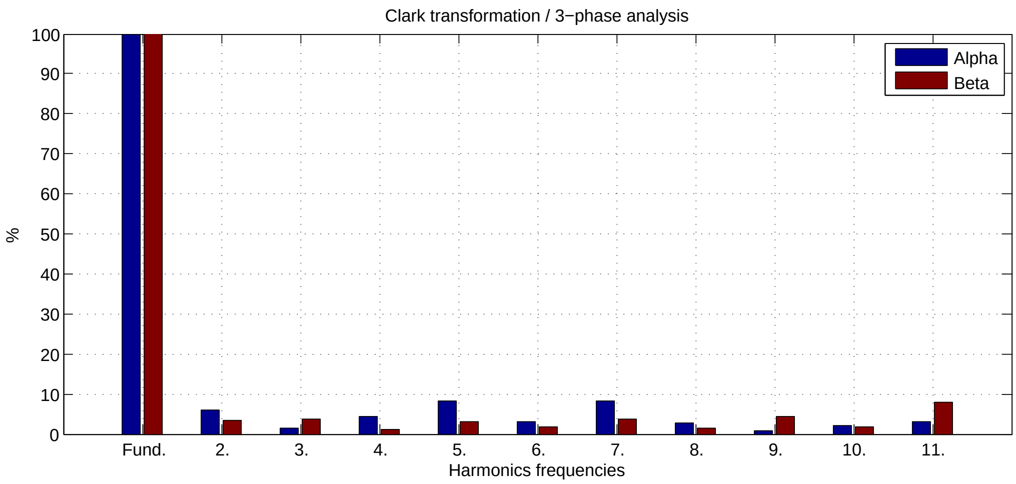
[27]Clarke transformation is also known as alpha-beta transformation.

$$I_\beta = \frac{1}{\sqrt{3}}(I_V - I_W). \tag{23}$$

Illustration of transformation from the star-connected three-phase power system into two-axis othogonal stationary reference frame is shown in Figure 14. The result of Clarke transformation applied on a real data signal as already mentioned in the previous chapter (figure 13) can be seen in Figure 15.



(a)



(b)

Figure 15: Clarke transformation of the real signal.

4.4 Windowing

In digital signal processing, windowing is the process of taking a time-restricted sample of a larger set of data especially in periodical signals. This process helps the digital device to save the infinite signal into a small subset of data whereof characteristic can represent the whole signal. There is a variety of window functions, which in addition can serve as a form of a mathematical transformation of a sampled signal. According to [9], there are several reasons to use windowing process:

- To reduce the spectral leakage.
- To separate a small amplitude signal from a larger amplitude signal with frequencies that are very close to each other
- To find a duration of the observation

Each type of window function has different characteristics and some of the windows are better than others depending on the type of signal. However, if the knowledge of the signal is not sufficient, experiments with different types of windows must be performed.

In this thesis, five types of window functions were tested in order to protect the resulting signal spectrum against an asynchronous sampling - *Rectangular, Hamming, Hannig, Blackmann and Triangular.* Asynchronous samplig is an effect of taking noninteger number of signal periods, which leads to the blurring of the resulting harmonic signal spectrum - also known as *spectral leakage.* In [10] is the connection of windowing of signal with spectral leakage described as follows: "Windows are weighting functions applied to data to reduce the spectral leakage associated with finite observation intervals."

In this subsection, each window will be described briefly. However, the theory and scientifical background in the field of window functions is a vast area in the digital signal processing and can be thorougly studied in article "On the use of windows for harmonic analysis with the discrete Fourier transform" from F.J. Harris [10].

The simplest type of the window function is the **rectangular window** (also known as Dirichlet window), which is defined as a rectangle of a constant magnitude and length.

Mathematical interpretaion of the rectangular window function is as follows:

$$w[n] = 1, \tag{24}$$

for

$$n = 0, 1, 2, ...N - 1, \tag{25}$$

where N is the number of samples. Definition of n and N as shown in equation 25) is valid for equations 26), 27), 28) and 30) as well.

Hannig window is a function, which has a shape similar to that of a half a cycle of a cosine wave. This type of signal transformation can be used for analyzing transient effects longer then the time duration of the window [9]. In general, it's recommended to start with Hanning windows when the signal characteristic in unknown. This window function is defined as follows.

$$w[n] = 0.5 - 0.5 \cos\left(\frac{2\pi n}{N}\right) \tag{26}$$

Hamming window is a modification of the Hanning window. The main difference is that the edges of the time domain of the window are not as close to zero as is the Hannig window. The Hamming window is defined as follows:

$$w[n] = 0.54 - 0.46 \cos\left(\frac{2\pi n}{N}\right) \tag{27}$$

Blackmann window is defined as:

$$w[n] = a_0 - a_1 \cos\left(\frac{2\pi n}{N-1}\right) + a_2 \cos\left(\frac{4\pi n}{N-1}\right), \tag{28}$$

where

$$a0 = \frac{1 - 0.16}{2}; a1 = \frac{1}{2}; a_2 = \frac{0.16}{2}. \tag{29}$$

Triangular window function has shape of a triangle. It is given by following equation:

$$w[n] = 1 - \left|\frac{2n - N}{N}\right| \tag{30}$$

All described windows were tested in order to find a proper fucntion to avoid a spectral leakage on the synthesized data samples. The discussion over the results of experiment can be found in the following subsection - 4.4.1.

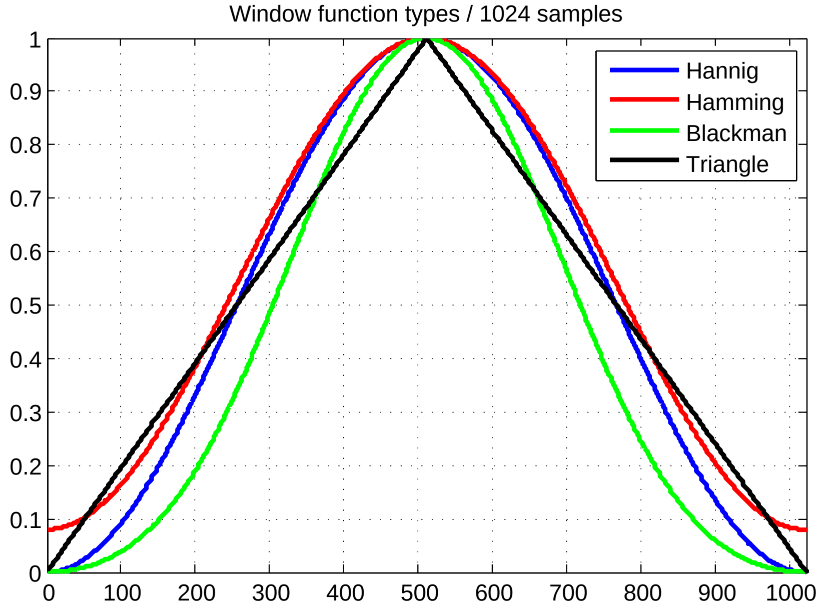


Figure 16: Different types of convolutional window functions.

