Open your mind. LUT.
Lappeenranta University of Technology

FACULTY OF TECHNOLOGY

LUT ENERGY

ELECTRICAL ENGINEERING

MASTER'S THESIS

Effects of Imbalances and Non-linear Loads in Electricity Distribution System

Examiners Prof. Jarmo Partanen

M.Sc. Oleg Gusev

Supervisor M.Sc. Tero Kaipia

Author Nikita Lovinskiy

Abstract

Lappeenranta University of Technology
Faculty of Technology
Electrical Engineering

Nikita Lovinskiy

Effects of Imbalances and Non-linear Loads in Electricity Distribution System

Master's thesis

2010

70 pages, 30 pictures, 16 tables and 4 appendixes

Examiners: Professor Jarmo Partanen
M.Sc. Oleg Gusev
M.Sc. Tero Kaipia

Keywords: Harmonics, harmonic filters, nonlinear load, total harmonic distortion (THD), resonance, power flow, system losses.

As the majority of electrical systems were designed for linear voltage and current waveforms (i.e. nearly sinusoidal), excessive non-linear loads can cause serious problems such as overheating of conductors and transformers, capacitor failures, inadvertent circuit breaker tripping, or malfunction of electronic equipment.

An important consideration is required when evaluating the impact of harmonics and their effect on distribution system components and loads. Present paper pursues the goal of estimation the influence of harmonic distortion on the whole distribution system up to 110kV. By creating the model, that describes invented distribution network, the excessive power losses in transformers and lines in the three-phase systems caused by nonlinear loads are calculated. Model can be undated in order to examine cases with unbalanced and single-phase non-linear load. Moreover comparative data about voltage drop in network elements are represented as a function of non-linear type and percentage to entire load.

Table of contents

Abbreviations and symbols

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
AC	Alternative Current
DC	Direct Current
HVDC	High-Voltage Direct current
UPS	Uninterruptable Power Supply
RMS	Root Mean Square
THD	Total Harmonic Distortion
DF	Distortion Factor
CF	Crest Factor
FF	Form Factor
PF	Total Power Factor
IDF	Input Displacement Factor
ABB	Asea Brown Boveri
HMT	Harmonic Mitigation Transformer
Q	Quality Factor
CFL	Compact Fluorescent Lighting
TDD	Total Demand Distortion

h	harmonic order
P	active power
t	time
V	voltage
S	apparent power
Q	reactive power
X	reactance
R	resistance
Z	impedance
C	capacitance
L	inductance

I	current
ω	frequency

Subindexes*

n	integer(1,2,3...)
sc	short circuit
c	capacitor
eq	equivalent
l	inductor
p	parallel
s	series
T	transformer
f	filter

* - some abbreviations from common list may be used as subindexes as well

Acknowledgments

The author of this work would like to thank Lappeenranta and Lappeenranta University of Technology for excellent environmental and work condition to write thesis.

Furthermore my gratitude goes out to Tero Kaipia for his interest and encouragement during the work.

I am also deeply grateful to Jarmo Partanen who has made this thesis possible by sharing their knowledge throughout making general corrections in research direction.

I would also like to thank Julia Khegay, Nadezda Savvina and Maxim Baranov for the interesting discussions and the suggestions they provided.

1 Introduction

The increase in recent decades of electrical equipment that produce harmonics has posed severe problems for electrical networks and power quality. Sinusoidal voltages or currents, the frequency of which are a multiple of the fundamental frequency (50 Hz) of the power system are called harmonics. Effect of harmonic presence is considerable in all sections of power systems such as distribution, transmission and generation.

The main sources of harmonic currents and voltage respectively, in power systems, are nonlinear loads. All appliances including power electronic switches operate as non-linear loads. Such load devices are increasingly being used both by residential and industrial customers. In order to evaluate the effects of harmonics in the network, first it is necessary to define the real characteristics of harmonics produced by different loads. Secondly, the characteristics of examined system with respect to distortive loads need to be known. Third, the proper method is needed to evaluate the harmonic presence impact.

High harmonic voltage levels and harmonic load currents, regardless of the source, will lead to operating problems on the electric power distribution system. These problems, which include equipment heating, overvoltage, and load disruption, have been discussed in IEEE 519-1992 (IEEE Standard 519-1992, 1993). This standard provides recommended practices for the harmonic evaluation of electrical power systems, which is widely accepted by the industries and utilities. European standard EN 50160 is set the boundaries for harmonic voltages. In addition there are recommendations for harmonic current, mainly following IEEE 519.

There is a great set of relevant papers in literature about influence of distortive harmonics on distribution networks and power quality in general. Mainly, they discuss about the harmonic loading capacity of the distribution networks and the sources of the harmonic currents and voltages on the system. These previously done works have significant benefits for researchers; they make the readers have a realistic view on the effects of harmonic currents and their causes, and provide several models for harmonic analysis in different system environments.

1.1 Main objectives of thesis

Present work according their goals can be divided into two general partitions – theoretical and practical. Theoretical part is aimed to bring together numerous researches in relevant themes to present the current notion about problem of non-linear load and its by-product – distortion harmonics. Some of these papers describe in common words the effects of distortion harmonics on power system equipment and loads. Others explore and determine real characteristics of harmonic loads and their behaviour during the 24 hours of a day. Moreover, there are various approaches to simulate the harmonic effect on main components of power system such as transformers, power lines, capacitors, protective relaying, rotating machines and other load.

Practical goal of this thesis is to create the network model that encloses harmonic dependence in the network. As an initial data different proportions between linear and non-linear load are used as well as vary non-linear load characteristics itself. According results obtained from model it becomes possible to make detailed analyse for each network element and estimate harmonic influence.

1.2 Smart Grids concept

The harmonic voltage levels on electric power distribution systems are generally increasing due to the changing nature of the system load. Nowadays, widespread use of power electronics significantly increases the percentage of non-linear load in power systems. Moreover, global trend in energy industry sector stimulates expansion of power electronics application.

As the most obvious case, the Smart Grid programme which goals imply to set in motion substantial amount of different inverters, rectifiers and other power electronic equipment. Programme defines the goal to implement the integration within networks; that means bundling all customers inside Smart Grid system with active coupling. Furthermore, interoperability of European electricity networks is proposed to be done. Simply to foresee consequences of such an increasing of power electronics: harmonics in power systems will definitely increase.

To deliver the promised benefits of the smart grid –- stability, seamless interconnectivity, real-time information for customers and grid operators –- the aging, isolated AC grids will have to be replaced by robust new ones partially. And that future dream looks like it will be tightly connected to a technology called superconducting high-voltage direct current (HVDC) power lines, which are superchilled to boost capacity and can carry gigawatts of electricity (Gerdes J., 2010). Debates under question of profitability of usage DC instead AC in energy transmission sector has been going for last two decades. However, real pilot projects that implement present idea were launched in recent years. For archiving satisfactory results once more increase of power electronic is expected.

The similar arrangements are discussed on the level of low-voltage networks. Thus, the project of distribution system replacement from 400V AC to 1500V DC under Smart Grid programme proved its justifiability.

The results of the DC distribution system analysis show the potential of the system. With the low voltage DC distribution systems also higher transmission powers and transmission distances can be achieved when compared to the traditional low voltage system. The DC distribution system is an economical solution as a replacement of medium voltage branch lines at typical transmission powers of the rural networks (Kaipia T. et al. 2007).

Future infrastructure of energy systems as the main research issue of smart grids implements the development of distributed generation and plug-in and hybrid cars having a grid connection. Obviously, these connections will be done using power electronic equipment as ACDC and DCAC converters. Distributed generation will affect the widespread creation of energy productions (fuel cells, solar, wind, etc.) and storages (batteries, etc.). Again it will cause increasing power electronics equipment usage.

As a result, in a number of power systems, harmonic levels will soon require reduction through the different methods or harmonic loading need to be considered more precisely in system dimensioning and component development. Therefore, ultimate attention should be directed to hardware and software that are used for of metering and monitoring the power system as well as to system planning.

2 Load characteristics

The voltage waveforms generated at centralized power plants and then stepped up to a transmission voltage level generally are very close to ideal (i.e. sinusoidal) and have negligible distortion. The nature of major transmission devices such as transmission lines, cables, and transformers are quite linear, thus they cause little distortion to voltage or current waveforms. However, variable frequency drives and uninterruptible power supplies which use electronic devices to rectify ac to dc and then invert back to ac are nonlinear devices. Several loads are nonlinear such as switch mode power supplies (Section 2.4.1) and fluorescent light ballasts (Section 2.4.2) and, of course, frequency converters of motor drives used in different applications both in industry and dwelling. Generated nonlinear currents result in distorted voltages and currents that can adversely impact the system performance in different ways.

Since the number of harmonic producing loads has increased over the years, it has become increasingly necessary to address their influence when making any additions or changes to an installation. To adequate appreciate the impact of this phenomenon there are two important concepts to keep in mind with regard to power system harmonics. The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

2.1 Harmonics introduction

Harmonics are sinusoidal voltages or currents having frequency that are whole multiples of the frequency (fundamental) at which the supply system is designed to operate. Any periodic wave form of current or voltage can be obtained by summarizing sinusoid of fundamental frequency and harmonics. Correspondingly, a change of harmonics amplitude, phase or frequency leads to changes in a curve of current or voltage as the result of harmonics synthesis. Frequencies above the fundamental are called harmonics, frequencies below the fundamental are called subharmonics. Harmonics are the multiple of the fundamental frequency, as shown in the Table 2.1.

In addition active devices and interference in systems cause nonlinear distortion that is so called interharmonics. The definition for them is given by IEC standard (IEC 1000-2-1:1990, 1990):

“Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum.”

Nowadays the influence of subharmonics and interharmonics is not so significant due to presence of only small amount of electric equipment that produces them. Thus, this work is focused only on impact of distortive harmonics.

In case of usage a rectifier as a non-linear load, the harmonic presence is based on the number of rectifying switches (line diodes) used in a circuit. Numbers of harmonics can be determined by the equation presented in the Table 2.1.

Table 2.1. Harmonics.

Harmonic	Frequency
1st	**50 Hz**
2nd	100 Hz
3rd	150 Hz
4th	200 Hz
5th	**250 Hz**
6th	300 Hz
7th	**350 Hz**
8th	400 Hz
9th	450 Hz
10th	500 Hz
11th	**550 Hz**
13th	**600 Hz**
:	**:**
49th	**2450 Hz**

Numbers of presence harmonics:
h = (n x p) ± 1

where: n = an integer (1, 2, 3, 4, 5 …)

p = number of pulses or rectifiers

For example, using a 6 pulse rectifier, the characteristic harmonics will be:

h = (1 x 6) ± 1 → 5th & 7th harmonics

h = (2 x 6) ± 1 → 11th & 13th harmonics

h = (3 x 6) ± 1 → 17th & 19th harmonics

h = (4 x 6) ± 1 → 23rd & 25th harmonics

2.2 Linear and non-linear loads

The objective of the electric utility is to supply their consumers with sinusoidal voltage at fairly constant magnitude. This objective is complicated by the fact that non-linear currents exist. Nonlinear currents can originate from any of three causes:

- non-sinusoidal generation of voltage (load generation);
- non-linear devices used in the transmission of electrical energy;
- non-linear load devices.

2.2.1 Linear load

A linear element in a power system is a component in which the current is proportional to the voltage at any time. In general, this means that the current waveform (sinusoidal) will be the same as the voltage (Figure 2.1). Typical examples of linear loads include: Power Factor improvement capacitors, motors, and resistive loads as heating resistors, incandescent lamps.

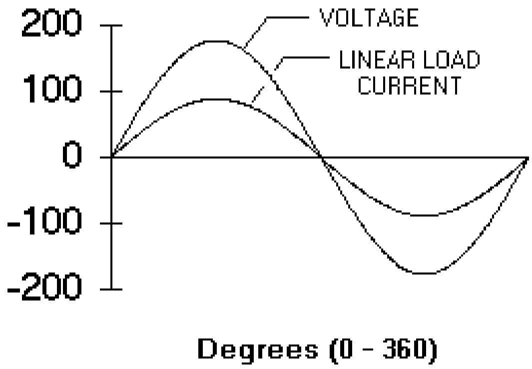

Figure 2.1. Voltage and current waveforms for linear loads. (Dugan R.C. et al. 1988)

2.2.2 Non-linear load

On the other hand, non-linear loads change the shape of the current waveform from a sine wave to some other form (Figure 2.2). The nature of non-linear loads is to generate harmonics in the current waveform. This distortion of the current waveform eventually leads to distortion of the voltage waveform, especially if the feeding grid is weak (large impedance) and proportion of non-sinusoidal currents is high enough. Under these conditions, the voltage waveform is no longer proportional to the current.

Typical examples of non-linear loads include: rectifiers (power supplies, discharge lighting, UPS units), adjustable speed motor drives, ferromagnetic devices, DC motor drives and arcing equipment (arc furnaces). (Renner H. et al. 2007)

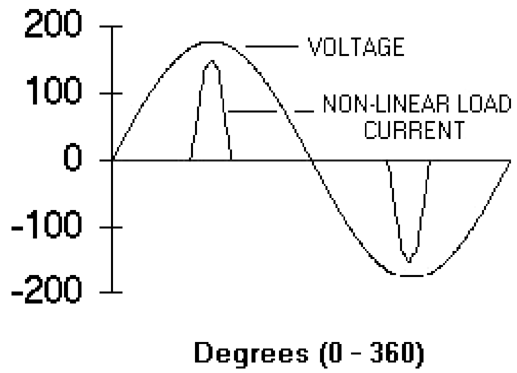

Figure 2.2. Voltage and current waveforms for non-linear loads. (Dugan R.C. et al. 1988)

2.2.3 Waveform shape types

The current drawn by non-linear loads is not sinusoidal but still it is periodic, meaning that the current wave remains the same from cycle to cycle. Mathematically, periodic waveforms can be described as a series of sinusoidal waveforms that have been summed together (Figure 2.3).

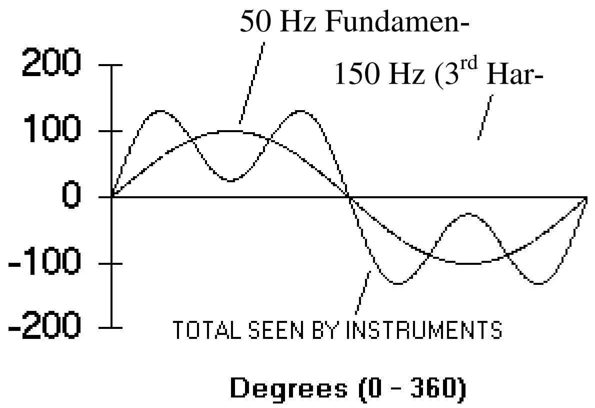

Figure 2.3. Waveform with symmetrical harmonic components. (Adopted from Dugan R.C. et al. 1988)

The harmonic content determines the different types of waveform shapes. Either only odd harmonics or both odd and even harmonics can be present in a waveform. Therefore, so called symmetrical waves contain only odd harmonics and unsymmetrical waves contain even and odd harmonics. According to Dugan

R.C. et al., a symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An unsymmetrical wave is determined as wave that contains a DC component (or offset) or the load; it is such that the positive portion of the wave is different than the negative portion. (Dugan R.C. et al. 1988)

Most power system elements are symmetrical. However, some normally-symmetrical devices are able to produce even harmonics because of component mismatches or failures. A typical example of unsymmetrical wave is a half-wave rectifier. Another common source of even harmonics is arc furnace that generates both even and odd harmonics alternately.

An ordinary multimeter will give great probing uncertainties when attempting to measure the AC current drawn by a non-sinusoidal load. A true RMS multimeter must be used to measure the actual RMS currents and voltages (and, consequently, apparent power). A wattmeter designed to properly work with non-sinusoidal currents must be used in order to measure the real power or reactive power. (Dugan R.C. et al. 1988)

2.2.4 Harmonics flow

When a non-linear load generates currents, these currents pass through all of the impedance that is between the system source and the load as illustrated on Figure 2.4. Thus, due to current flow, harmonic voltages are produced by impedance in the system for each harmonic. Voltage distortion is produced by summarizing all these voltages and adding to the nominal voltage. Obviously, parameters affecting to magnitude of the voltage distortion are the source impedance and the harmonic currents produced. For instance, if the source impedance is low the voltage distortion caused by harmonic currents will be low. According to Dugan R.C. et al., the following can be said: if a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically. More about resonant phenomena are in Section 2.6.