4.4.1 Effects of window functions utilization in power generation applications

In order to explore effects of window functions on asynchronously sampled signal, experiment on synthesized signal was performed. The sampling frequency of the synthesized signal as shown in Figure 17 is set to 5.12 kHz, where each window has 1024 samples. Therefore this configuration provides 5 Hz spectral resolution (distance between two frequency terms in discrete visualization of spectrum). To simulate an effect of asynchronous sampling, the fundamental frequency was weaken from standard 50 Hz to 47.9 Hz. This resulted in non-integer number of sine periods, which led to spectral leakage. As the experiment is focused on application in power generating systems, 3^{rd} (15% ratio) and 5^{th} (8% ratio) harmonic frequencies were artificially injected to simulate the real signal.

Experiment was performed utilizing Rectangular, Hannig, Hamming, Blackman and Triangular convolution windows. In order to compare the synchronous with asynchronous sampling, redundant part of period was eliminated and the zero padding was applied to the whole signal. The resulting spectra can be observed in Figure 18.

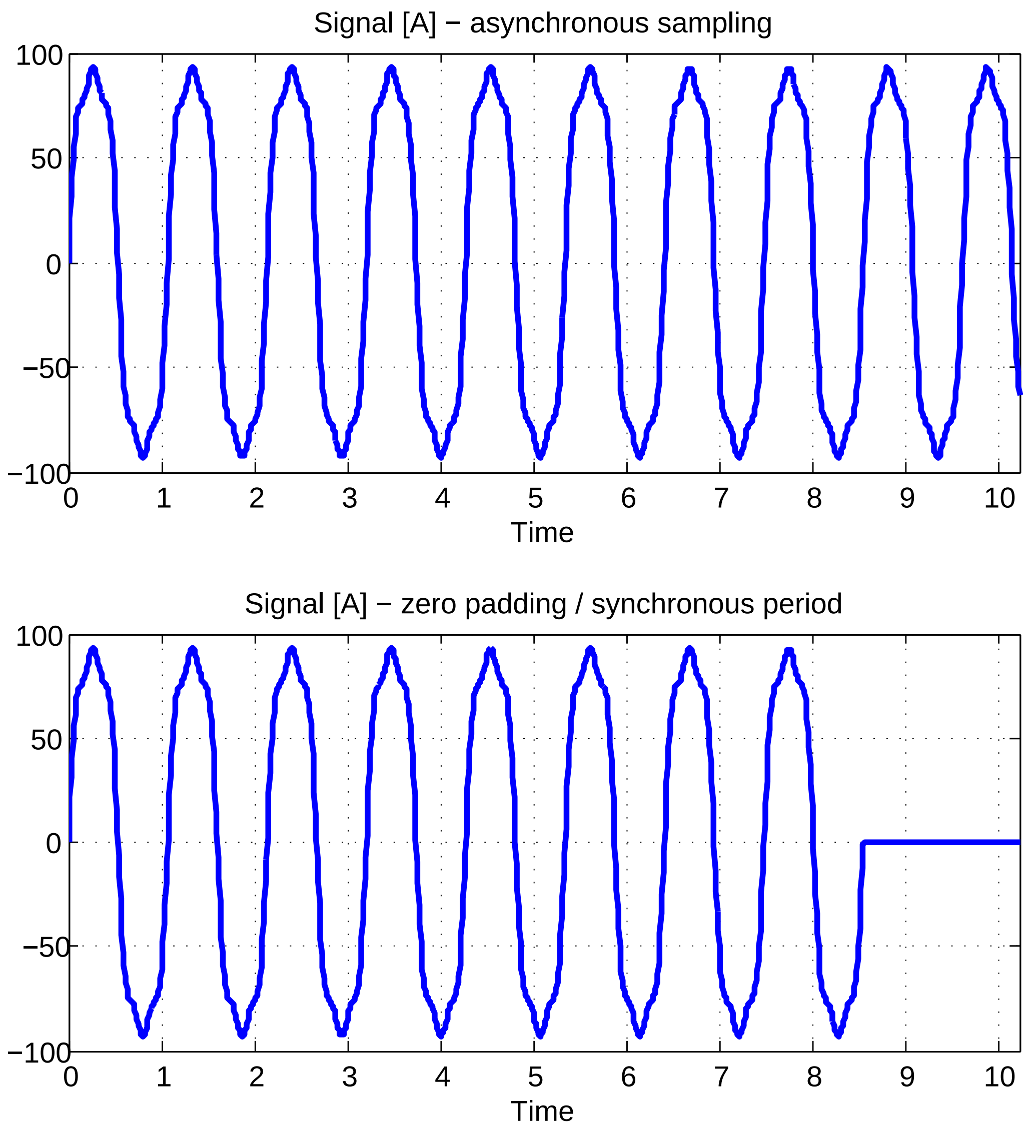


Figure 17: The synthesized signal distorted with 3^{rd} (15% ratio) and 5^{th} (8% ratio) harmonic frequencies.

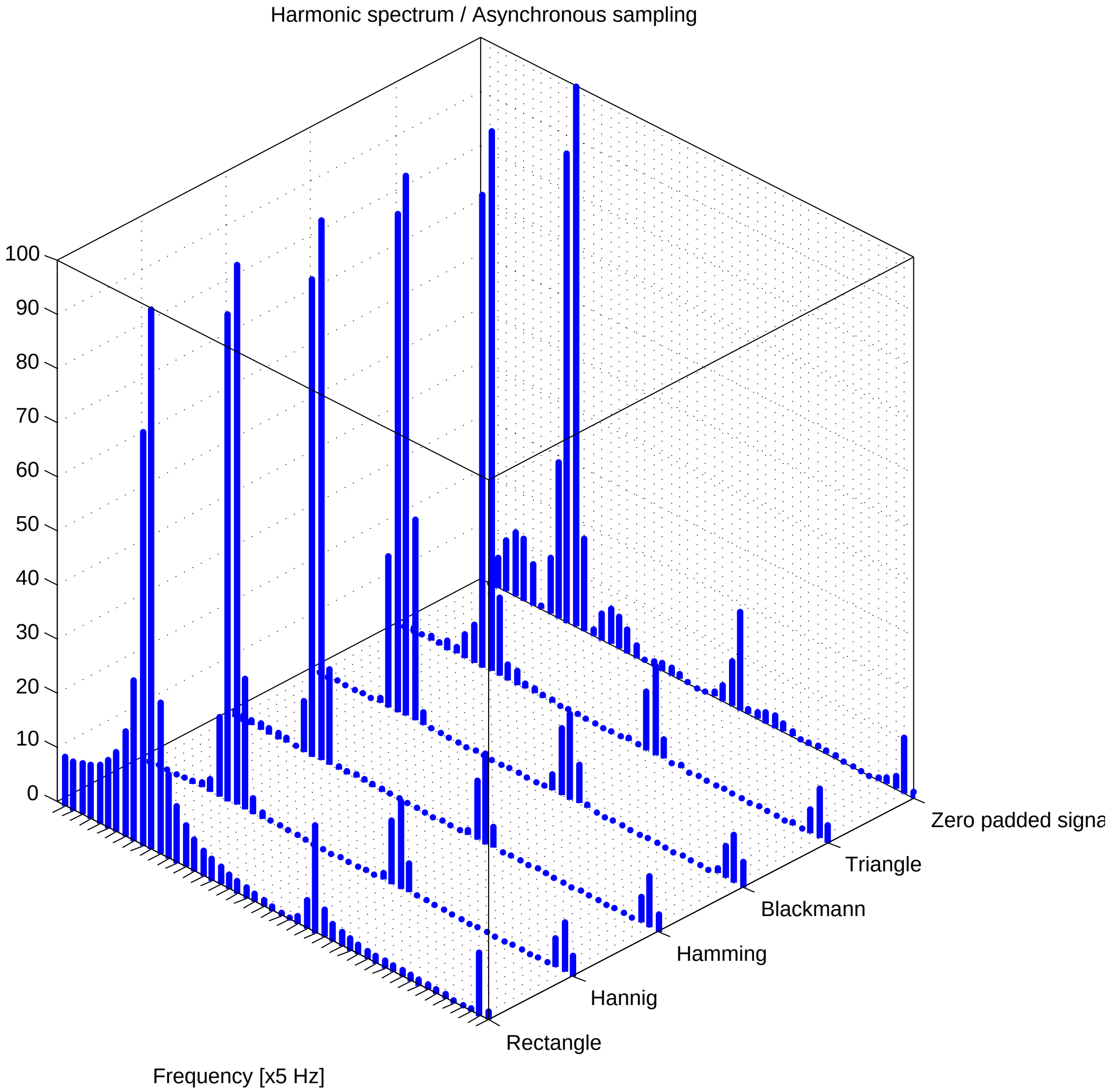


Figure 18: The resulting spectra for synthesized signal with different convolution windows applied.

Numeric results are shown in the following table (5):

	3rd harmonic	5th harmonic
Rectangle	19.8839	11.7467
Hannig	16.1017	8.9148
Hamming	16.5665	9.2627
Blackmann	15.8453	8.6994
Triangle	16.3391	9.1855
Zero padding	18.1581	10.2211

Table 5: The results of 3^{rd} and 5^{th} harmonic contributions in the spectral analysis employing different convolutional windows.

If the exploration is focused on the resulting spectra shown in Figure 18, despite the spectral leakage, the utilization of Rectangular window provides the most credible results of harmonic analysis. Tested convolution windows eliminated the spectral leakage between fundamental and third harmonic, but they are also responsible for blurring artificially injected harmonic frequencies and for the significant decrese of their magnitude, thus with the sensitivity of harmonic detection.

4.4.2 Recommendation

Based on this experiment, the utilization of convolution windows is not recommended as its usage does not have a significant positive effect to reduction of a spectral leakage when signal is sampled asynchronously. For general signal with unknown characteristics, Hannig window is recommended. However, for tested data, the utilization of Rectangular window embodied the most creadible analysis of harmonic spectrum for given synthesized signal.

In order to avoid a spectral leakage completely, the synchronicity of a signal sampling must be ensured.

5 Experiments on embedded platform

In this chapter, experiments on the real platform were performed in order to measure performance of all implemented algorithms and to find out the hardware requirements. The experiments were evaluated on a static, but real data measured on the real site as described in the previous chapter. The following issues will be discussed within this section:

1. The description of chosen platform
2. The description of evaluation criteria
3. Experiments on the real platform

Figure 19: Sleepy Cat Kit.

5.1 Platform description

The calculation of the discrete spectrum harmonic frequencies is a challenging task in the field of the embedded microprocessors. It takes a significant amount of useful time of the central processing unit in the microcontroller unit. For purposes of this thesis, Sleepy Cat development kit configured with the STM32F407 microprocessor was chosen. This embedded platform was developed on the Department of Measurement at Faculty of Electrical Engineering at Czech Technical University in Prague. The reason of choosing this platform was the integrated embedded FPU[28] in combination with Cortex M4 core, which provides a set of hybrid DSP instructions.

Cortex M4 core is able of digital signal processing and its instruction set includes DSP instructions that are specialized for the calculation of the Fast Fourier Transform. This set of special instructions is beneficial especially if the official STMicroelectronics DSP libraries are employed as they might enhance the calculation performance significantly. On the other hand, these libraries dispose of a very high static flash and memory requirements.

5.2 Algorithm evaluation criteria

There are several criteria, which were subjected to research in this thesis in order to find the most suitable algorithm to detect 3^{rd} and 5^{th} harmonic frequency. However, regarding to findings in the chapter 2.7, the selective detection of harmonic frequencies will not be considered as the main criteria of algorithm selection. The recommendation to algorithm selection will be based on algorithm complexity and memory requirements.

5.2.1 Algorithm complexity

The assesment of the complexity of the implemented algorithms was based on the results of the experiments described in this chapter. The intention of the first series experiments of experiments was to test the evaluation time of each algorithm compared with the number of calculated harmonics[29].

In Figures 20, 21 and 22, algorithms were compared successively for ν_{10}, ν_{13} and ν_{50}. The dependency on the number of samples was also observed to reveal the possible relation on the time of calculation. According to mention Figures, the utilization of Goertzel algorithm was beneficial in cases of ν_{10} and ν_{13}. For ν_{50}, employed FFT algorithm was faster.

[28] Floating Point Unit.
[29] Also denotated as ν.

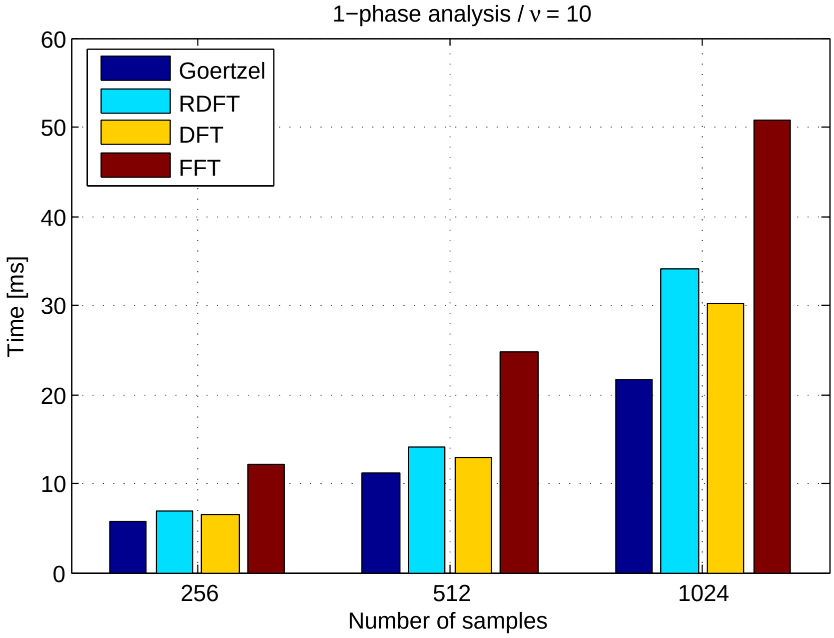


Figure 20: Comparison of implemented algorithms in terms of time of evaluation for ν_{10}.