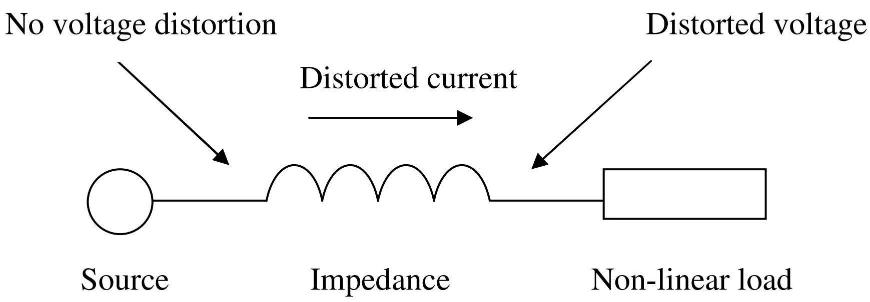

Figure 2.4. Normal flow of harmonic currents.

2.3 Distortion measurements

Harmonics are usually defined as periodic steady state distortions of voltage and current waveforms in power system (Chang G. W. et al. 2001). The purpose of this chapter is to present basic harmonic theory. Initially, the Fourier series and analysis method that can be used to interpret waveform phenomenon are reviewed. The general harmonics theory, the definitions of harmonic quantities, harmonic indices in common use, and power system response are then described.

2.3.1 Fourier analysis

The theory of the Fourier series was first introduced by the French physicist and mathematician, Joseph Fourier, in his article 'Analytic Theory of Heat' which was published in 1882. It proves that any non-sinusoidal periodic function $f(\mathrm{t})$ in an interval of time T could be represented by the sum of a fundamental and a series of higher orders of harmonic components at frequencies which are integral multiples of the fundamental component. The series establishes a relationship between the function in time and frequency domains. This expression is called Fourier series representation.

Using the Fourier series, any voltage $V(t)$ or current $I(t)$ waveform could be reproduced from the fundamental frequency component and the sum of the harmonic components.

$$V(t) = V_o + \sum_{h=1}^{N} V_h \cdot \sin(h \cdot 2 \cdot \pi \cdot f \cdot t + \theta_h) \quad , \qquad (2.1)$$

where

h is integer multiplier,

f is fundamental frequency,

t is time,

θ_h is phase angle,

V_h is peak voltage level,

V_o is dc component,

$V(t)$ is called non-sinusoidal periodic of the voltage function.

The Fourier series can also be used to deconstruct a waveform into the fundamental and harmonic components. This is the principle behind performing a harmonic analysis on a power system. A waveform is recorded and the magnitudes of the harmonics in the wave are calculated.

2.3.2 *Root Mean Square (RMS)*

The root mean square value also known as the effective value. It is the true measure of electrical parameters. Equation (2.2) shows how to find the RMS value of a current waveform where the amplitude of each of the harmonic is known.

$$I_{RMS} = \sqrt{\sum_{h=1}^{N} {I_h}^2} \quad , \qquad (2.2)$$

where

I_h is the amplitude of the harmonic current of order *h*,

I_{RMS} is the RMS value of all harmonics plus the fundamental component of the current.

2.3.3 Total Harmonic Distortion (THD)

A common term that is used in relation to harmonics is THD or Total Harmonic Distortion. Total harmonic distortion is the contribution of all the harmonic frequency currents to the fundamental. THD is used to describe voltage or current distortion and is calculated as follows:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}, \tag{2.3}$$

where

I_1 is the RMS value of the fundamental component of current.

The numerator gives the RMS current due to all harmonics and I_1 is the RMS value of fundamental component of current only. Equation given above is IEEE definition of THD. However, IEC standards are set different formulation that is given below (IEEE Std. 1159-1995, 1995):

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_{RMS}}. \tag{2.4}$$

The difference between two definitions is about denominator. At the equation (2.4) denominator is RMS current due to all harmonics and fundamental component of the current.

2.3.4 Crest Factor (CF) and Form Factor (FF)

Two other measures of distortion are the crest factor and the form factor. The crest factor is the ratio of the peak of a waveform to its RMS value. For a linear sinusoidal waveform, the crest factor would be the square root of 2, or 1.414. (Mohan N. et al. 1989)

$$Crest_{Factor} = \frac{I_{peak}}{I_{RMS}}, \tag{2.5}$$

where

I_{peak} is the peak value of current.

The form factor or distortion factor is the ratio of the RMS value of a waveform to the RMS of the waveform's fundamental component value. For a linear sinusoidal waveform, the form factor would be 1.0. (Mohan N. et al. 1989)

$$Form_{Factor} = \frac{I_{RMS}}{I_1} \tag{2.6}$$

Symmetrical components are a mathematical tool used to analyze power systems. Harmonic orders can be divided into positive, negative, and zero sequence components (Mohan N. et al. 1989). Positive sequence components are the given phase order and include the following harmonic orders: 1st (fundamental), 4th, 7th, 10th, etc. Negative sequence components are reverse phase order and include the following harmonic orders: 2nd, 5th, 8th, 11th, etc. Zero sequence components have all three components in phase and include the following harmonic orders: 3rd, 6th, 9th, 12th, etc. Phase and amplitude balanced positive and negative sequence components sum to zero in the neutral or ground. Balanced zero sequence components, however, add in the neutral or ground. Because the zero sequence harmonics are divisible by 3, they are referred to as triplens.

2.3.5 Distortion Factor (DF) and Power Factor (PF)

There are two different types of power factor that must be considered when voltage and current waveforms are not perfectly sinusoidal. In circuits having only sinusoidal currents and voltages, the power factor effect arises only from the difference in phase between the current and voltage. This is tightly known as "displacement power factor".

Distortion Factor - another variation of THD representation - is defined as follows:

$$DF = \frac{1}{\sqrt{1 + THD^2}} \tag{2.7}$$

The Distortion Factor will decrease as the harmonic content goes up. The Distortion Factor will be lower for voltage source type drives at reduced speed and load.

According to some representation (Grady W.M. et al. 1993), true PF is a figure of merit that measures how efficiently energy is transmitted. For efficient transmission of energy from a source to a load, it is desired to maximize average power, while minimizing RMS current and voltage (and hence minimizing losses). It is defined as:

$$PF_{true} = \frac{P_{avg}}{V_1 \cdot I_1} \cdot \frac{1}{\sqrt{1 + THD_V^{\,2}} \cdot \sqrt{1 + THD_I^{\,2}}}, \tag{2.8}$$

where

P_{avg} is the average power,

V_1 is the RMS value of the fundamental component of voltage,

THD_V is total voltage distortion,

THD_I is total current distortion.

Exact equation is valid for both sinusoidal and non-sinusoidal situations. Obviously, if no harmonics are present, then the THD_V and THD_I are zero.

2.4 Non-linear load types

In order to evaluate the effects of harmonics in the network, first it is necessary to refer to their sources and define the real characteristics of harmonics produced by different load types. This chapter is aimed to describe the commonly used types of non-linear loads.

The harmonic sources differentiation can be done according to following categories. (Arrillaga J. et al. 2000)

- Large numbers of distortion non-linear components of small rating.

This category consists mainly of single-phase diode bridge rectifiers that provide the power supply of most domestic electric appliances. Another commonly used non-linear load in this list is gas discharge lamp. Though the individual ratings are quite small, their accumulated effect can be significant, considering their large numbers and lack of phase diversity.

- Large and continuously randomly varying non-linear loads.

The main electric appliance of this category is the arc furnace, with power rating in tens of megawatts that is connected to the high voltage transmission network directly. The main difficulties in terms of simulation occur due to furnace arc impedance character that is randomly variable and extremely asymmetrical.

- Large static power converters and transmission systems level power electronic devices.

The feature of these devices and, thus, the main reason of considerable difficulties, is large size. Another reason is referred by (Arrillaga J. et al. 2000). The operation of the converter is highly dependent on the quality of the power supply, which is itself heavily influenced by the converter plant.

Below, the concrete examples of non-linear load are described in influence decreasing order.

2.4.1 AC-DC converters

As it was repeatedly mentioned above, the most common harmonic source is various size rectifiers. These electric appliances are described on basis of data provided by greatest manufacturers in this particular niche. Lion share of theoretical and actual data presented below refer to ABB product line.

Figure 2.5 shows how the first stage of a switching-type power supply works. The AC voltage is converted into a DC voltage, which is further converted into other voltages that the equipment needs to run. The rectifier consists of semiconductor devices (such as diodes) that only conduct current in one direction. In order to do so, the voltage on the one end must be greater than the other end. These devices feed current into a capacitor, where the voltage value on the capacitor at any time depends on how much energy is being taken out by the rest of the power supply.

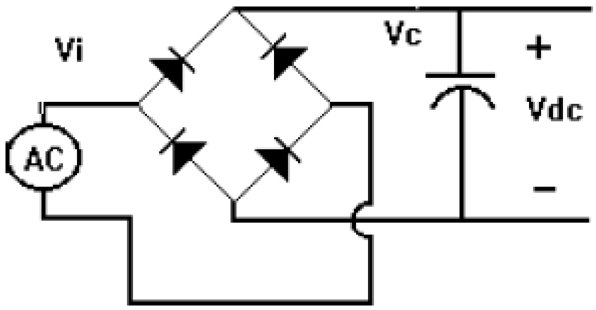

Figure 2.5. Typical AC-DC Converter.

Certain types of loads also generate typical harmonic spectrum signatures that can point the investigator towards the source. This is related to the number of pulses, or paths of conduction (Bingham R.P.). Table 2.2 shows examples of such.

Table 2.2. Typical Harmonics Found for Different Converters.

Type of device	Number of pulses	Harmonics present
Half wave rectifier	1	2, 3, 4, 5, 6, 7…
Full wave rectifier	2	3, 5, 7, 9…
Three phase, full wave	6	5, 7, 11, 13, 17, 19…
(2) three phase, full wave	12	11, 13, 23, 25, 35, 37…

The connections for various rectifier solutions are shown in Figure 2.6. The most common rectifier circuit in 3-phase AC drives is a 6-pulse diode bridge. It consists of six uncontrollable rectifiers or diodes and an inductor, which together with a DC-capacitor forms a low-pass filter for smoothing the DC-current. The inductor can be on the DC- or AC-side or it can be left totally out. The 6-pulse rectifier is simple and cheap but it generates a high amount of low order harmonics 5th, 7th, 11th especially with small smoothing inductance.

The current form is shown in Figure 2.6. If the major part of the load consists of converters with a 6-pulse rectifier, the supply transformer needs to be oversized and meeting the requirements in standards may be difficult. Often some harmonics filtering is needed. (ABB, 2004)

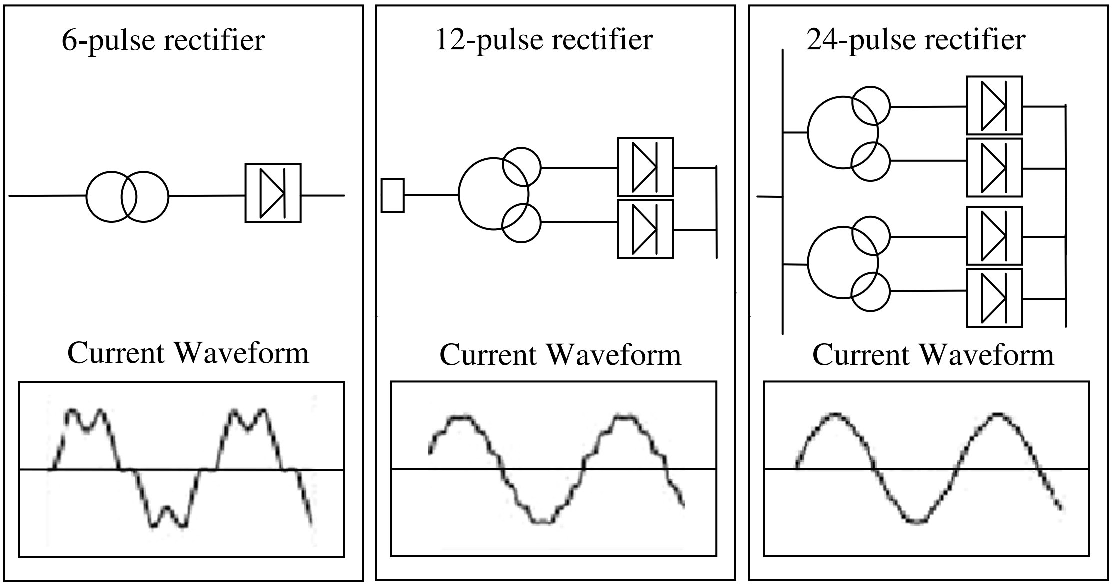

Figure 2.6. Harmonics in line current with different rectifier constructions.

The 12-pulse rectifier is formed by connecting two 6-pulse rectifiers in parallel to feed a common DC-bus. The input to the rectifiers is provided with one three-winding transformer. The transformer secondaries are in 30° phase shift. The benefit with this arrangement is that in the supply side some of the harmonics are in opposite phase and thus eliminated. In theory the harmonic component with the lowest frequency seen at the primary of the transformer is the 11th.
The major drawbacks are special transformers and a higher cost than with the 6-pulse rectifier.

The principle of the 24-pulse rectifier is also shown in Figure 2.6. It has two 12-pulse rectifiers in parallel with two three-winding transformers having 15° phase shift. The benefit is that practically all low frequency harmonics are eliminated but the drawback is the high cost. In the case of a high power single drive or large multi-drive installation a 24-pulse system may be the most economical solution with lowest harmonic distortion. (ABB, 2004)

Distortion harmonics to fundamental ratio is shown in Figure 2.7 for rectifier types described above.

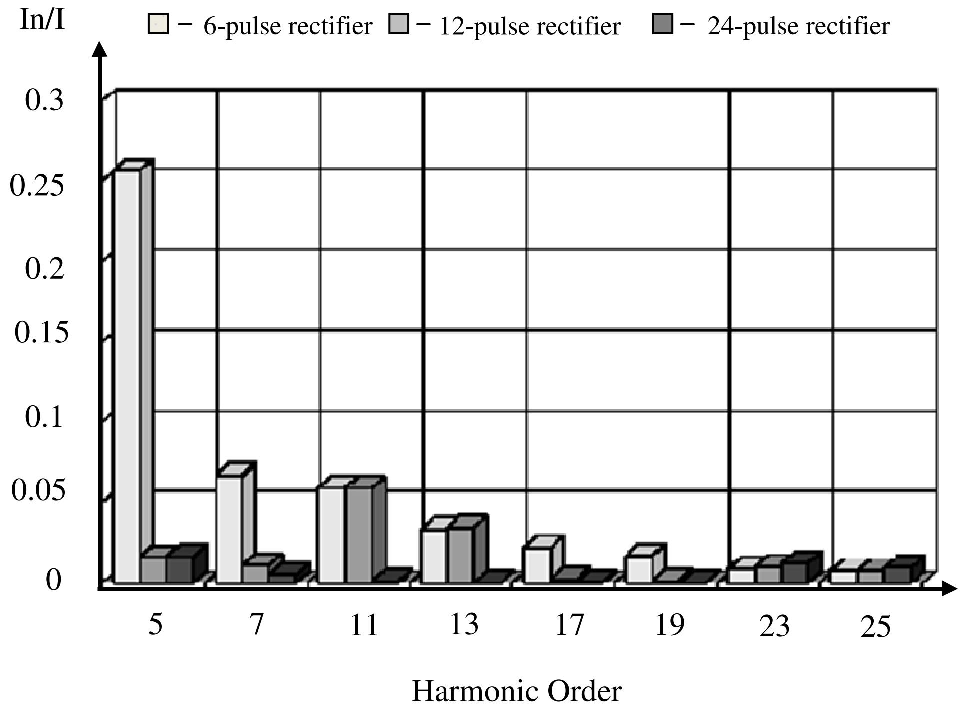

Figure 2.7. Harmonic components with different rectifiers. (ABB, 2004)

A phase controlled rectifier is accomplished by replacing the diodes in a 6-pulse rectifier with thyristors. Since a thyristor needs a triggering pulse for transition from non-conducting to conducting state, the phase angle at which the thyristor starts to conduct can be delayed. By delaying the firing angle over 90°, the DC-bus voltage goes negative. This allows regenerative flow of power from the DC-bus back to the power supply.

Standard DC-bus and inverter configurations do not allow polarity change of the DC-voltage and it is more common to connect another thyristor bridge anti-parallel with the first one to allow the current polarity reversal. In this configuration the first bridge conducts in rectifying mode and the other in regenerating mode.

The current waveforms of phase controlled rectifiers are similar to those of the 6-pulse diode rectifier, but since they draw power with an alternating displacement power factor, the total power factor with partial load is quite poor. The poor power factor causes high apparent current and the absolute harmonic currents are higher than those with a diode rectifier.

In addition to these problems, phase-controlled converters cause commutation notches in the utility voltage waveform. The angular position of the notches varies along with the firing angle.

2.4.2 Fluorescent lighting

While some of these loads are large point sources of harmonics located primarily in industrial areas, residential and commercial loads are also generating increasing levels of harmonics from traditional electronic loads as well as the newer, higher power loads such as high efficiency lamps. Fluorescent lights can be the source of harmonics, as the ballasts are non-linear inductors. The predominate harmonic here is third one (Table 2.3).