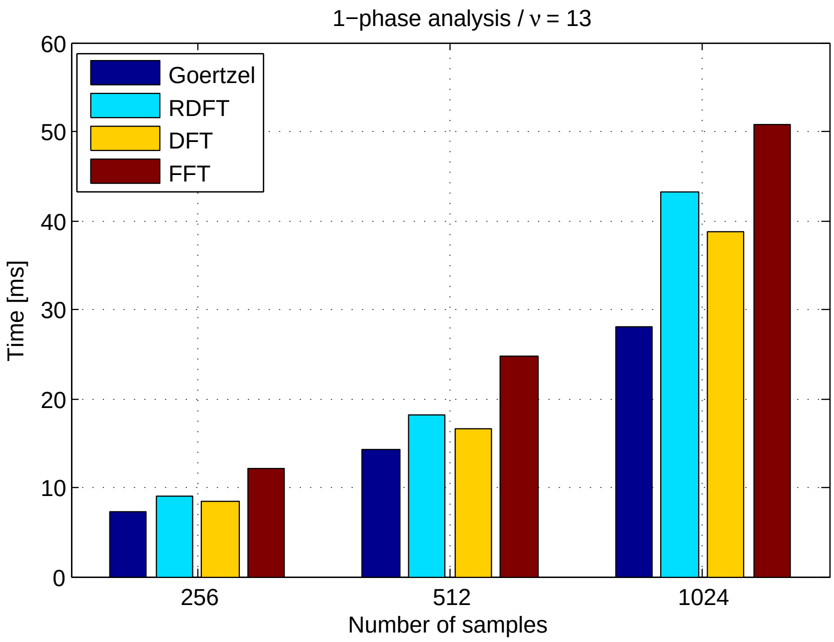


Figure 21: Comparison of implemented algorithms in terms of time of evaluation for ν_{13}.

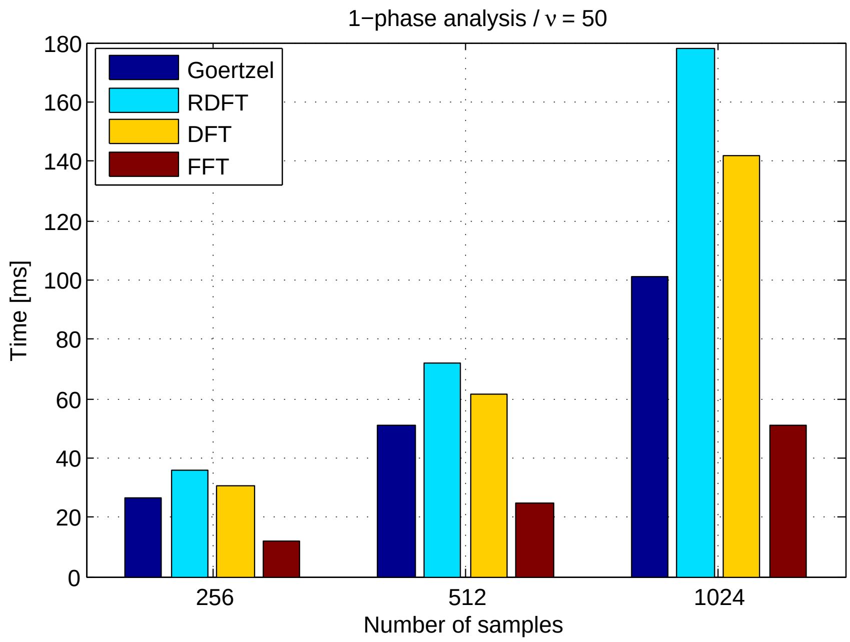


Figure 22: Comparison of implemented algorithms in terms of time of evaluation for ν_{50}.

In Figure 23, the comparison of algorithms depending on the use of Clarke transformation was performed. According to results, Clarke transformation saved approx. 33 % of calculation time. However, the transformation itself is a time-consuming mathematical operation, which should be considered (on tested platform, Clarke transformation of 1024 samples took 3.16 ms to calculate). However, the transformation can be performed during ADC conversion instead of transforming all samples at a time.

If we take a closer look at the result of experiment visualized in Figure 24, it can be seen that if only ν_{24} is desirable to calculate, it is still beneficial to use Goertzel algorithm. For number of harmonics higher then 24, the calculation time is higher. From these results flows out that if european EMC standards[30] are suppose to be fullfilled in terms of calculating the total harmonic distortion as described in chapter 2.4, FFT algorithm is recommended to be employed instead of Goertzel, which is faster only up to 24^{th} harmonic order.

[30] As mentioned in chapter 2.7.

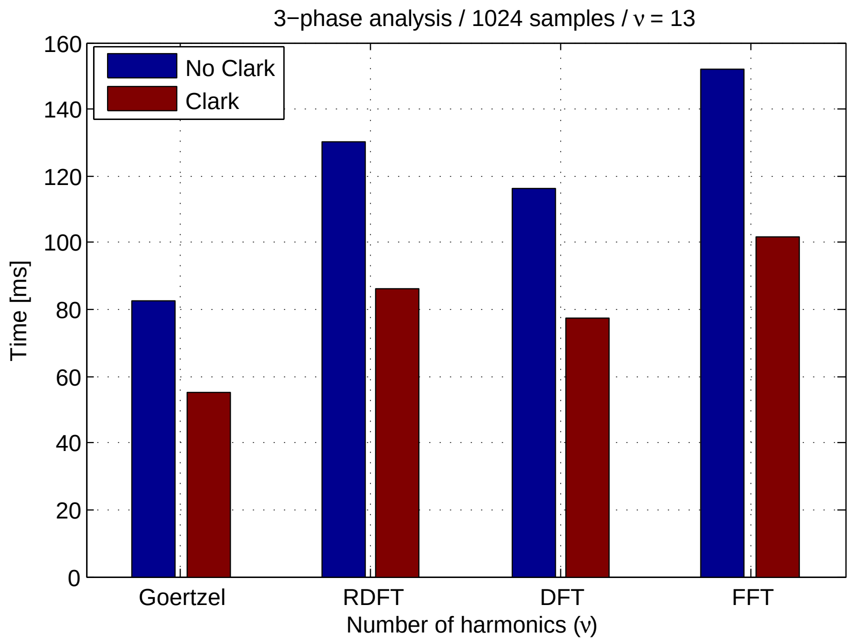


Figure 23: Comparison of tested methods before and after Clarke transfomation was implemented.

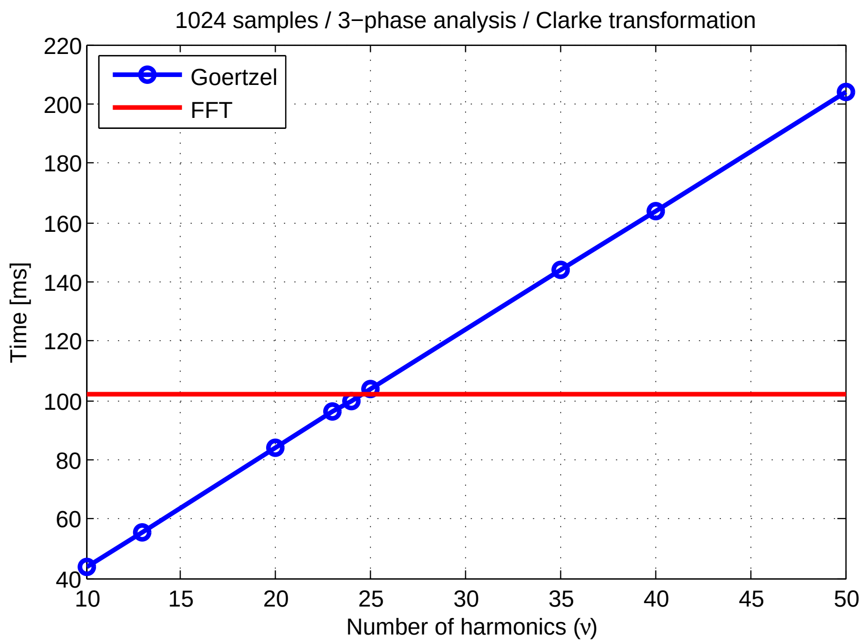


Figure 24: Comparison of Goertzel algorithm and FFT.

5.2.2 Memory requirements

In this chapter, a memory requirements of each algorithm will be studied. The following experiments are focused mainly on Flash and SRAM[31] memory requirements, which ranks among very limited hardware sources as the added price for these components (memory parts of a microcontroller unit) is still very high these days.

The overview of memory requirements for each algorithm can be seen in Figure 25, where the memory usage of FFT is unambigously biggest. The lowest memory usage has non-optimized DFT[32] algorithm as the look up table is not implemented and all triangluar coefficients calculates on-the-fly. In comparison with an optimized DFT, used amount of SRAM descreased of about 95.3 %. In spite of higher memory requirements when look-up-table employed, increase in calculation performance is enormous as shown in Figure 26. According to experiment in Figure 26, for ν_{50} calculation performance increased about 94.4 %.

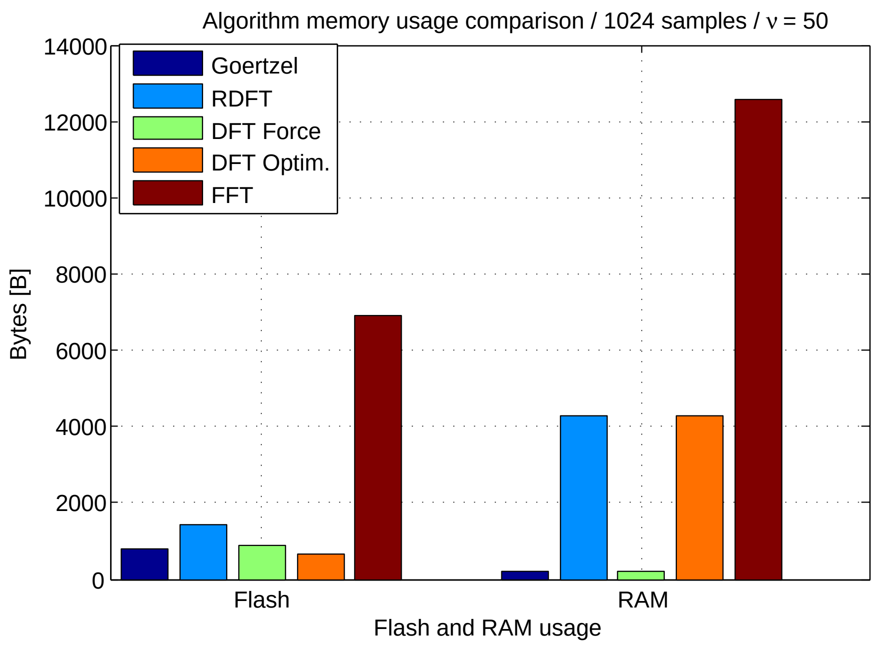


Figure 25: Memory requirements.

[31]Static Random Access Memory

[32]In graph marked as DFT Force.

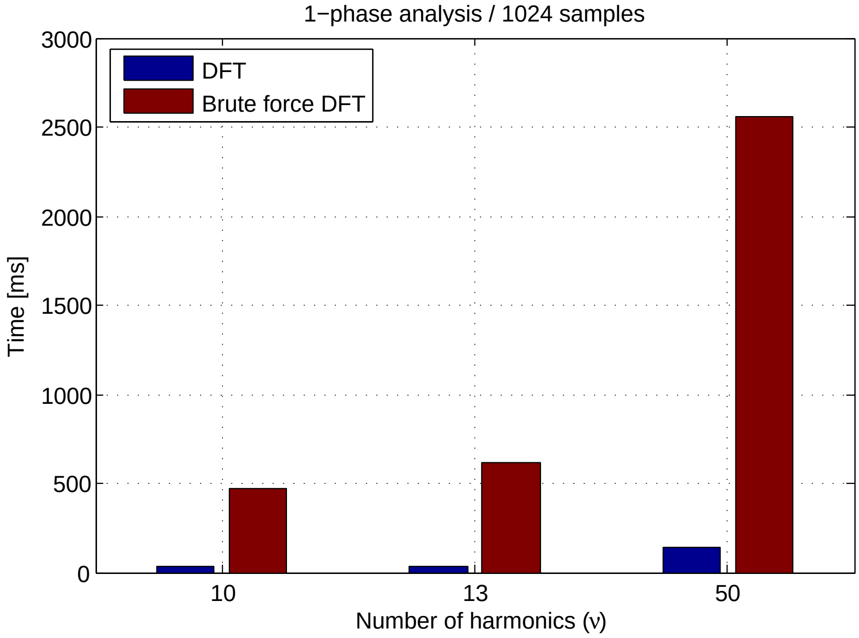


Figure 26: Effect of look-up-table on DFT algorithm.

5.3 Chapter summary

For this chapter, experiments on the real platform were performed and assesed according to set of evaluation criteria, where algorithm complexity and requirements for memory were deeply considered. Based on experiments, for limited number of harmonics (up to ν_{24}), Goertzel algorithm is better to use as its memory requirements are very low and the computational time is still lower then in case of FFT. However, if THD calculation for more than ν_{24} is desired, in spite of a very high memory requirements, FFT algorithm is recommended.