The trend across the globe is for benefit of fluorescent lighting industry development. Many counties encourage the adoption of CFLs (Compact Fluorescent Lighting) or even entirely displace incandescents. Thus the harmonic income to world energy systems due to this source will constantly grow.

Table 2.3. Harmonic spectrum for fluorescent light ballast. (Tolbert L. M. et al. 1996)

Harmonic	Magnetic Ballast		Electronic Ballast	
	Phase	Neutral	Phase	Neutral
Current THD	12.8	171.2	16.3	44.0
3rd	10.6	169.8	3.6	11.9
5th	6.7	16.6	11.7	31.6
7th	1.6	3.3	5.2	3.7
9th	0.8	12.7	3.9	20.1
11th	0.2	2.3	3.5	2.0
13th	0.3	2.5	3.4	4.1
15th	0.1	3.4	2.1	10.1
17th	0.1	0.0	2.1	3.2
19th	0.0	0.7	2.2	3.1
21st	0.0	0.5	2.0	9.6
23rd	0.0	0.0	1.7	1.5
25th	0.0	0.4	1.9	3.7
27th	0.0	0.0	1.7	8.2
29th	0.0	0.0	1.5	3.0
31st	0.0	0.0	1.5	3.5
33rd	0.0	0.0	1.4	6.4
Voltage THD	2.7		3.7	
3rd	0.6		0.4	
5th	2.6		3.7	
7th	0.3		0.3	
9th	0.0		0.2	
11th	0.0		0.1	

Table 2.3 is a data of the harmonic components of current and voltage for the magnetic and electronic ballasts surveyed by Tolbert L. M. et al. As a result, the following can be said:

- the voltage THD for the magnetic ballasts averaged 2.67 % THD with almost all of the distortion due to a fifth harmonic component,

- the voltage THD for the electronic ballasts, at the lighting panel averaged 3.70% THD with most of the distortion due to a fifth harmonic component,
- the increase in voltage distortion is directly correlated to the increase in fifth harmonic current distortion,
- the fifth harmonic content of the current increased by 73.4 % when the magnetic ballasts were replaced by electronic ballasts.

2.5 Limits

There are two separate approaches that can be applied to limit the harmonics amount that are present in power systems. The first, developed by the International Electrotechnical Commission (IEC), is a number of limits that is appropriate for application at the terminals of any various nonlinear loads. The second, promoted by the IEEE and the basis for IEEE 519-1992, is a number of limits that is appropriate for application at a central point of supply to multiple nonlinear loads. The objective of the IEC limits according Halpin S. M. et al. is formed on the presumption that limiting harmonic production from every piece of equipment will effectively limit any combined effects. However, it is supposed (Halpin S. M. et al. 1993) more restrictive limits set by IEEE due to the use of both voltage and current harmonic limits. Thus, IEC limits are considered to be closer to actual ones.

Standards and their content related to operate zone are represented below:

- IEC 61000-3 and EN 50160 - Europe
- IEEE Std. 519 - USA

2.5.1 IEC 61000-3 and EN 50160

The major European product standard is IEC/EN 61000-3 which will affect most electrical products. However, original primogenitor of this paper was another standard that have been operated more than two decades ago, IEC 555.

There are some divisions inside IEC 61000-3 itself that response for different categories of appliances. IEC 61000-3-2 standard assesses and sets the limit for equipment with rated current ≤16A per phase. Equipment with rated current >16A and ≤75A per phase is covered by IEC/TS 61000-3-12. Harmonics measurement and evaluation methods for both standards are governed by IEC 61000-4-7.

Equipment can be grouped into one of four classes based on the following criteria as evaluated by the IEC committee members:

- Number of pieces of equipment in use (how many (volume) are being used by consumers)
- Duration of use (number of hours in operation)
- Simultaneity of use (are the same type of equipment used on the same time frame)
- Power consumption
- Harmonics spectrum, including phase (how clean or distorted is the current drawn by the equipment)

According to above criteria, equipment is classified as follows:

Table 2.4. Equipment classification. (IEC 61000-3, 2000)

Class A	• Balanced three-phase equipment • Household appliances, excluding equipment identified by Class D • Tools excluding portable tools • Dimmers for incandescent lamps • Audio equipment • Everything else that is not classified as B, C or D
Class B	• Portable tools • Arc welding equipment which is not professional equipment
Class C	• Lighting equipment
Class D	• Personal computers and personal computer monitors • Television receivers Note: Equipment must have power level 75W up to and not exceeding 600W

Maximum harmonic levels in accordance with number of harmonic are presented in Table 2.5.

Table 2.5. Harmonics limit. (IEC 61000-3, 2000)

Harmonics [n]	Class A [A]	Class B [A]	Class C [% of fund]	Class D [mA/W]
Odd harmonics				
3	2.30	3.45	30 x λ	3.4
5	1.14	1.71	10	1.9
7	0.77	1.155	7	1.0
9	0.40	0.60	5	0.5
11	0.33	0.495	3	0.35
13	0.21	0.315	3	3.85/13
15 ≤n ≤39	0.15 x 15/n	0.225 X 15/n	3	3.85/n
Even harmonics				
2	1.08	1.62	2	-
4	0.43	0.645	-	-
6	0.30	0.45	-	-
8 ≤n ≤40	0.23 x 8/n	0.345 x 8/n	-	-

It should be noticed that present standard has a number of modifications. Starting from 1995 to current moment there was three general editions of it.

The main document dealing with requirements concerning the supplier's side is standard EN 50160, which characterises voltage parameters of electrical energy in public distribution systems. The characteristics of supply voltage in terms of harmonics presence are shown in Table 2.6. In the Finnish national Sener recommendation the limitations are set also for currents.

Table 2.6. Values of individual harmonic voltages at the supply terminals for orders up to 25, given in percent of *Un.* (EN 50160 1999)

Odd harmonics				Even harmonics	
Not multiplied of 3		Multiplied of 3			
Order *h*	Relative voltage, (%)	Order h	Relative voltage, (%)	Order *h*	Relative voltage, (%)
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,5	6...24	0,5
13	3	21	0,5		
17	2				
19	1,5				
23	1,5				
25	1,5				

The interharmonics standardisation process is in its infancy, with knowledge and measured data still being accumulated. The limit level 0.2% for interharmonic voltages is widely applied, mostly because of the lack of a better suggestion. This limit is recommended by IEC in document IEC 61000-2-2: 2002 for the frequency range from DC component to 2 kHz.

2.5.2 IEEE Std. 519

This recommended practice intends to establish methodology for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling; and observance of the design goals will minimize interference between electrical equipment.

Here are several aspects of IEEE 519 described in (Lowenstein M.Z., 2002) that are particularly relevant.

- IEEE 519 isn't an individual standard — it's a system standard. So any attempt to apply its limits to an individual piece of equipment or a particular location within a facility is a misuse.
- The reason for limiting current distortion at the PCC is to ensure a consumer won't draw so much harmonic current from the utility through the unity impedance that the utility voltage distortion will be excessive.
- Limiting this voltage distortion prevents it from spreading to other facilities.

Going into a thorough description of limitations, the IEEE boundary values for voltage and current harmonics shown in Tables 2.7-2.10 are dependent on several variables and concepts defined as follows:

I_{SC} is available short circuit current,

I_L is 15 or 30 minute (average) maximum demand current.

Table 2.7. Current Distortion Limits (in % of I_L) for General Distribution Systems (120-69,000 V). (IEEE Standard 519-1992, 1993)

I_{SC}/I_L	≤11	11≤h<17	17≤h<23	23≤h<25	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2.8. Current Distortion Limits (in % of I_L) for General Subtransmission Systems (120-69,000 V). (IEEE Standard 519-1992, 1993)

I_{SC}/I_L	≤11	11≤h<17	17≤h<23	23≤h<25	35≤h	TDD
<20	2.0	1.0	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4.0
50-100	5.0	2.25	2.0	0.75	0.35	6.0
100-1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

Table 2.9. Current Distortion Limits (in % of I_L) for General Transmission Systems (120-69,000 V). (IEEE Standard 519-1992, 1993)

I_{SC}/I_L	≤11	11≤h<17	17≤h<23	23≤h<25	35≤h	TDD
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75

Table 2.10. Voltage Distortion Limits (in % of V_1). (IEEE Standard 519-1992, 1993)

PCC Voltage	Individual Harmonic Magnitude (%)	THD_V (%)
≤69 kV	3.0	5.0
69-161 kV	1.5	2.5
≥161 kV	1.0	1.5

Where:

PCC is point of common coupling. This point is defined as the point in the utility service to a particular customer where another customer could be connected.

TDD is total demand distortion. TDD is identical to THD except I_L is used instead of the fundamental current component.

2.6 Results Resonance

Power systems are able to absorb a considerable amount of current distortion without problems and the distortion produced by a facility may be below levels recommended in standards. However, the collective effect of many industrial customers, taken together, may impact a distribution system. When problems arise, they are usually associated with resonant conditions.

2.6.1 Parallel resonance

Every circuit that contains both capacitances and inductances has one or more natural frequencies. When one of those frequencies becomes equal to a frequency that is being produced on the power system, a resonance phenomenon may appear in which the voltage and current at that frequency continue increasing till very high values. This is the cause of most problems with harmonic distortion on power systems. Figure 2.8 shows a typical system with potential parallel resonance problems.

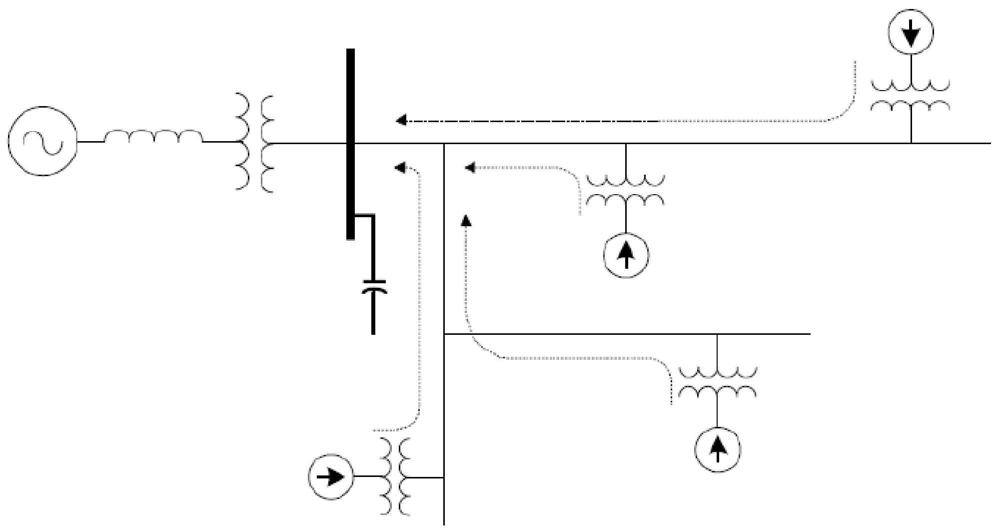

Figure 2.8. System with potential parallel resonance problems. (Ozdemir A., 2009)

From the perspective of harmonic sources the shunt capacitor appears in parallel with the equivalent system inductance (source and transformer inductances) at harmonic frequencies as illustrated in Figure 2.9b. Parallel resonance occurs when the reactance of X_c and the distribution system cancel each other out. The frequency at which this phenomenon occurs is called the parallel resonant frequency. It can be expressed as follows (Ozdemir A., 2009):

$$f_p = \frac{1}{2\pi} \cdot \sqrt{\frac{1}{L_{eq}C} - \frac{R^2}{4L_{eq}^2}} \approx \frac{1}{2\pi}\sqrt{\frac{1}{L_{eq}C}} \quad , \tag{2.9}$$

where

R is resistance of combined equivalent source and transformer,

L_{eq} is inductance of combined equivalent source and transformer,

C is capacitance of capacitor bank,

f_p is parallel resonance frequency.

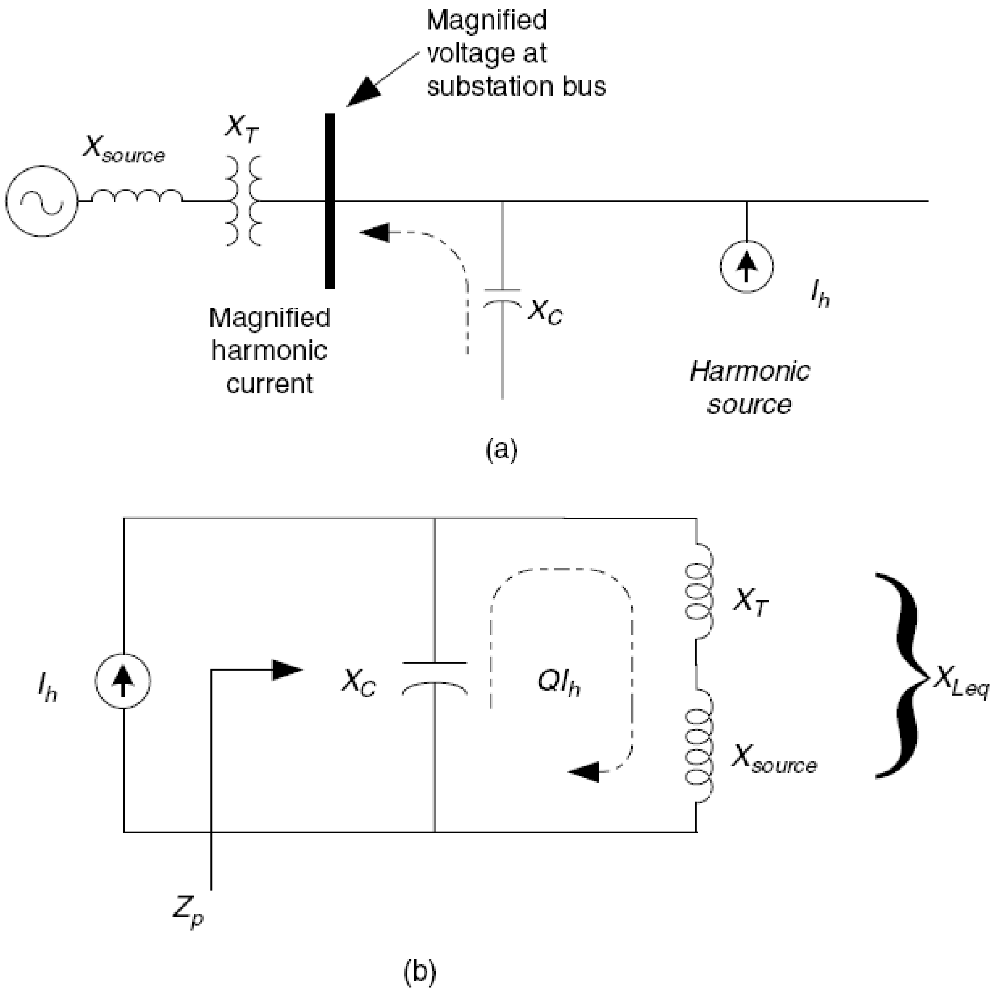

Figure 2.9. (a) Simplified distribution circuit; (b) parallel resonant circuit as seen from the harmonic source. (Ozdemir A., 2009)

At the resonant frequency, the apparent impedance of the parallel combination of the equivalent inductance and capacitance as seen from the harmonic current source becomes very large, i.e.:

$$Z_p = \frac{X_c\left(X_{Leq} + R\right)}{X_c + X_{Leq} + R} = \frac{X_c\left(X_{Leq} + R\right)}{R} \approx \frac{X_{Leq}^2}{R} = \frac{X_C^2}{R} = QX_{Leq} = QX_C \quad , (2.10)$$

where

X_c is capacitance of capacitor bank,

Q is quality factor of resonant circuit.

$$Q = \frac{X_L}{R} = \frac{X_C}{R} \quad (2.11)$$

$$R \ll X_{Leq} \quad (2.12)$$

It should be pointed, that the reactance in this equation is calculated at the resonant frequency. Quality factor of a resonant circuit (Q) determines the sharpness of the frequency response. Q varies considerably by location on the power system. It might be less than 5 on a distribution feeder and more than 30 on the secondary bus of a large step-down transformer. It is clear that during parallel resonance, a small harmonic current can cause a large voltage drop across the apparent impedance that can be expressed as following:

$$V_p = QX_{Leq}I_h \quad , \quad (2.13)$$

where

V_p is voltage drop during parallel resonance,

I_h is the amplitude of the harmonic current of order *h*.