6 Conclusion

In this thesis, the theoretical background of harmonic distortion and effects of non-linear load in terms of power generating system were studied and described. In order to evaluate the methods of harmonics detection, several algorithm were tested and implemented on the real embedded device. All accomplished experiments were based on the real data measured on the industrial installation.

In the following section, all conclusions flowing from the research within this thesis are summarized whereas all recommendations are described in section 6.1.

6.1 Recommendations for application

Based on the analysis and results flowing from this research, the following technical arrangements were recommended:

6.1.1 Recommendations for harmonic detection method utilization

- If is desired to calculate THD according to European EMC standards, the use of FFT algorithm for calculation of harmonic spectrum is recommended. However, if only third and fifth harmonic frequency detection is desired, then Goertzel algorithm is the most suitable as the computational time and memory requirements are - in comparison with FFT - very low.
- It's recommended to use look-up-table to avoid calculation of the trigonometric coefficients during a runtime.
- In order to simplify the calculation of three phase signal spectrum, the utilization of Clarke transformation is recommended.

6.1.2 Recommendations for application robustness

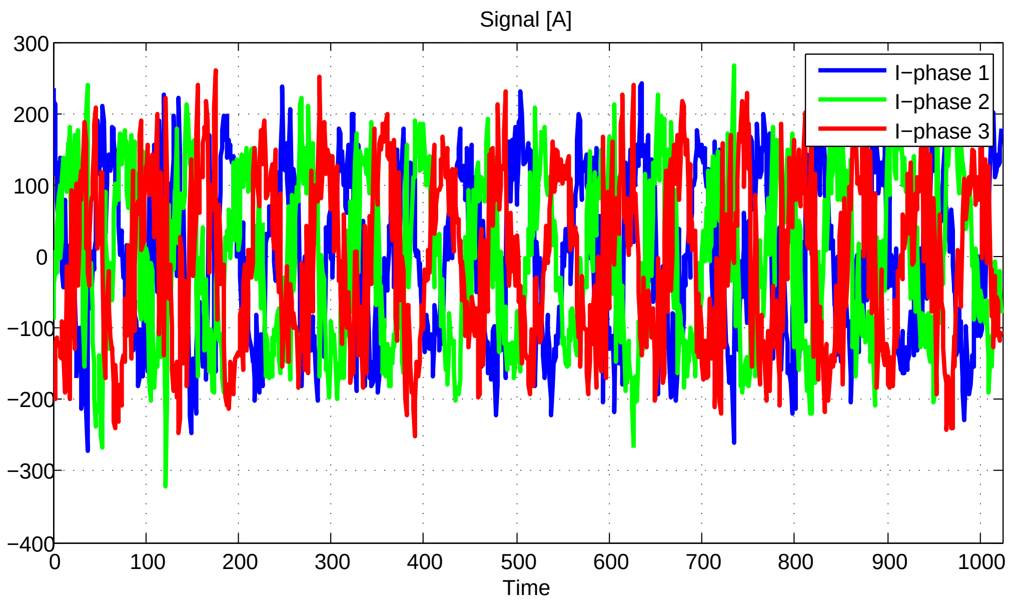
- It was shown that the synchronicity of sampling must be ensured to avoid a spectral leakage within applications in power generating systems.
- For applications in power generating systems, the utilization of convolutional window is not recommended as may be responsible for blurring the useful information about odd harmonic frequencies presented in the signal. However, for general signal with unknown characteristic, Hanning window is the most suitable choice.

- It is recommended to use longer window length as it is desirable to increase the resolution of harmonic bins. The main reason is that the fundamental frequency of an alternator can be slightly under or over 50Hz depending on the type of industrial installation and connected load. This fundamental frequency variances may lead to spectral analysis errors. Following recommended configuration will provide 3.125 Hz resolution - 12800 Hz sampling rate with factor 4 decimation and 1024 points.

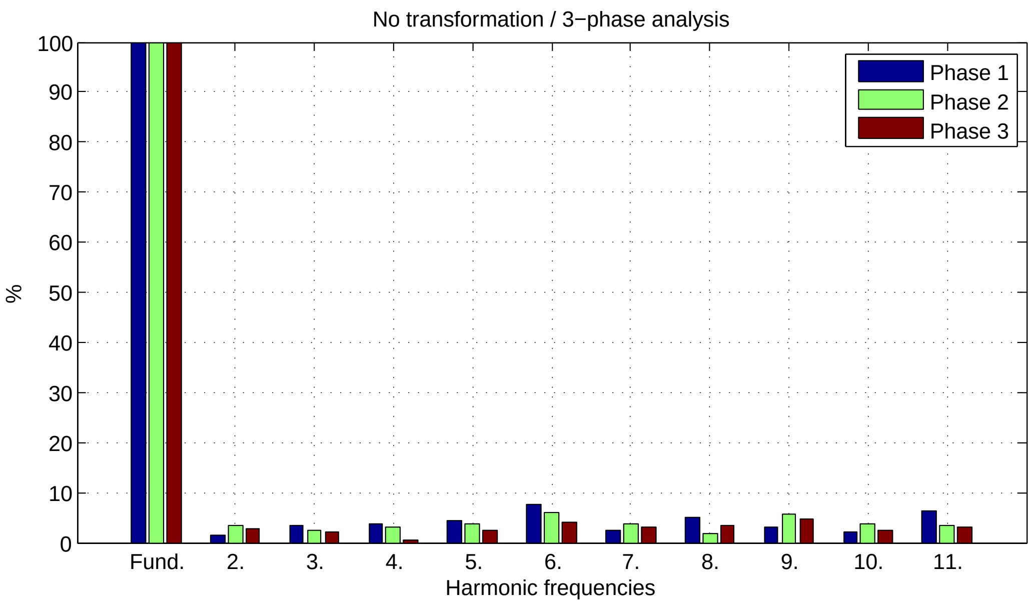
6.1.3 Requirements on MCU

- There is no specific recommendation for ADC unit and other MCU peripherals such as I/O's.
- In order to calculate floating point data directly, microcontroller unit with integrated FPU is recommended.
- To run full spectrum (1024 points) analysis utilizing FFT detection algorithm, at least 14 kB of RAM is required.

Appendix

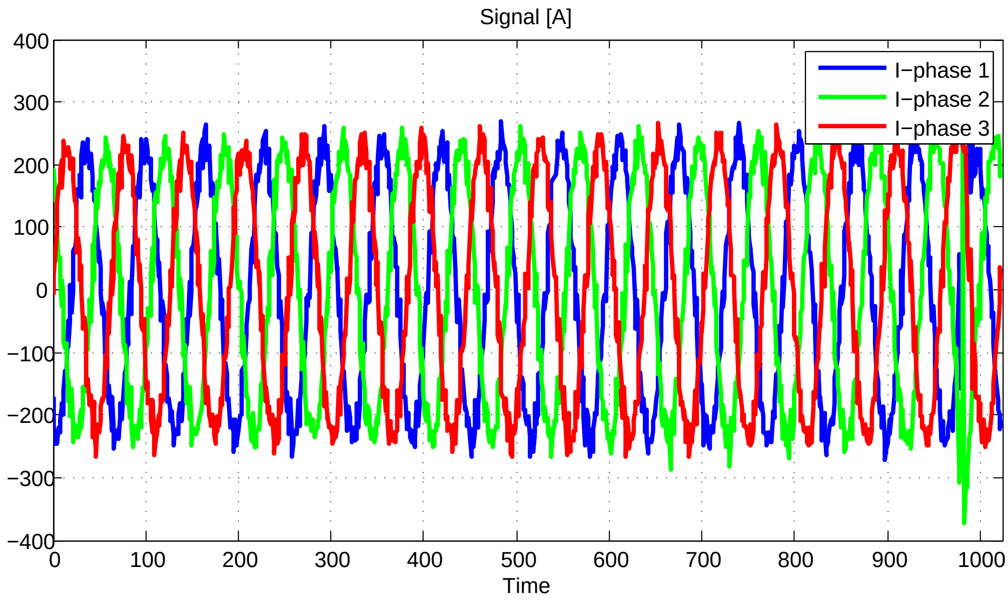


(a)



(b)

Figure 27: Real samples 1



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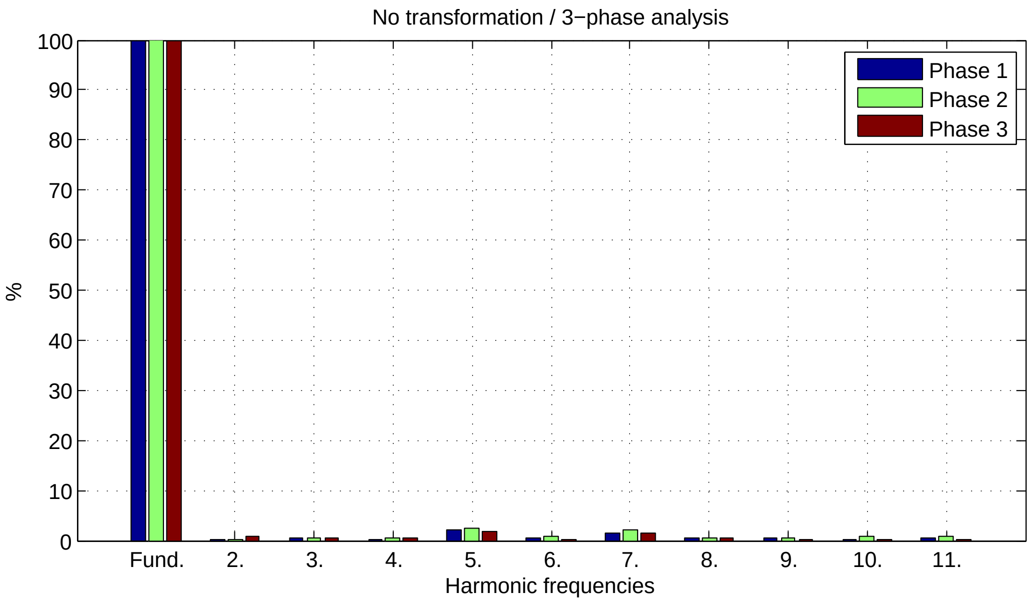
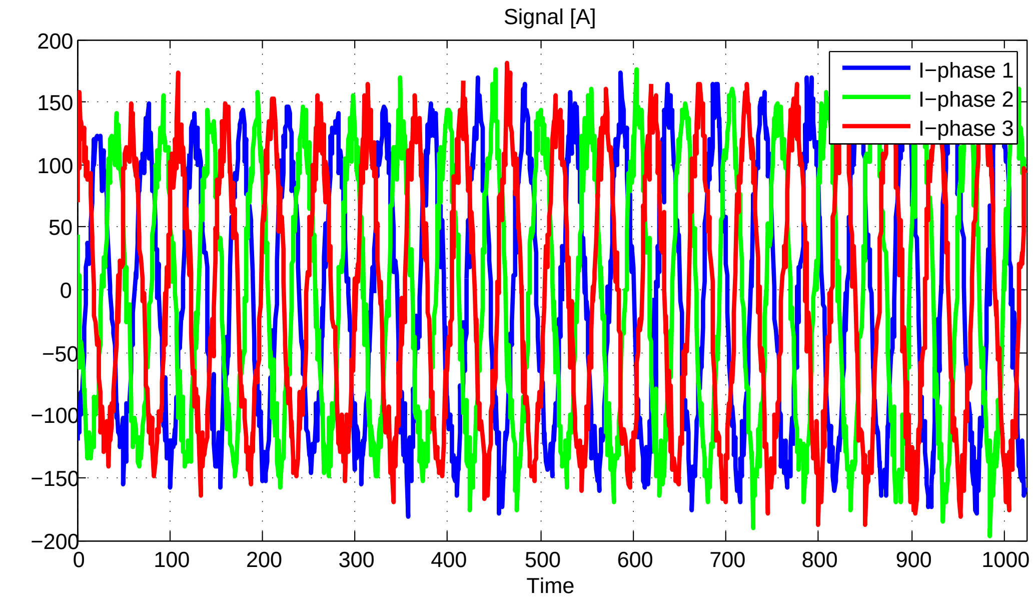


(b)