The voltage near the capacitor bank will be magnified and heavily distorted. Let us now examine current behavior during the parallel resonance. According Ozdemir A. the current flowing in the capacitor bank or into the power system is determined according following formula:

$$I_{resonance} = \frac{V_p}{X_c} = \frac{QX_cI_h}{X_c} = QI_h \quad (2.14)$$

$$I_{resonance} = \frac{V_p}{X_{Leq}} = \frac{QX_{Leq}I_h}{X_{Leq}} = QI_h \tag{2.15}$$

It is clear that currents flowing in the capacitor bank and in the power system (i.e., through the transformer) will also be magnified Q times. This phenomenon will likely cause capacitor failure, fuse blowing, or transformer overheating.

2.6.2 Series resonance

There are certain instances when a shunt capacitor and the inductance of a transformer or distribution line may appear as a series LC circuit to a source of harmonic currents. If the resonant frequency corresponds to a characteristic harmonic frequency of the nonlinear load, the LC circuit will attract a large portion of the harmonic current that is generated in the distribution system. A customer having no nonlinear load, but utilizing power factor correction capacitors, may in this way experience high harmonic voltage distortion due to neighboring harmonic sources. This situation is depicted in Figure 2.10.

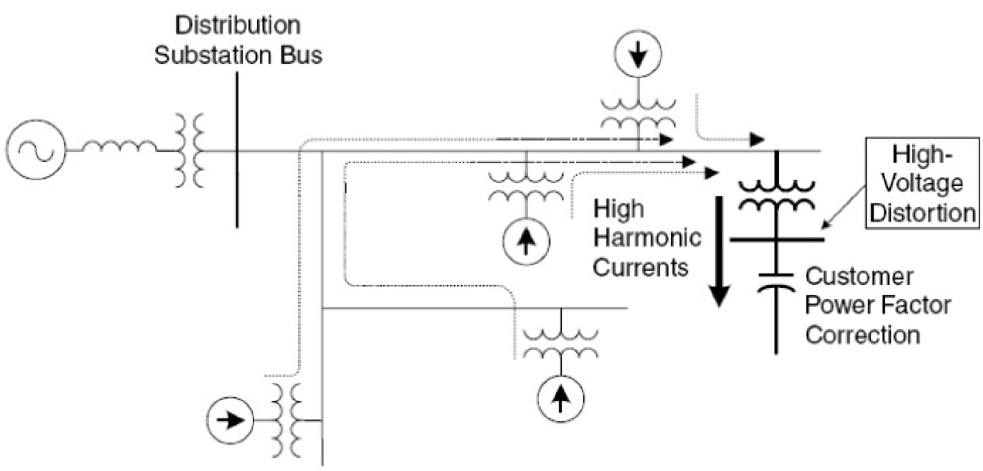

Figure 2.10. System with potential series resonance problems. (Ozdemir A., 2009)

During resonance, the power factor correction capacitor forms a series circuit with the transformer and harmonic sources. The simplified circuit is shown in Figure 2.11.

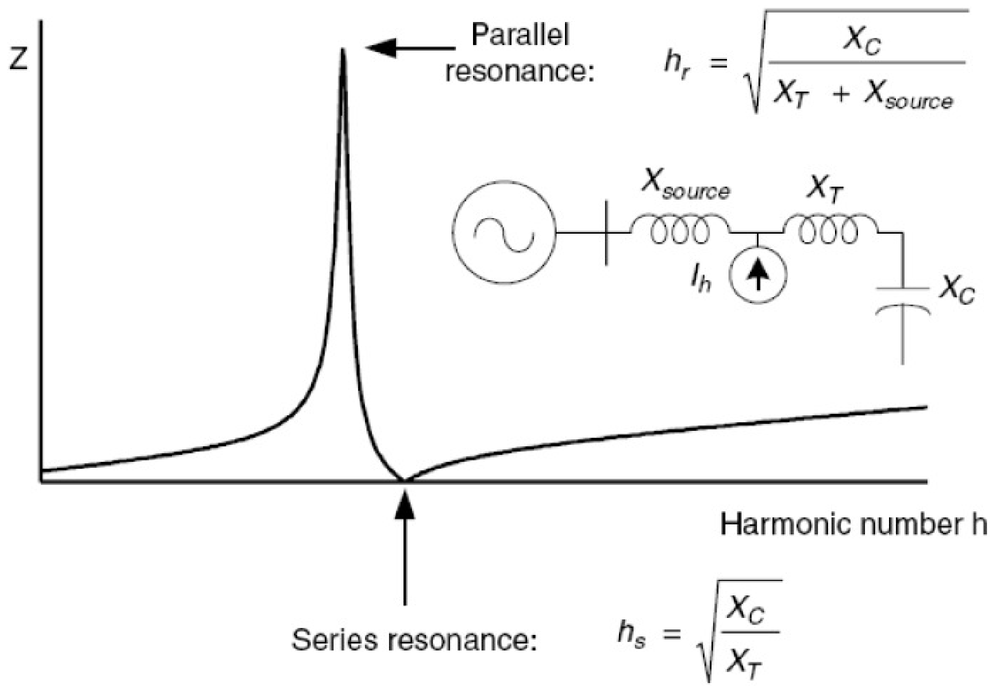

Figure 2.11. Frequency response of the circuit with series resonance. (Ozdemir A., 2009)

The harmonic source shown in this figure represents the total harmonics produced by other loads. The inductance in series with the capacitor is that of the service entrance transformer. The series combination of the transformer inductance and the capacitor bank is very small (theoretically zero) and only limited by its resistance. Thus the harmonic current corresponding to the resonant frequency will flow freely in this circuit. The voltage at the power factor correction capacitor is magnified and highly distorted. This is apparent from the following equation:

$$V_s = \frac{X_c}{X_T + X_c + R} V_h \approx \frac{X_c}{R} V_h \quad , \qquad (2.16)$$

where

V_h is the harmonic voltage corresponding to the harmonic current I_h,

V_s is the voltage at the power factor capacitor bank;

R is resistance of the series resonant circuit (small compared to the reactance).

3 Harmonic reducing

3.1 Introduction in methods

Prevention is known as the best way to deal with harmonics problems. The idea of prevention technique is choosing equipment and installation practices that minimize the level of harmonics in any one facility or even part of circuit. The great number of power quality problems that result from harmonics, occur when new equipment is rashly added to older systems. However, even within existing systems, the harmonics problems can often be solved with simple solutions. For instance it might be:

- fixing poor or nonexistent grounding on individual equipment or the facility as a whole,
- moving a few loads between branch circuits,
- adding extra circuits to help isolate the sensitive equipment from what is causing the harmonic distortion.

In case problems cannot be solved by prevention methods, two basic choices exist: to make the distribution system reinforcement in order to withstand the harmonics or to install devices to mitigate or remove the harmonics. To reinforce the distribution system following actions can be used:

- installation double-size neutral wires or installing separate neutral wires for each phase,
- installation oversized or K-rated transformers, which allow for more heat dissipation,
- usage harmonic-rated circuit breakers and panels, which are designed to prevent overheating due to harmonics.

Generally this method is more suited to new facilities, because the costs of renovation an existing facility could be significant. Harmonics mitigation methods according Platts Ltd. consideration, from cheap to more expensive, are present below:

- passive harmonic filters,
- isolation transformers,
- harmonic mitigating transformers (HMTs),
- active filters.

More detailed information about solutions to mitigate harmonics is described in Table 3.1 below.

Table 3.1. Harmonic mitigation methods analysis.

Solution	Best application	Notes
Reinforce distribution system (add double-sized neutral wires, harmonics-rated breakers, oversized or K-rated transformer, etc.)	New facilities	Simple, relatively low capital costs, but does not remove problem
Passive filter	For circuits that include three-phase loads, where there are only minor voltage imbalances between phases	Lower-cost that active filters, but requires analysis and a trial-and-error approach; does not adapt to changes in system
Isolation transformer	Where source of harmonics are on separate branches from harmonics-sensitive equipment	Isolates but does not remove the problem
Harmonic mitigation transformer	On a moderately to heavily loaded transformer with high harmonic content in system, and/or where critical loads are backed up by an uninterruptible power supply	Reduces energy losses in transformer; cast: about $25 to $30/KVA
Harmonic suppression system	For circuits with only single-phase loads and existing or new facilities with high reliability needs; where problems exist downstream of distortion panel	Removes the source of the problem and reduces energy costs; cost; about $80 to $120/KVA
Active harmonic filter	For circuits that include three-phase loads; voltage imbalances between phases can be present	Adapts to changes in system; self-regulates to avoid overloading; cost: about $500/KVA

3.2 AC drives

Talking about AC drives, harmonics reduction can be done either by structural modifications in the drive system or by using external filtering. The structural modifications can be done in different ways such as:

- strengthening the supply,
- using 12 or more pulse drive,
- using a controlled rectifier,
- improving the internal filtering in the drive.

The typical AC drive system and related parameters of facilities are shown in Figure 3.1. Varying the parameters it is possible to determine the effect to harmonic levels and presence in system as well. These factors and results are described in Table 3.2 provided by ABB crew. The main dependence used in analyze is that voltage harmonics are the current harmonics multiplied by the supply impedances. Also, the fact that current harmonics depend on the drive construction is taken into consideration.

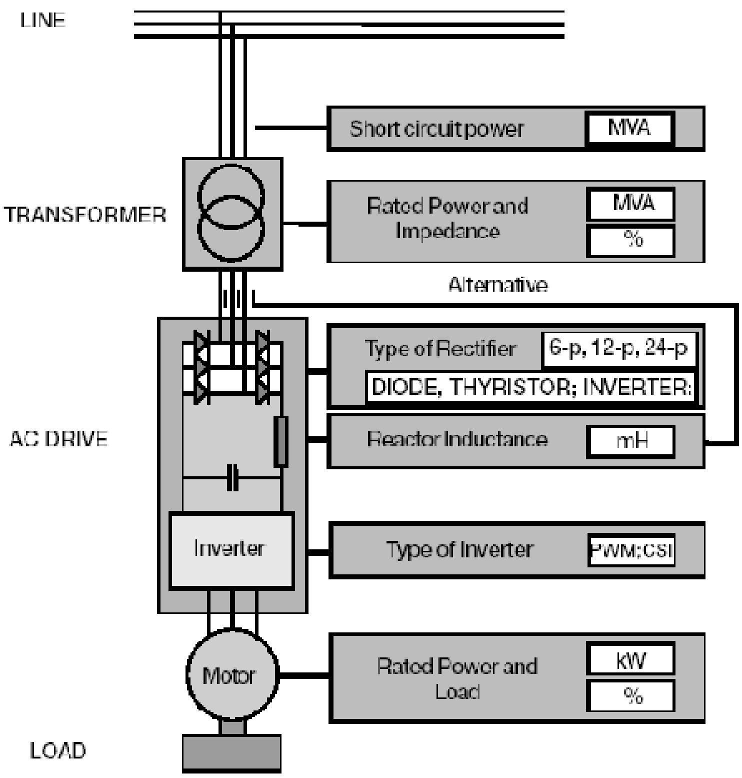

Figure 3.1. Drive system features affecting harmonics.(ABB, 2004)

Table 3.2. Different factors and their effects.

The cause	The effect
The larger the motor	the higher the current harmonics
The higher the motor load	the higher the current harmonics
The larger the DC or AC inductance	the lower the current harmonics
The higher the number of pulses in the rectifier	the lower the current harmonics
The larger the transformer	the lower the voltage harmonics
The lower the transformer impedance	the lower the voltage harmonics
The higher the short circuit capacity of supply	the lower the voltage harmonics

3.3 Harmonic filters

3.3.1 Passive harmonic filters

Filtering is a method to smooth out current demand over each cycle of alternating current and so reduce the general harmonic currents. This filtering is utilized when the harmonic distortion has been gradually increased or as an initial solution in a new electrical installation. Harmonic filters can be used in industrial plants as well as in particular electrical facility. There are two basic methods: passive and active filters.

Traps or simply known as passive filters include devices that provide low-impedance paths to retarget harmonics to ground and devices that create a higher-impedance path to make the flow of harmonics through it difficult . Both of these devices change the impedance characteristics of the circuits where they are installed. The weakness of passive harmonic technologies is that, they cannot adapt to changes in the electrical systems in which they operate. In other words, changes to the electrical system (for example, the addition or removal of power factor–correction capacitors or the addition of more nonlinear loads) could cause them to be overloaded or to create “resonances” (Section 2.6) that could actually amplify, rather than diminish, harmonics.

Passive filters according their constructive features can be divided into single and multiply tuning frequency arm. The principle of a tuned arm passive filter is shown in Figure 3.2. A tuned arm passive filter should be applied at the single lowest harmonic component (fifth harmonic for industrial load) where there is significant harmonic generation in the system. The objective of such filters is that the harmonics above the tuned frequency are absorbed but ones below that frequency may be amplified.

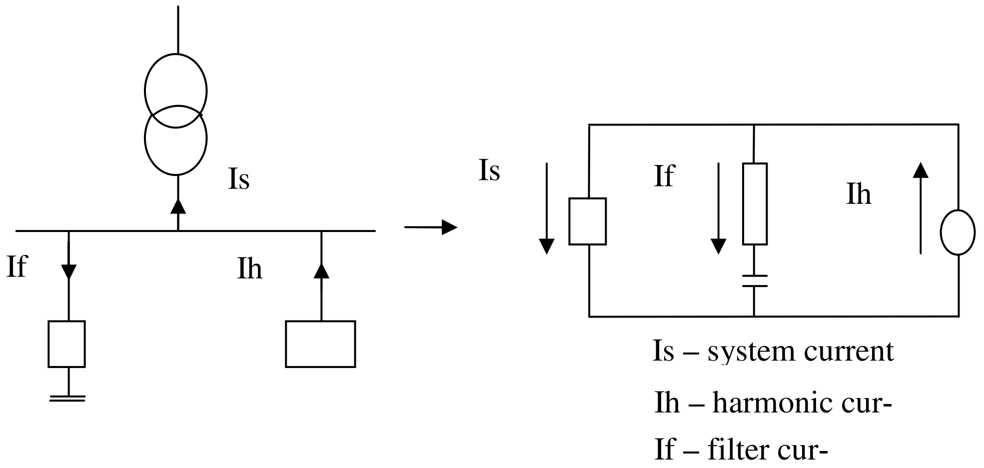

Figure 3.2. Tuned single arm passive filter.

Objectives of tuned single arm passive filter are summarized below:

- Detuned - Single tuning frequency
- Above tuned frequency harmonics absorbed
- Below tuned frequency harmonics may be amplified
- Harmonic reduction limited by possible over compensation at the supply frequency and network itself.

This type of filter consists of an inductor in series with a capacitor bank and the best location for the passive filter is close to the harmonic generating loads. This solution is not normally used for new installations.

The principle of tuned multiple arm filter is shown in Figure 3.3. This filter has several arms tuned to two or more of the harmonic components which should be the lowest significant harmonic frequencies in the system. The multiple arm filters have better harmonic absorption than the one arm system.

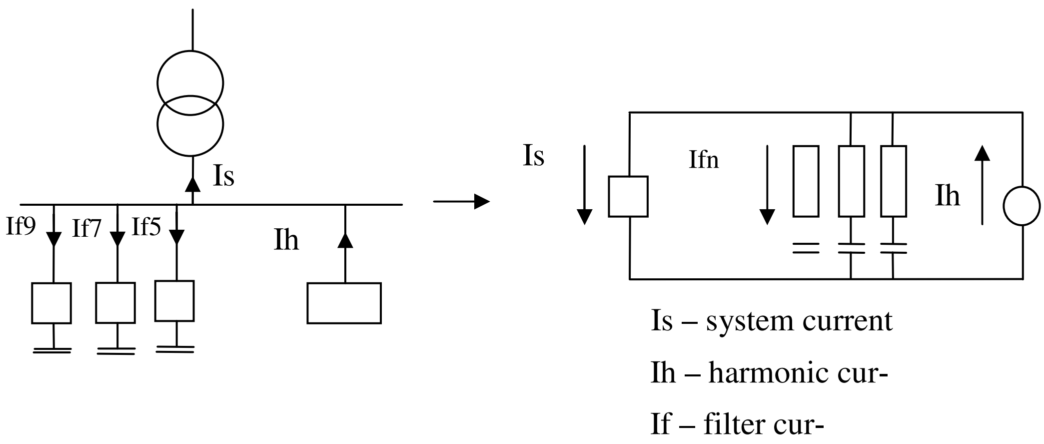

Figure 3.3. Tuned multiple arm passive filter.

Objectives of tuned single arm passive filter are summarized below:

- Capacitive below tuned frequency/Inductive above
- Better harmonic absorption
- Design consideration to amplification harmonics by filter
- Limited by KVAr and network

The multiple arm passive filters are often used for large DC drive installations where a dedicated transformer is supplying the whole installation. Passive filtration has one significant drawback, it causes losses as the power of non-wanted harmonics is converted to heat in filters.

3.3.2 Active harmonic filters

Active filters in contrast, continuously adjust their behavior in response to the harmonic current content of the circuit where they are installed, and another essential feature they will not cause resonance. These filters are designed to accommodate a full range of expected operating conditions upon installation, without requiring further adjustments by the operator. The general active filter system is represented in Figure 3.4.

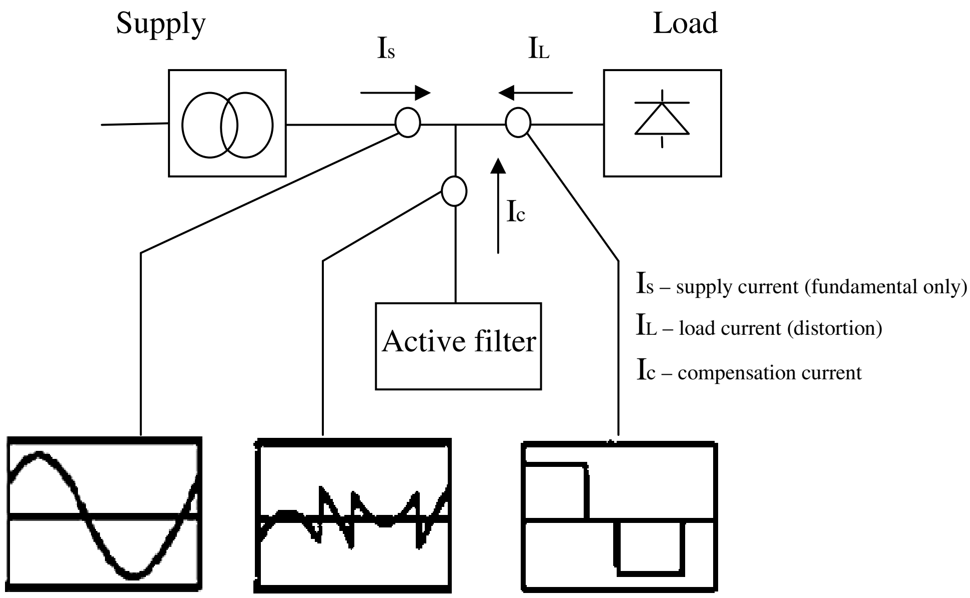

Figure 3.4. External active filter principle diagram. (ABB, 2004)

The active filter compensates the harmonics generated by nonlinear loads by generating the same harmonic components in opposite phase as shown in Figure 3.5. External active filters are most suited to multiple small drives. They are relatively expensive compared to other methods.

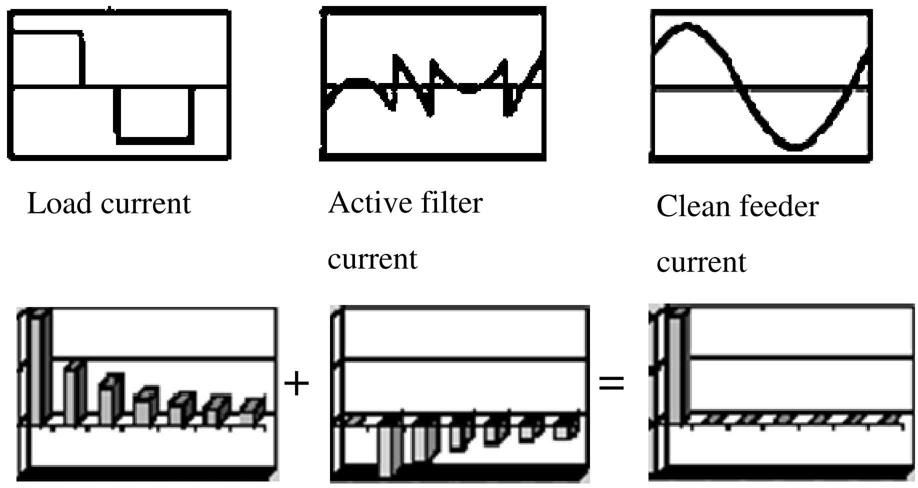

Figure 3.5. External active filter waveforms and harmonics. (ABB, 2004)

3.4 Isolation transformers

Isolation transformers are filtering devices that allocate harmonics in the particular circuit in which they are installed, thus protecting upstream equipment from the effects of harmonics. However, these transformers do not remove the problem in the circuit generating the harmonics, but they can prevent the harmonics from affecting more sensitive equipment elsewhere within the facility.

3.5 Harmonic mitigation transformers (HMT)

Usage of harmonic mitigation transformers relieves problematic harmonics. HMTs can be effective in terms of price in the right application, because they can both improve reliability and reduce energy costs. The proper application includes transformers that are heavily or moderately loaded and where high levels of harmonic currents are present. Moreover, HMTs are very effective in supporting critical loads that are backed up by a UPS. UPSs and backup generators tend to have high impedance, which results in high voltage distortion under nonlinear loading. Because of this, equipment that operates flawlessly when supplied by utility power may malfunction when the backup system engages during a utility outage.

3.6 Alternative methods (current injection)

Current injection technique is thoroughly described by Maswood A.I. et al. Technique based on injecting a 3rd current harmonic in the inter-phase transformer of converters. Two groups of converters have to be available. As well, the source of the 3rd current harmonic is connected between the star points of the two groups as shown in Figure 3.6. The injected current circulates within the two converters groups and the transformer secondary winding. Selecting the appropriate phase shift and magnitude of the injected current results in nulling one current harmonic and reducing other harmonics significantly. The order of the nullified harmonic is determined by the magnitude of the injected current. The current sources in the developed schemes are connected across the secondary windings of the converter transformer allowing this technique to be applied to any type of converter. This scheme does not suffer from the problems associated with filtering, in particular the effect of system impedance. Although this scheme does not eliminate completely more than one harmonic for a given operating condition, it provides a significant improvement. (Maswood A.I. et al. 2006)

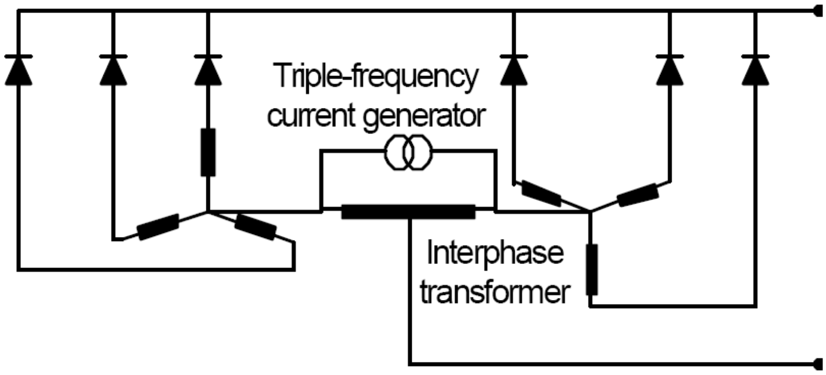

Figure 3.6. Principle of harmonic elimination by the harmonic injection technique. (Maswood A.I. et al. 2006)

4 Development of calculation model

The practical part of thesis implies creation model of distribution network that will be able to demonstrate the effect of different non-linear loads on power quality. Also the comparison data about power losses and voltage drop in the whole network and each component of it will be obtained.

4.1 Model overview

The single-line diagram shown in Fig. 4.1 represents designed distribution system. The electric utility distributes power at 110 kV, which in turn feeds a 20.5 kV distribution system via a 20 kV, 3-phase, 50-Hz, 10MVA distribution transformer. Further mostly 2000 kVA service transformers are used to step the voltage down from 20.5 kV to 0.4 V. Only in one point of the distribution network a transformer with less capacity (100 kVA) is set up. So called “basic load” is chosen to make procedure of initial data entering to system simpler. However existing model allows easily change initial load value manually.

Equivalent circuit with totally linear load is given in Figure 4.2. Nodes are numbered for network parameters visualization. Model is designed so that it requires predefined power value of the basic load and for each harmonic. Impedances of the network units are set up as frequency dependant elements. Different approaches for evaluation of these dependences are chosen. Furthermore detailed information is discussed in Section 4.2. DC resistances and inductances for lines as well as directory data for transformers are represented in Figure 4.2. Thus obtaining all these initial data the power flow and voltage drop calculations can be done for each harmonic and eventually for summarized distorted voltages and currents. Obviously only harmonic numbers that are present in load spectrum are under consideration.

Calculation is held into two stages: power flow and voltage in network nodes calculations. Power flow is calculated starting from customer side. By knowing the power flow inside network the further voltage in nodes is determined. This second stage calculation starts from the supplier point. In order to obtain accurate results two extra iterations are used. Voltage values in every node from previous iteration are set as the initial data.

There is one difference in comparison the first and the rest iterations. First stage implies the rated voltage levels in network nodes. Correspondently, no-load losses in transformers will remain as rated for this stage. When calculating real no-load losses in transformers for further iterations the voltage deviation is taken into account in response to following equation:

$$P_0 = P_0 \cdot \left(\frac{U_{2fact}}{U_{2rated}}\right)^2 , \qquad (4.1)$$

where

P_0 is no-load losses in a transformer,

U_{fact} is secondary voltage of a transformer,

U_{2rated} is rated secondary voltage of a transformer.

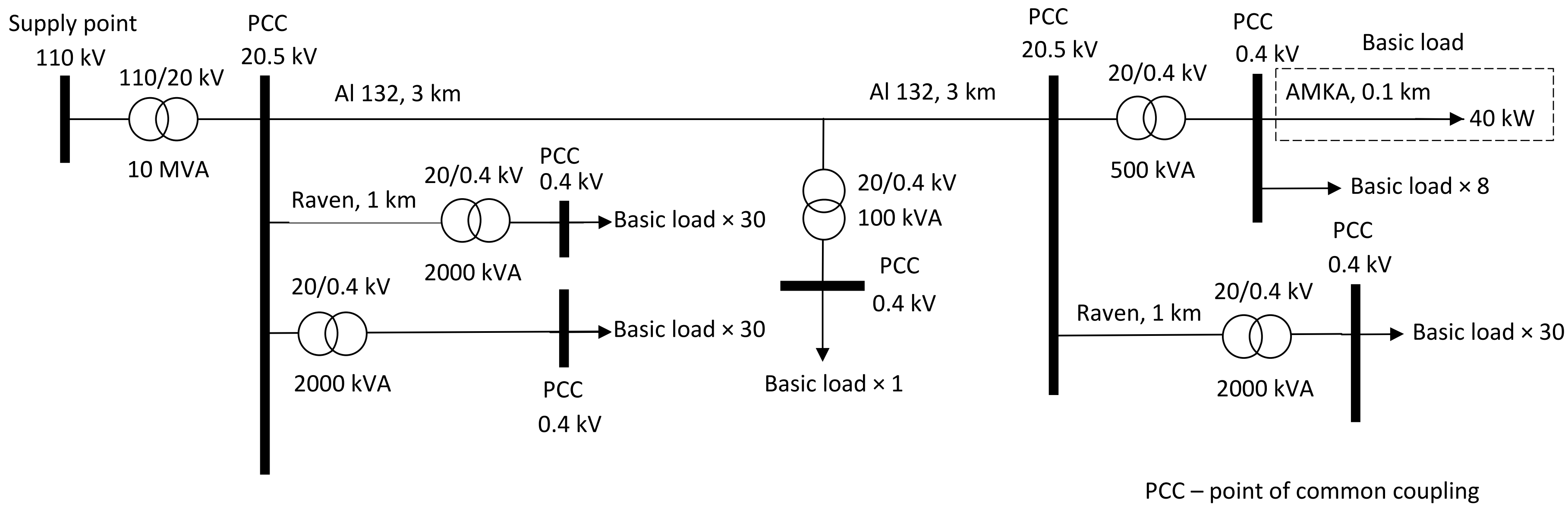

Figure 4.1. Designed distribution network circuit.

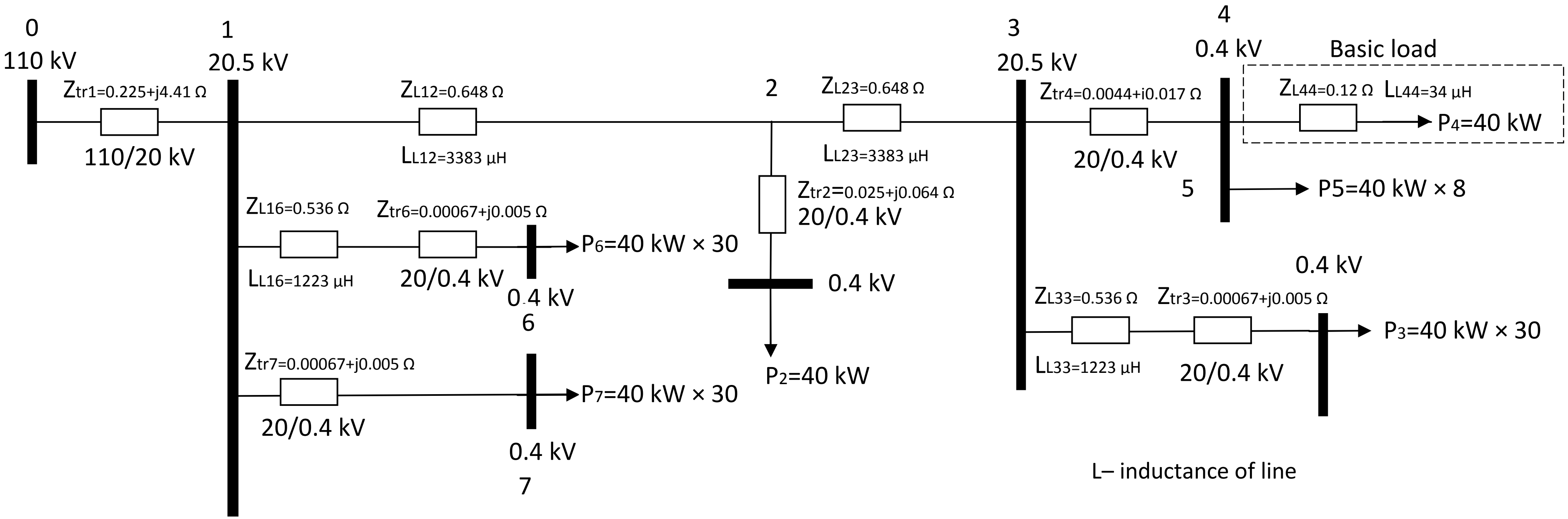

Figure 4.2. Equivalent circuit.

4.2 Frequency dependent load flow

Proposed calculation model requires the knowledge of network elements impedances for each frequency that is calculated. Different approaches and approximations are chosen for this purpose.

4.2.1 Impedance of lines and cables

When considering a conductor carrying high alternating currents, two effects should be taken into account in order to accuracy estimate AC resistance of conductor. These are two independent effects known as skin effect and proximity effect. They affect to distribution of current throughout the cross section of the conductor.

In case conductor is composed of one or more concentric circular elements, then the centre portion of the conductor will be wrapped by greater magnetic flux than those on the outside. Thus the current density is less at the centre than at the conductor surface. The effective resistance is increasing due to this extra concentration at the surface in respect to following equation (IEC 60287, 1994):

$$y_s = X_s^4 / (192 + 0.8 \cdot X_s^4) \quad , \tag{4.2}$$

where

y_s is skin effect factor,

x_s is skin effect coefficient.

$$X_s^2 = 8 \cdot \pi \cdot f \cdot 10^{-7} \cdot k_s / R_{dc_t} \quad , \tag{4.3}$$

where

f is frequency (Hz),

k_s is factor determined by conductor construction (1 for circular, stranded, compacted and sectored),

R_{dc_t} is DC resistance at operating temperature *t*.

In spite of that temperature dependence here is considered, in element modeling for network calculation it is counted as negligible.

Proximity effect also increases the effective resistance of conductor. It is allocated with the magnetic fields of few conductors which are close together. In case of the same directions of currents carried by conductors, the remote halves of them will carry greater share. If the currents are in opposite directions, the halves in close to proximity will carry the greater density of current.

The effect can be applied practically for three core and three single core cables using following equation (IEC 60287, 1994):

$$y_p = \frac{X_p^4}{(192 + 0.8 \cdot X_p^4)} \cdot \left(\frac{d_c}{S}\right)^2 \cdot \left[0.312 \cdot \left(\frac{d_c}{S}\right)^2 + \frac{1.18}{\frac{X_p^4}{(192 + 0.8 \cdot X_p^4)} + 0.27}\right], \tag{4.4}$$

where

y_p is proximity effect factor,

x_p is proximity effect coefficient.

$$X_p^2 = \frac{8 \cdot \pi \cdot f \cdot 10^{-7} \cdot k_p}{R_{dc_t}}\ , \tag{4.5}$$

where

d_c is diameter of conductor (mm),

k_p is factor determined by conductor construction (1 for circular, stranded, compacted and sectored; 0.8 if above conductors are dried and impregnated),

S is spacing between conductor centers (mm).