Figure 28: Real samples 2



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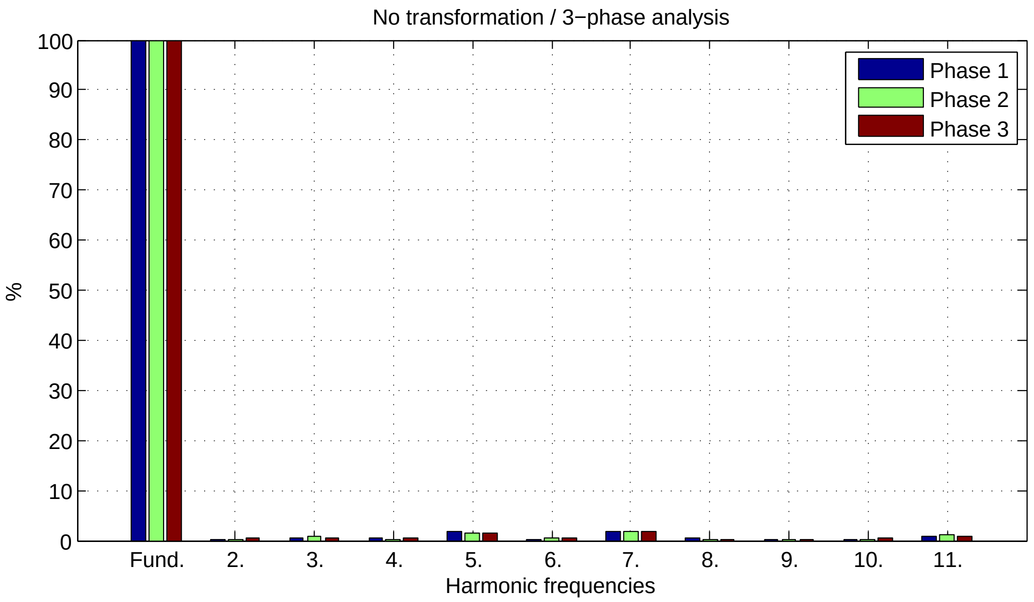
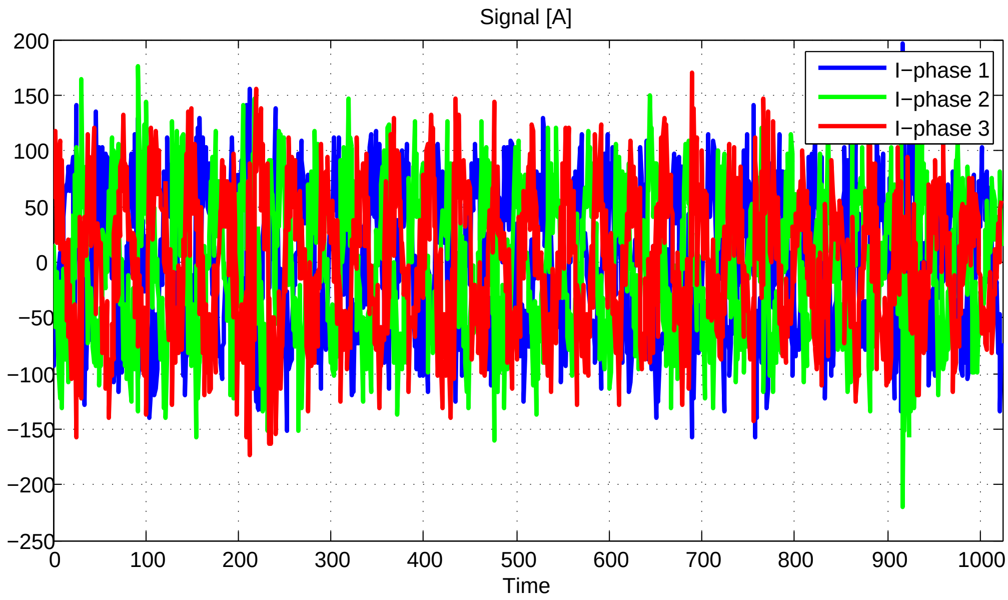


(b)

Figure 29: Real samples 3



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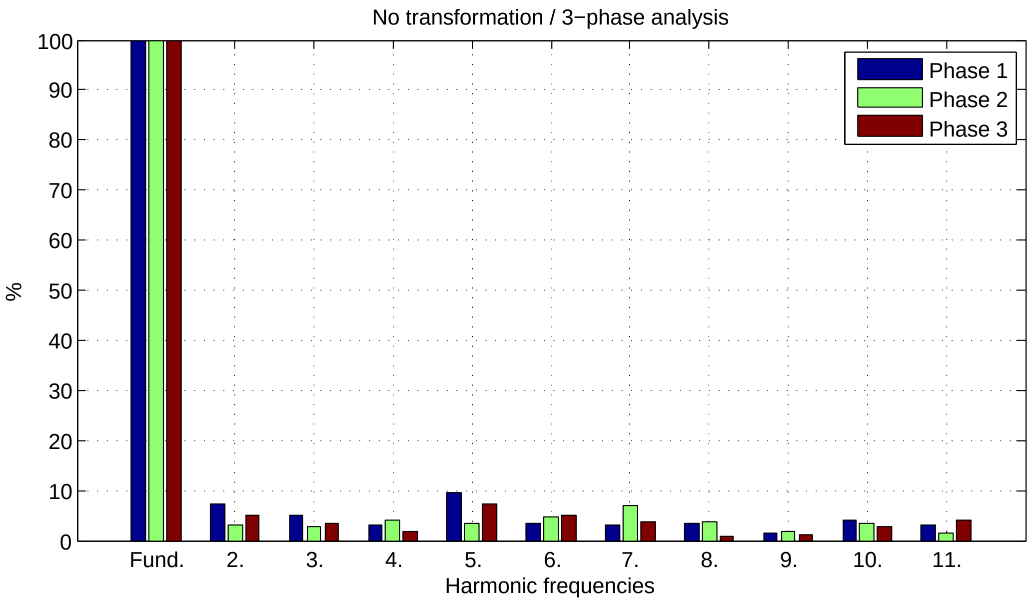

(b)

Figure 30: Real samples 4

References

[1] Mirus International Inc. Harmonic Mitigation Transformers FAQ. http://www.mirusinternational.com/downloads/hmt_faq01.pdf, 2003. [Online; accessed 26.3.2015].

[2] J.A. Pomilio and S.M. Deckmann. Flicker effect produced by harmonics modulation. In *Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference On*, volume 2, pages 1168–1172 vol.2, Oct 1998.

[3] S. Nikunj. Harmonics in Power Systems, Siemens Industry, Inc. http://www.industry.usa.siemens.com/drives/us/en/electric-drives/ac-drives/Documents/DRV-WP-drive_harmonics_in_power_systems.pdf, 2013. [Online; accessed 20.1.2015].

[4] D. Chapman. Power Quality Application Guide, Harmonics Causes and Effects. http://admin.copperalliance.eu/docs/librariesprovider5/power-quality-and-utilisation-guide/31-causes-and-effects.pdf?sfvrsn=4&sfvrsn=4, 2001. [Online; accessed 26.3.2015].

[5] Arthur Charles Franklin, David Peter Franklin. The J & P Transformer Book: A Practical Technology of the Power Transformer. In *Butterworths (Canada) Limited*, 1983.

[6] Steven W. Smith. The Scientist and Engineer's Guide to Digital Signal Processing. In *California Technical Publishing San Diego, California*, 1999.

[7] Richard Lyons. Single tone detection with the Goertzel algorithm. http://www.embedded.com/design/real-world-applications/4401754/Single-tone-detection-with-the-Goertzel-algorithm, 2012. [Online; accessed 26.3.2015].

[8] Claude Balman. RFT : a simplified fast real-time sliding DFT algorithm. http://www.convict.lu/Jeunes/ultimate_stuff/RFT.pdf, 2005. [Online; accessed 26.3.2015].

[9] National Instruments Corporation. LabVIEW Signal Processing Course Manual. http://www.meo.etc.upt.ro/materii/cursuri/PG_MASTER/LVSP.pdf, 1997. [Online; accessed 26.3.2015].

[10] F.J. Harris. On the use of windows for harmonic analysis with the discrete fourier transform. *Proceedings of the IEEE*, 66(1):51–83, Jan 1978.