Thus, with all above consideration the final AC resistance for each frequency can be obtained as:

$$R_{ac_f} = R_{dc_t} \cdot [1 + y_s + y_p] \,. \tag{4.6}$$

Frequency dependence of reactance that is used in the model for every line and cable is shown below:

$$X_f = 2 \cdot \pi \cdot f \cdot L \cdot l \quad , \tag{4.7}$$

where

X_f is conductor reactance for frequency *f*,

L is conductor inductance [H/km],

l is conductor length [km].

4.2.2 Voltage drop and losses in lines and cables

The model is developed for three phase calculation only. The symmetrical component networks, positive, negative and zero sequence networks, are not applied. Therefore, one phase loads cannot be considered in the model at current state. When considering the symmetrical three phase load flow only positive sequence network impedances need to be known.

Present model implies the calculation of power losses and voltage drop in lines and cables in three stages:

- calculation power losses with DC resistance parameters,
- thereafter at the standard sinusoidal 50 Hz current,
- and at a frequency other than 50 Hz.

The following figure shows the main principal of system impedance division into ideal DC-part and frequency dependent part.

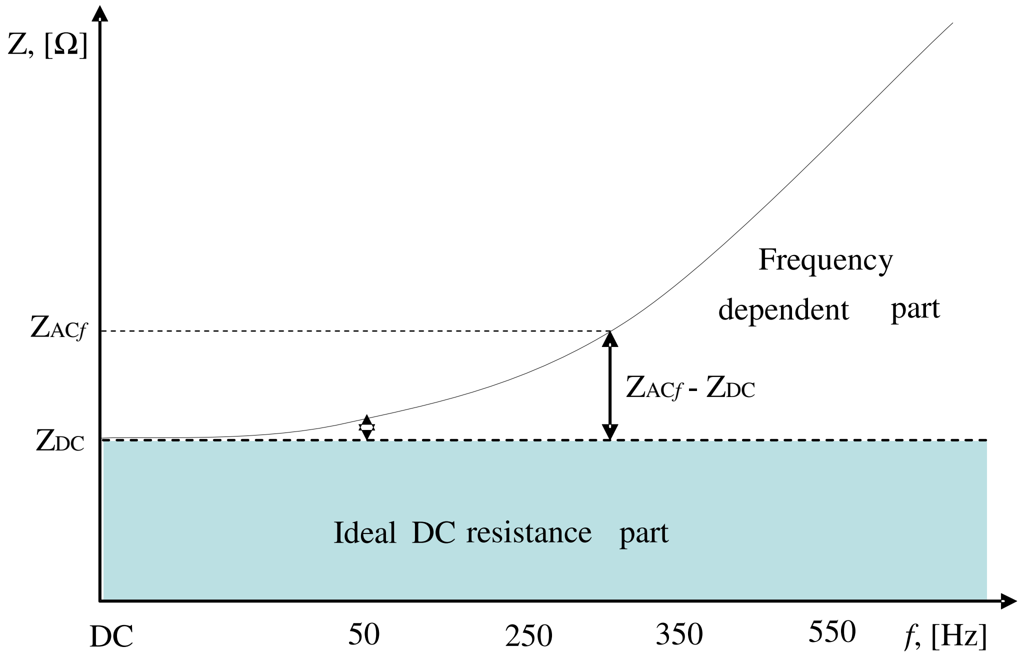

Figure 4.3. System impedance components.

First stage implies calculation of model guessing the RMS current flows only through DC resistance. In both the second and the third stages the impedance in deduction of DC component is used. Thus harmonic currents of each frequency are calculated through corresponding AC part. Total voltage drop and power losses are obtained by summarizing resulted losses components from three stages. For total power losses calculation the simply summation is used. However, total voltage drop is the RMS value of losses components.

RMS values are used to obtain the resultant value of voltage drop in lines as well as in transformers.

The power losses in cables and lines are computed using following formula:

$$\Delta S_{line}=\frac{P_{line}^{2}+Q_{line}^{2}}{U_{fact}^{2}}\cdot(R_{line}+j\cdot X_{line})\cdot\sqrt{3}\quad, \tag{4.8}$$

where

ΔS_{line} is apparent power losses in a line,

$\mathbf{P_{line}}$ and $\mathbf{Q_{line}}$ are active and reactive power through a line respectively,

$\mathbf{R_{line}}$ and $\mathbf{X_{line}}$ are resistance and reactance of a line respectively,

U_{fact} is voltage level at the beginning of a line.

Equation below allows getting voltage drop:

$$\Delta U_{line} = \frac{\mathbf{P_{line}} \cdot \mathbf{R_{line}} + \mathbf{Q_{line}} \cdot \mathbf{X_{line}}}{U_{fact}}, \qquad (4.9)$$

where

ΔU_{line} is voltage drop in a line.

4.2.3 Transformer impedances

According to measurements (Zheng J. 2000) that have been done for 2 KVA and 10 KVA transformers the assumption made that reactance increases proportionally to frequency as follows:

$$X_{ac_f} = \frac{\mathbf{Z_k} \cdot \mathbf{U_{2\,rated}^2}}{\mathbf{100} \cdot \mathbf{S_{rated}}} \cdot \mathbf{h}, \qquad (4.10)$$

where

X_{ac_f} is transformer reactance at frequency *f*,

$\mathbf{Z_k}$ is short-circuit impedance of the transformer,

$\mathbf{S_{rated}}$ is rated power of the transformer,

$\mathbf{U_{2\,rated}}$ is rated secondary voltage of the transformer,

h is harmonic order.

Resistances at high frequencies can be stated as negligible, because the frequency dependence curve far less steep than compare with the same curve for reactance. However, for low frequencies it cannot be frown away. The AC resistance calculation method is based on the results obtained from the same AC winding measurements (Zheng J. 2000). Resistance is expressed in accordance to following polynomial:

$$R_{AC_h} = R_{DC} + R_{co} \cdot \left({}^{f_h}/_{f_1} \right)^x \quad , \tag{4.11}$$

where

R_{AC_h} - resistance of the transformer at frequency f_h,

R_{DC} - DC resistance of the transformer,

R_{co} – polynomial coefficient,

x - polynomial order.

Using above formula and approximation approach the equation for 100 KVA AC resistance calculation can be obtained:

$$R_{ac_f} = \frac{\mathbf{P_o \cdot 10^{-3} \cdot U_{2\,rated}^2}}{\mathbf{S_{rated}}^2} + \mathbf{0.0065414} \cdot \left({}^{f_h}/_{f_1} \right)^{1.034} \quad , \tag{4.12}$$

where

$\mathbf{P_o}$ - rated load losses (MW).

The polynomial order and coefficient are extracted from proposed resistance-frequency curve for each transformer individually. If there is a method error, it should not be significant in respect of goals persuaded in this work.

Basic 50 Hz resistance and reactance values for each network element as well as those that are calculated using abovementioned formulas for 250 Hz are represented in Table 4.1.

Table 4.1. 50 Hz and 250 Hz resistance and reactance values for network elements.

Network element	Symbol on scheme	R_{1st}, Ω	X_{1st}, Ω	R_{5th}, Ω	X_{5th}, Ω
110/20 kV transformer 1	Tr1	0,305	4,410	0,647	22,051
20/04 kV transformer 6	Tr6	0,00099	0,005	0,0023	0,025
20/04 kV transformer 7	Tr7	0,00099	0,005	0,0023	0,025
20/04 kV transformer 2	Tr2	0,031	0,064	0,059	0,320
20/04 kV transformer 4	Tr4	0,006	0,017	0,015	0,085

20/04 kV transformer 3	Tr3	0,00099	0,005	0,0023	0,025
Al 132 line 12	L12	0,649	1,062	0,675	5,310
Al 132 line 23	L23	0,649	1,062	0,675	5,310
Raven line 16	L16	0,536	0,384	0,539	1,920
Raven line 33	L33	0,536	0,384	0,539	1,920
AMKA line 44	L44	0,120	0,010	0,120	0,053

4.2.4 Voltage drop and losses in transformers

As with power losses in conductors the calculation of transformer power losses are implemented in three stages:

- calculation transformer losses at DC (including no-load losses),
- thereafter at the standard sinusoidal 50 Hz current,
- and at a frequency other than 50 Hz.

By summing these three results together the total losses are obtained. Total transformer losses are divided into load and no-load losses. The last one does not depend on frequency, thus they are added within DC calculation stage.

The load losses in transformers are subdivided into loss as measured with DC (I^2R loss) and, in addition, eddy current loss in windings and connections, and stray losses in conductive structural parts of the transformer.

The power losses in transformers are computed using following equation:

$$\Delta S_{tr} = \frac{\mathbf{S}_{\mathbf{tr}}^2}{\mathbf{U}_{\mathbf{fact}}^2} \cdot (\mathbf{R}_{\mathbf{tr}} + \mathbf{j} \cdot \mathbf{X}_{\mathbf{tr}}) \cdot \sqrt{3} \quad , \tag{4.13}$$

where

ΔS_{tr} is apparent power losses in a transformer,

$\mathbf{S}_{\mathbf{tr}}$ is apparent power through a transformer,

$\mathbf{R}_{\mathbf{tr}}$ and $\mathbf{X}_{\mathbf{tr}}$ are resistance and reactance of a transformer respectively,

U_{fact} is voltage level at the beginning of a transformer.

Equation below allows getting voltage drop:

$$\Delta U_{tr} = \frac{\mathbf{P_{tr} \cdot R_{tr} + Q_{tr} \cdot X_{tr}}}{U_{fact}}, \tag{4.14}$$

where

ΔU_{tr} is voltage drop in a transformer.

5 Case studies

Examination of different load content as source of various set of harmonics is carried out within case studies scheme represented in Table 5.1. In order to get comparative data the example network with only linear load is calculated first.

Next three cases are aimed to give results to compare parameters of main network elements depending on percentage of non-linear load. Moreover, two last ones give comparison between utilization of two different types of rectifiers: 6-pulse and 12-pulse. Thus for industrial area three phase 6-pulse rectifier is that load. So far model is allowed to calculate 3-three phase load only. However, opportunities for further model development are available. Single phase rectifier as the most common load for areas with domestic and office buildings can be considered for calculation. Incandescent light bulbs are seemed soon will entirely replaced by CFLs all over the globe. Thus, it would be useful to know CFL spread impact on the distribution network and the equipment in the harmonically rich electrical network.

Table 5.1. Case studies scheme.

	Linear load	Non-linear load
CASE 1	100%	0%
CASE 2	90%	10% 6-pulse rectifiers
CASE 3 A	70%	30% 6-pulse rectifier
B		30% 12-pulse rectifier
CASE 4 A	50%	50% 6-pulse rectifier
B		50% 12-pulse rectifier

The same can be said for cases with unbalanced load studies, the model should be updated for single phase calculation mode to be able implement it.

Summarized active and reactive power losses of the entire example system depending on non-linear load proportion are represented in Figures 5.1 and Figure 5.2 respectively. Herewith, 100% value of vertical axis corresponds to situation with linear load. Further, losses for other cases are compared with this value.
Theoretically, both total active and reactive power losses cannot be less in case with non-linear load component compare with ideal in terms of load linearity case. From Figure 5.1 it is seen some curve dip (less than 0.2%) with small doze of non-linear load. It can be explained by uncertainty of designing frequency dependence for transformers resistances. To avoid this inaccuracy more precise dependence based on real measurements should be done. However, total active power losses to reactive ones ratio shown that apparent power losses are mostly based on reactive component. Thus, this error should not affect to voltage drop values and whole calculation model results significantly.

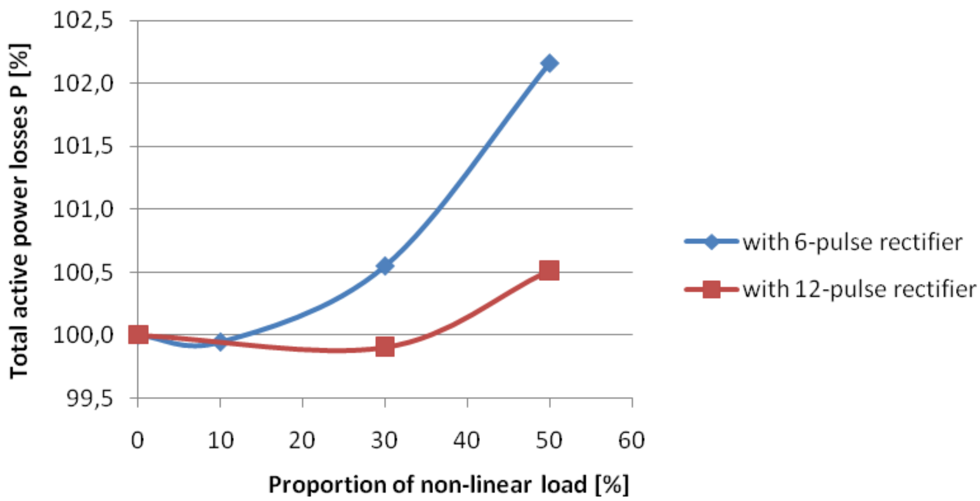

Figure 5.1. Summarized active power losses of the entire example network.

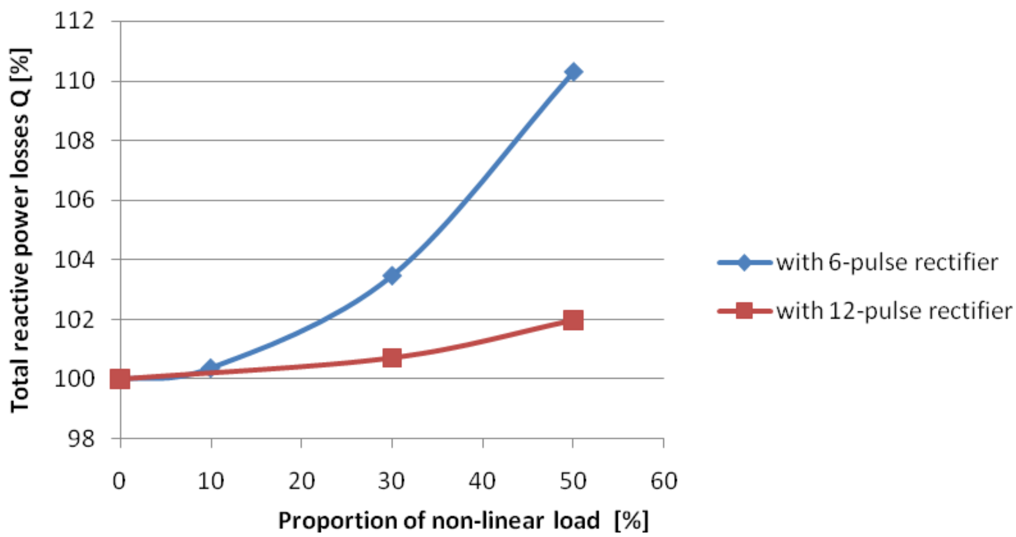

Figure 5.2. Summarised reactive power losses of the entire example network.

Whole calculation cycle consists of three iterations that sequentially make result more accurate. Each iteration data of Case 1(DC calculation stage, line 33) are shown in Table 5.2.

Table 5.2. Iteration procedure results.

Parameter	Iteration 1	Iteration 2	Iteration 3
ΔP, W	5007,220	5237,079	5220,700
ΔQ, VAR	3588,260	3754,055	3742,315
ΔU, V	48,447	49,029	49,027
ΔU, %	0,236	0,239	0,239

Full three iteration analysis for every observable element from Case 1 is in Appendix A. Hereinafter the results from final third iteration are under review.

Below, case studies results for each component of network are represented on the Figure 5.3 and Figure 5.4. First value is given for 100% linear load in correspondence to Case 1. Values in the figures are rounded in order to not overcharge plot, exact values are represented in Table 5.3.

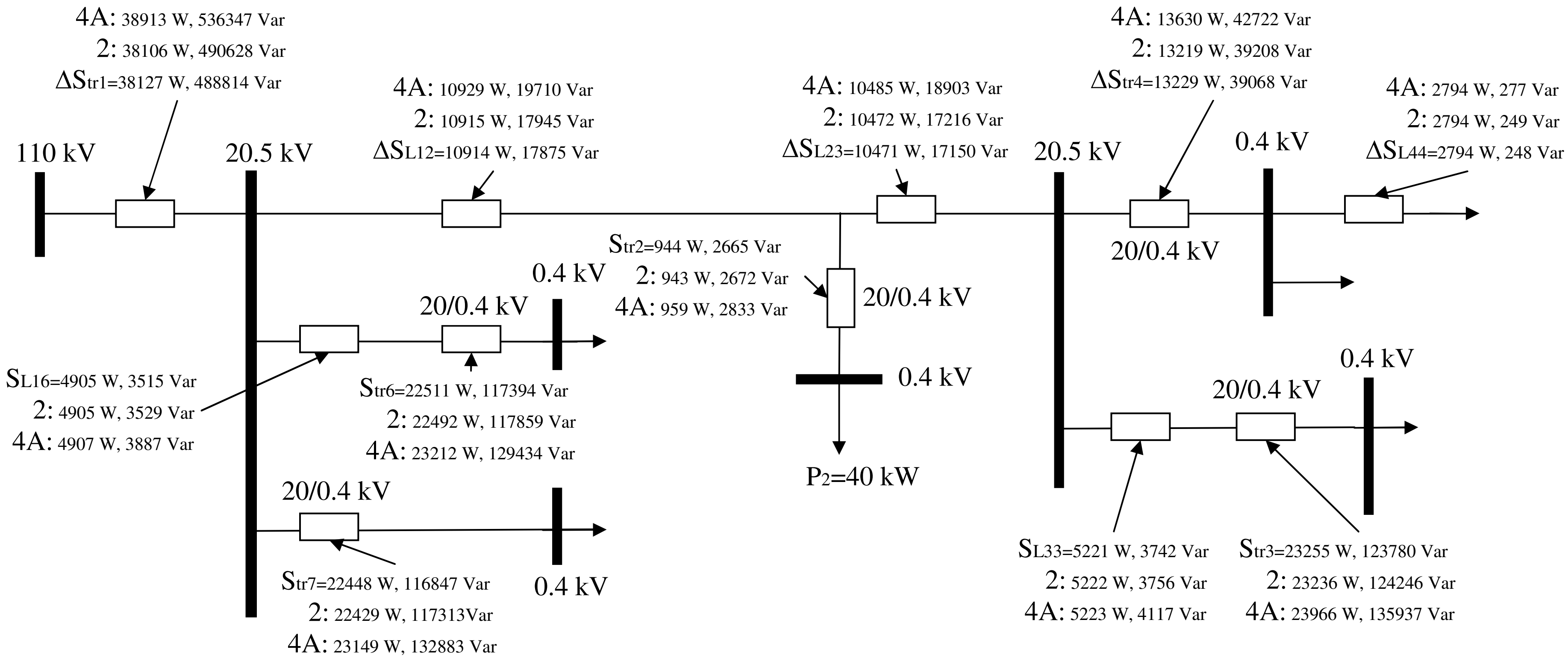

Figure 5.3. Total power losses in network elements for Case 1, 2 and 4A.

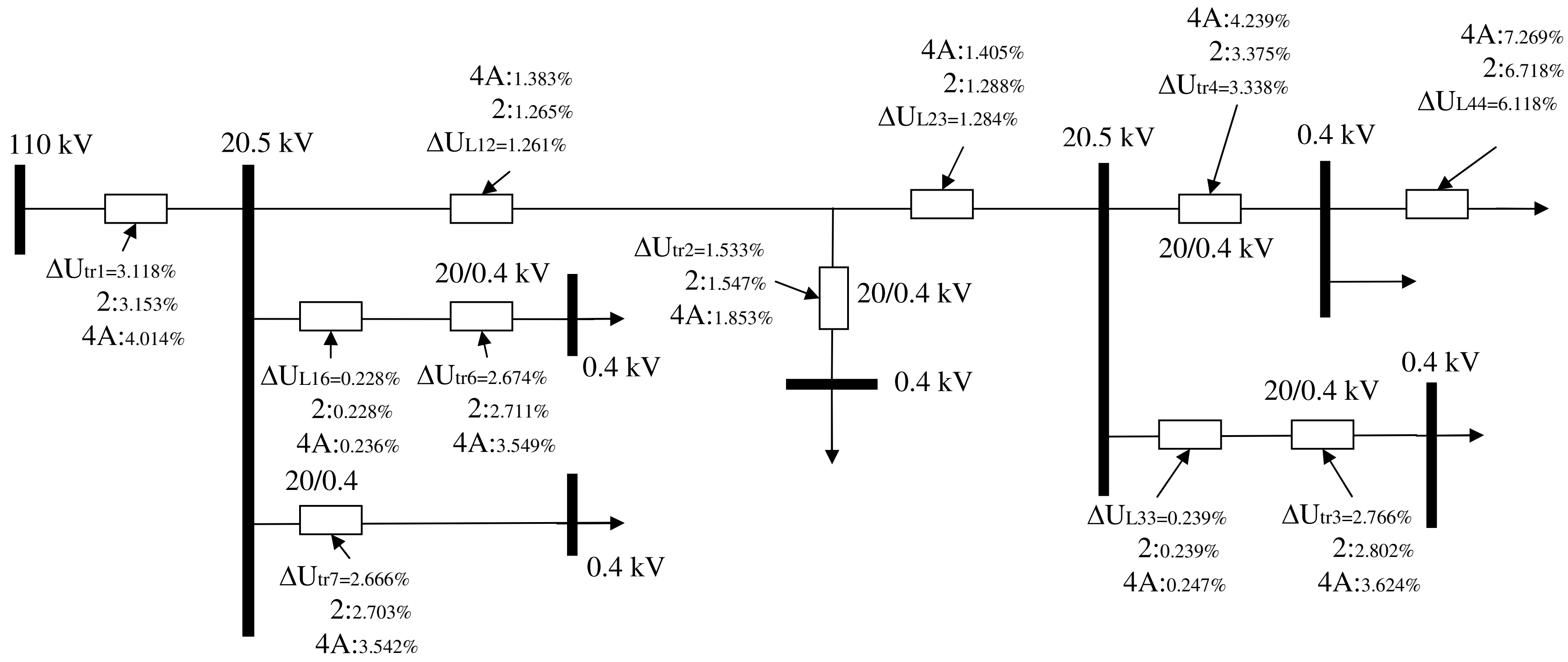

Figure 5.4. Voltage drop in network elements for Case 1, 2 and 4A.

Table 5.3. Results from case 1,2 and 4A studies.

Network element	Symbol on scheme	CASE 1			CASE 2			CASE 4A		
		ΔP, W	ΔQ, W	ΔU, %	ΔP, W	ΔQ, W	ΔU, %	ΔP, W	ΔQ, W	ΔU, %
110/20 kV transformer 1	Tr1	38127,334	488814,287	3,118	38106,926	490628,048	3,153	38913,671	536347,308	3,526
20/04 kV transformer 6	Tr6	22511,095	117394,015	2,674	22492,718	117859,304	2,711	23212,301	129434,516	3,087
20/04 kV transformer 7	Tr7	22448,046	116847,914	2,666	22429,668	117313,161	2,703	23149,240	132883,844	3,080
20/04 kV transformer 2	Tr2	944,210	2665,470	1,533	943,795	2672,004	1,547	959,842	2833,897	1,680
20/04 kV transformer 4	Tr4	13229,738	39068,700	3,338	13219,241	39208,564	3,375	13630,093	42722,426	3,754
20/04 kV transformer 3	Tr3	23255,396	123780,640	2,766	23236,895	124246,713	2,802	23966,092	135937,159	3,167
Al 132 line 12	L12	10914,817	17875,552	1,261	10915,247	17945,450	1,265	10929,222	19710,208	1,316
Al 132 line 23	L23	10471,941	17150,443	1,284	10472,346	17216,948	1,288	10485,673	18903,165	1,338
Raven line 16	L16	4905,683	3515,728	0,228	4905,728	3529,936	0,228	4907,135	3887,200	0,231
Raven line 33	L33	5221,781	3742,315	0,239	5222,055	3756,547	0,239	5223,243	4117,550	0,242
AMKA line 44	L44	2794,055	248,683	6,118	2794,052	249,774	6,718	2794,363	277,228	6,957

5.1 Transformers

Influence on power transformer is examined from two main positions: both active and reactive power losses and voltage drop. Two transformers are chosen to be represented below: transformer № 4 (Figure 4.2) 20/0.4 kV and transformer № 1 (Figure 4.2) 110/20 kV. Figure 5.5 illustrates dependence of active power losses from non-linear load (6-pulse rectifier) percentage to entire load. Even 50 percent of this load affects insignificantly to active power losses.

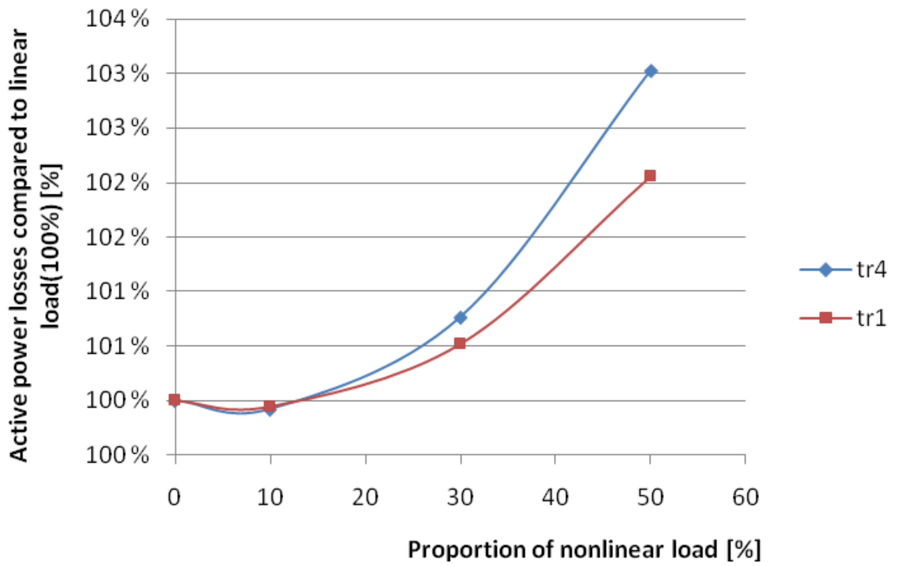

Figure 5.5. Active power losses (%) in transformers (100% correspond to situation with linear load).

Different situation stand with reactive power losses, Figure 5.6 shows the growth up to 10 percent with increasing non-linear load share. Herewith the apparent power losses are 8.72 percent.

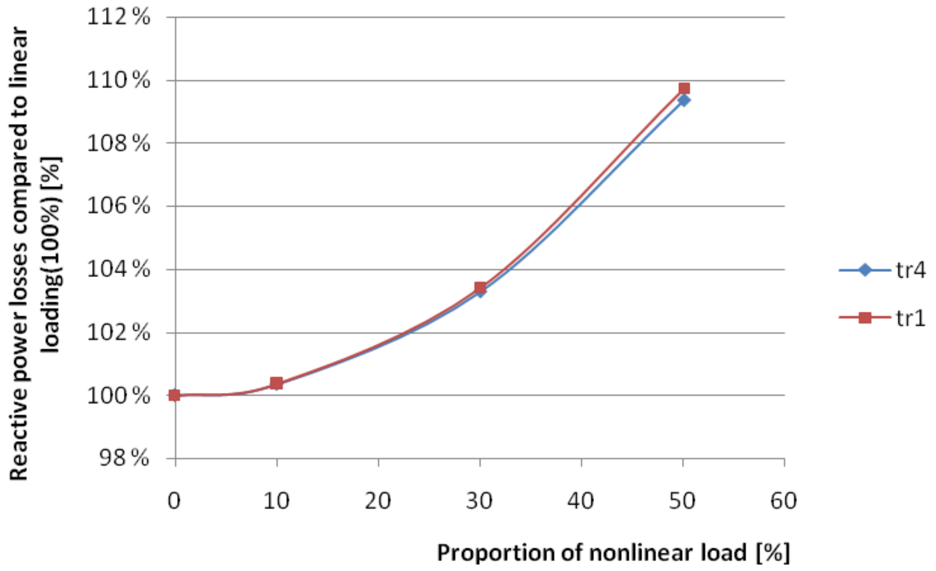

Figure 5.6. Reactive power losses (%) in transformers.

Voltage drop in particular transformer due to harmonics effects to whole system is shown at Figure 5.7. Additional curves show the effect of replacement 6-pulse rectifiers to 12-pulse analogue. Thus by 50 percent of non-linear load the benefits can be 14.53 percent of absolute voltage drop value.

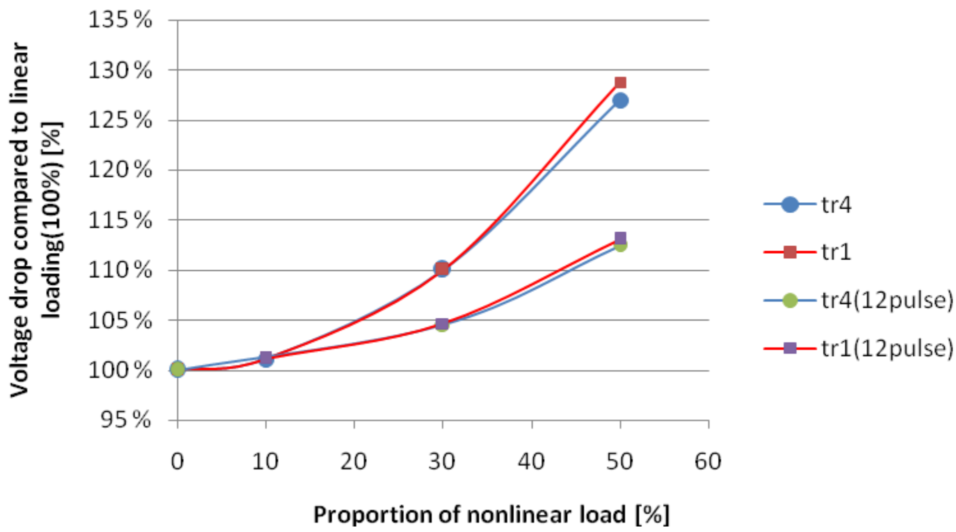

Figure 5.7. Voltage drop (%) in transformers.

Curves are based on data represented in Appendixes, as well as the rest results from simulation are consolidated there.

5.2 Lines

The same main parameters as in transformer chapter are under consideration when lines are observed. For demonstration results the following lines are chosen: line №33 Raven 1 km (Figure 4.2) and line №12 Al132 3km (Figure 4.2).

Figure 5.8 demonstrate how negligible active power losses in conductors with increasing the non-linear share.

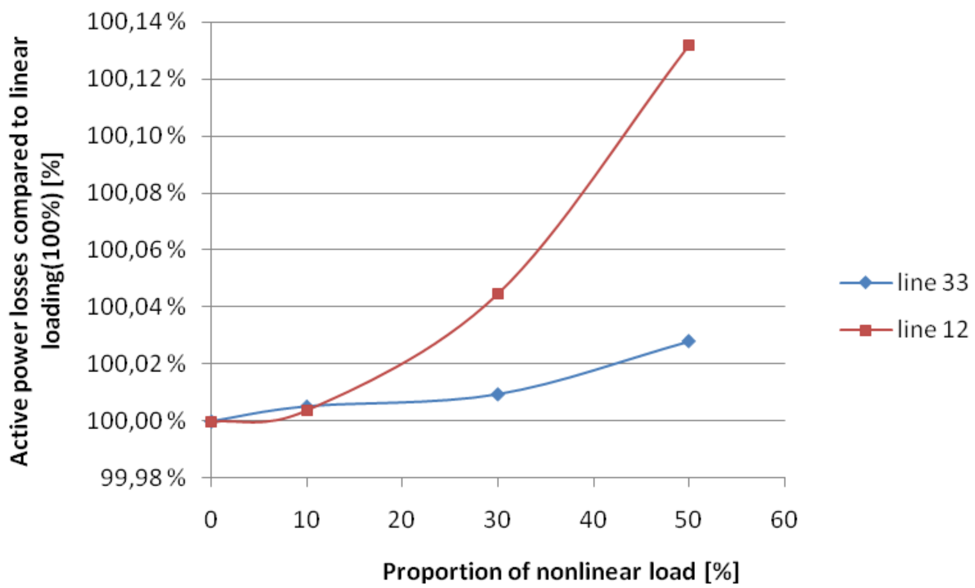

Figure 5.8. Active power losses (%) in lines.

Reactive power losses in lines as in case with transformer are constantly growing up to 10 percent in respond to 50 percent increasing of Load%. Figure 5.9 demonstrates this fact.

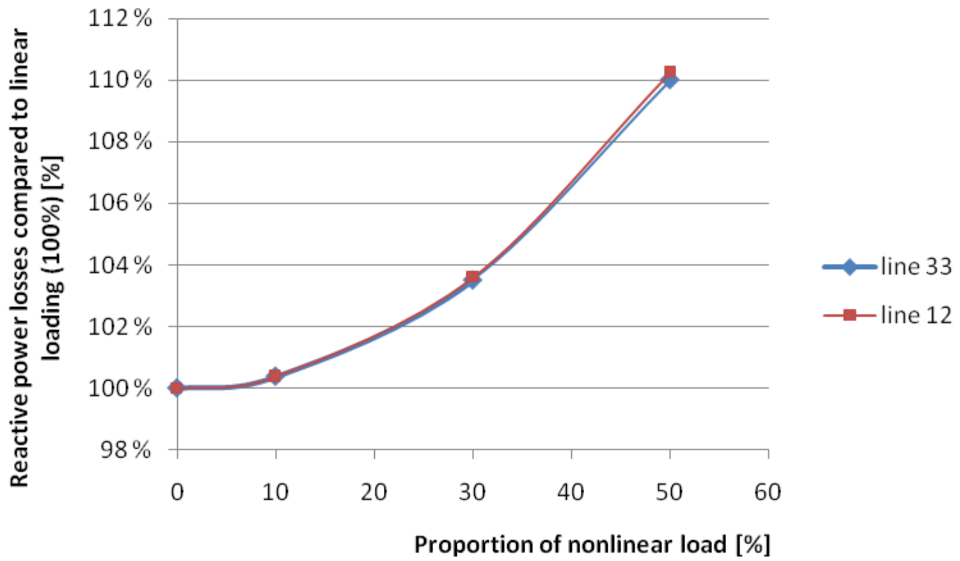

Figure 5.9. Reactive power losses (%) in lines.

Voltage drop in lines is significantly lower than compare with the same in transformers. Replacement option here can give only 5.31 percent of absolute voltage drop value. Figure 5.10 illustrates these dependences.

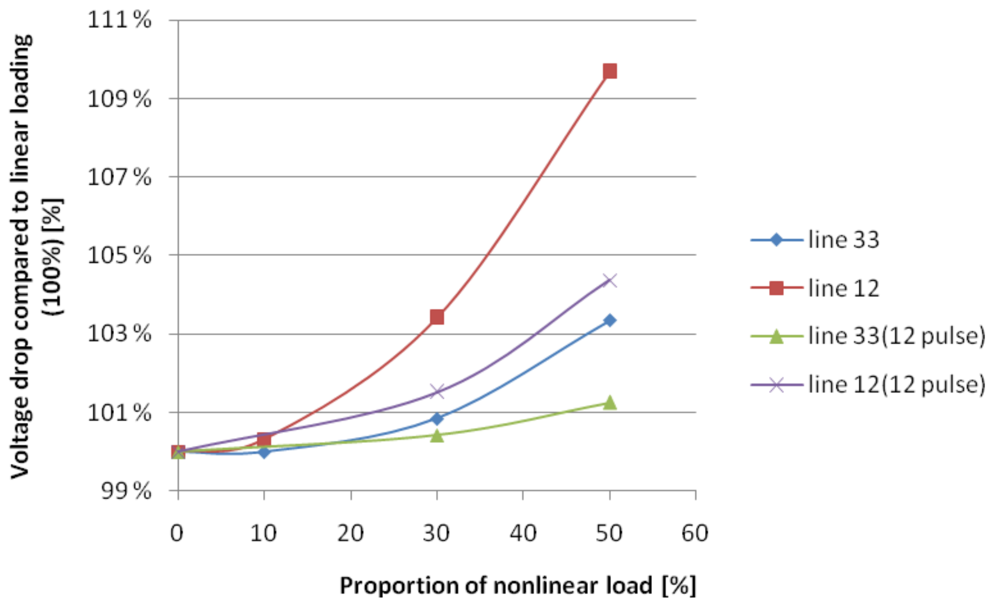

Figure 5.10. Voltage drop (%) in lines.

6 Conclusion

The primary goal of Master thesis was to understand how non-linear loads and harmonics generated by them affect to power quality in distribution networks and parameters of their elements. Another objective of work is to figure out what is the difference in influences of various non-linear types that are commonly used nowadays. For these purposes scientific literature in particular niche was examined and the most essential information was consolidated.

For numerical evaluation the model of a distribution system was invented. So far the model allows working with three-phase tasks. That means only three-phase non-linear load can be put as initial data for examination. However, typical; non-linear loading of public distribution system due to household appliances implies that the model have to be updated to be able solve single-phase questions as well. That allows exploring such a typical non-linear load among domestic customers as single-phase rectifiers and CFL bulbs. Moreover it will be possible to consider questions connected with other load unbalances.

In this work three-phase 6- and 12-pulse rectifiers and their different portion in entire load are explored. Herewith, the apparent power losses rise in 110/20 kV transformer due to 50 percent of 6- and 12-pulse rectifiers compare with absolutely linear load are 9.37 percents and 1.97 percents respectively. Almost the same effect is observed doing with lines: 7.60 percents and 1.54 percents. The replacement of 6-pulse rectifiers to 12-pulse analogue is worth to be considered.

Harmonics have the effect of increasing equipment losses and thus the thermal stress. Equipment derating becomes a preventive requirement in this case. Besides that, additional active power losses in network components lead extra costs for distribution companies. Reactive power losses increase voltage drop in the network and thus make conditions for voltage regulation worse.

References

ABB,2004. Guide to Harmonics with AC Variable Frequency Drives. [Article available at www.joliettech.com]

Arrillaga J., Smith B.C., Watson R., Wood A., 2000. Power System Harmonic Analysis, John Wiley & Sons Ltd.

Bingham R.P. Harmonics - Understanding the Facts. [Article available at www.dranetz-bmi.com/pdf/harmonicspart1.pdf]

Chang G. W., Ribeiro P.F., Ranade S.G., 2001.Harmonics theory.

Dugan R.C., Rizy D. T., 1988. "Harmonic Considerations for Electrical Distribution Feeders", National Technical Information Service, Report No. ORNL/Sub/81-95011/4 (Cooper Power Systems as Bulletin 87011, "Electrical Power System Harmonics, Design Guide")

EN 50160, 1999. Voltage characteristics of electricity supplied by public distribution systems.

Gerdes J., 2010. The Future of Smart Grid Transmission: Superconducting High-Voltage Power Lines. [Available online at www.earth2tech.com, Feb. 23, 2010]

Grady W.M., Gilleskie R. J., 1993. Harmonics and how they relate to power factor, Proc. Of the EPRI Power Quality Issues & Opportunities Conference (PQA '93).

Halpin S. M., Burch F. R., 1993. Harmonic Limit Compliance Evaluations Using IEEE 519-1992. [Available online at www.calvin.edu/~pribeiro/ IEEE/ieee_cd/chapters/pdffiles/c9pdf.pdf]

IEC 1000-2-1:1990, 1990. Electromagnetic Compatibility, Part 2: Environment, Sect. 1: Description of the environment – Electromagnetic environment for low-frequency conducted desturbances and signalling in public power supply system.

IEC 60287, 1994. Electric cables – Calculation of the current rating.

IEC 61000-2-2: 2002, 2002. Electromagnetic compatibilty (EMC), Part 2: Environment, Sect. 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.

IEC 61000-3, 2000. Group of Harmonics Standarts by International Electrotechnical Commission (IEC), Electromagnetic Compatibility (EMC) – Limits.

IEEE Standard 519-1992, 1993. Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, The Institute of Electrical and Electronics Engineers.

IEEE Std. 1159-1995, 1995. "IEEE recommended practice for monitoring electric power quality", IEEE, New York.

Kaipia T., Salonen P., Lassila J., Partanen J., 2007. Possibilities of the low voltage DC distribution systems. Lappenranta University of Technology.

Körner T. W., 1988. Fourier Analysis, Cambridge University Press.

Lowenstein M.Z., 2002. PQ Corner: Harmonic Current and Voltage Distortion, Electrical Construction & Maintenance. [Article available at http://ecmweb.com/mag/electric_harmonic_current_voltage/]

Mohan N., Undeland T. M., Robbins W. P., 1989. Power Electronics: Converters, Applications, and Design. John Wiley & Sons.

Maswood A.I., Haque M.H., 2006. Harmonics, Sources, Effects and Mitigation Techniques, School of EEE, Nanyang Technological University.

Nazarudin M., 2006. IEC 61000-3-2 Harmonics Standards Overview, Schaffner EMC Inc.

Ozdemir A., 2009. Effects of Harmonic Distortion on Power Systems. [Article available at http://triton.elk.itu.edu.tr/~ozdemir/psh.pdf]

Procario J.C., 2010. The Politics of Transmission. EnergyBiz. [Available online at www.energycentral.com/magazines/energybiz, January/February 2010]

Platts, 2005. Harmonics, Division of The McGraw Hill Companies Inc.

Renner H., Sikulin M., 2007. Power Quality, Course material, Helsinki University of Technology.

Tolbert L. M., Hollis H.D., Hale P.S., 1996. Survey of Harmonics Measurements in Electrical Distribution Systems, IEEE IAS annual meeting.

Zheng J., 2000. Master Thesis: Transformer AC winding resistance and derating when supplying harmonics-rech current, Michigan Technological University.

Following equations was used for calculations (order is remained the same as in main document):

$$\Delta S_{line} = \frac{\mathbf{P_{line}}^2 + \mathbf{Q_{line}}^2}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{line}} + \mathbf{j} \cdot \mathbf{X_{line}}) \cdot \sqrt{3}, \quad (4.8)$$

where

ΔS_{line} is apparent power losses in a line ($\Delta S = \Delta P + j \cdot \Delta Q$),

$\mathbf{P_{line}}$ and $\mathbf{Q_{line}}$ are active and reactive power through a line respectively,

$\mathbf{R_{line}}$ and $\mathbf{X_{line}}$ are resistance and reactance of a line respectively,

U_{fact} is voltage level at the beginning of a line.

$$\Delta U_{line} = \frac{\mathbf{P_{line}} \cdot \mathbf{R_{line}} + \mathbf{Q_{line}} \cdot \mathbf{X_{line}}}{U_{fact}}, \quad (4.9)$$

where

ΔU_{line} is voltage drop in a line.

$$\Delta S_{tr} = \frac{\mathbf{S_{tr}^2}}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{tr}} + \mathbf{j} \cdot \mathbf{X_{tr}}) \cdot \sqrt{3}, \quad (4.13)$$

where

ΔS_{tr} is apparent power losses in a transformer ($\Delta S = \Delta P + j \cdot \Delta Q$),

$\mathbf{S_{tr}}$ is apparent power through a transformer,

$\mathbf{R_{tr}}$ and $\mathbf{X_{tr}}$ are resistance and reactance of a transformer respectively,

U_{fact} is voltage level at the beginning of a transformer.

$$\Delta U_{tr} = \frac{\mathbf{P_{tr}} \cdot \mathbf{R_{tr}} + \mathbf{Q_{tr}} \cdot \mathbf{X_{tr}}}{U_{fact}}, \quad (4.14)$$

where

ΔU_{tr} is voltage drop in a transformer.

CASE 1 (100% linear load), Iteration 1

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2566,001	228,404	5007,220	3588,260	10340,648	16957,445	11062,092	18140,529	5005,787	3588,260
1	0,243		1,190		14,981		15,758		1,190	

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	8853,860	34310,078	15823,368	108700,640	784,769	2545,470	15823,400	108700,015	15823,351	108700,914	30619,219	453920,287
1	3335,610		5921,980		133,138		5921,980		5921,980		6260,166	

ΔP - active power losses in a network component, ΔQ – reactive power losses in a network component.

Voltage Drop in Lines

	Line №							
	12		16		23		33	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	261,733	1,246	47,380	0,226	266,372	1,268	48,447	0,236
1	0,219	0,001	0,009	0,000	0,219	0,001	0,009	0,000

Voltage Drop in Transformers

	Transformer №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	638,913	3,042	10,788	2,631	10,763	2,625	6,2211	1,515	11,077	2,702	13,315	3,248
1	15,343	0,073	0,929	0,227	0,929	0,227	0,626	0,153	0,929	0,227	1,752	0,427

ΔU - voltage drop in a network component

CASE 1(100% linear load), Iteration 2

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2804,380	249,622	5237,079	3754,055	10487,050	17197,528	10927,093	17919,146	4915,570	3523,591
1	0,222		1,108		13,603		14,308		1,081	

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10056,660	39218,208	17635,746	124261,302	817,924	2669,575	16871,400	117708,884	16807,243	117151,602	31901,404	489885,826
1	3210,179		5676,939		127,441		5676,695		5676,695		6267,117	

Voltage Drop in Lines

	Line №							
	12		16		23		33	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,974	1,262	47,812	0,228	269,719	1,284	49,029	0,239
1	0,219	0,001	0,009	0,000	0,219	0,001	0,009	0,000

Voltage Drop in Transformers

	Transformer №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	655,253	3,120	10,930	2,666	10,898	2,658	6,257	1,526	11,312	2,759	13,585	3,313
1	15,340	0,073	0,929	0,227	0,929	0,227	0,625	0,153	0,929	0,227	1,751	0,427

CASE 1(100% linear load), Iteration 3

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2793,827	248,683	5220,700	3742,315	10458,338	17150,443	10900,509	17875,552	4904,602	3515,728
1	0,228		1,081		13,603		14,308		1,081	

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10019,559	39068,700	17578,484	123780,640	816,769	2665,470	16834,400	117394,015	16771,351	116847,914	31860,219	488814,287
1	3210,179		5676,912		127,441		5676,695		5676,695		6267,115	

Voltage Drop in Lines

	Line №							
	12		16		23		33	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,849	1,261	47,795	0,228	269,588	1,284	49,027	0,239
1	0,219	0,001	0,009	0,000	0,219	0,001	0,009	0,000

Voltage Drop in Transformers

	Transformer №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	654,707	3,118	10,925	2,665	10,893	2,657	6,256	1,526	11,304	2,757	13,576	3,311
1	15,340	0,073	0,929	0,227	0,929	0,227	0,625	0,153	0,929	0,227	1,751	0,427

Total Power Losses in Lines

№	44	33	23	12	16
ΔP, W	2794,055	5221,781	10471,941	10914,817	4905,683
ΔQ, VAR	248,683	3742,315	17150,443	17875,552	3515,728

Power Losses in Transformers

№	4	3	2	6	7	1
ΔP, W	13229,738	23255,396	944,210	22511,095	22448,046	38127,334
ΔQ, VAR	39068,700	123780,640	2665,470	117394,015	116847,914	488814,287

Voltage Drop in Lines

№	12	16	23	33
ΔU, V	264,849	47,795	269,588	49,027
ΔU, %	1,261	0,228	1,284	0,239

Voltage Drop in Transformers

№	1	6	7	2	3	4
ΔU, V	654,886	10,964	10,932	6,287	11,342	13,688
ΔU, %	3,118	2,674	2,666	1,533	2,766	3,338

Following equations was used for calculations (order is remained the same as in main document):

$$\Delta S_{line} = \frac{\mathbf{P_{line}}^2 + \mathbf{Q_{line}}^2}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{line}} + \mathbf{j} \cdot \mathbf{X_{line}}) \cdot \sqrt{3} , \quad (4.8)$$

where

ΔS_{line} is apparent power losses in a line ($\Delta S = \Delta P + j \cdot \Delta Q$),

$\mathbf{P_{line}}$ and $\mathbf{Q_{line}}$ are active and reactive power through a line respectively,

$\mathbf{R_{line}}$ and $\mathbf{X_{line}}$ are resistance and reactance of a line respectively,

U_{fact} is voltage level at the beginning of a line.

$$\Delta U_{line} = \frac{\mathbf{P_{line}} \cdot \mathbf{R_{line}} + \mathbf{Q_{line}} \cdot \mathbf{X_{line}}}{U_{fact}} , \quad (4.9)$$

where

ΔU_{line} is voltage drop in a line.

$$\Delta S_{tr} = \frac{\mathbf{S_{tr}^2}}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{tr}} + \mathbf{j} \cdot \mathbf{X_{tr}}) \cdot \sqrt{3} , \quad (4.13)$$

where

ΔS_{tr} is apparent power losses in a transformer ($\Delta S = \Delta P + j \cdot \Delta Q$),

$\mathbf{S_{tr}}$ is apparent power through a transformer,

$\mathbf{R_{tr}}$ and $\mathbf{X_{tr}}$ are resistance and reactance of a transformer respectively,

U_{fact} is voltage level at the beginning of a transformer.

$$\Delta U_{tr} = \frac{\mathbf{P_{tr}} \cdot \mathbf{R_{tr}} + \mathbf{Q_{tr}} \cdot \mathbf{X_{tr}}}{U_{fact}} , \quad (4.14)$$

where

ΔU_{tr} is voltage drop in a transformer.

CASE 2 (90% linear load, 10% nonlinear load – 6-pulse rectifier), Iteration 3

Total Power Losses in Lines

№	44	33	23	12	16
ΔP, W	2794,052	5222,055	10472,346	10915,247	4905,728
ΔQ, VAR	249,774	3756,547	17216,948	17945,450	3529,936

Power Losses in Transformers

№	4	3	2	6	7	1
ΔP, W	13219,241	23236,895	943,795	22492,718	22429,668	38106,926
ΔQ, VAR	39208,564	124246,713	2672,004	117859,304	117313,161	490628,048

ΔP - active power losses in a network component, ΔQ – reactive power losses in a network component.

Voltage Drop in Lines

№	12	16	23	33	44
ΔU, V	265,819	47,857	270,542	49,088	13,968
ΔU, %	1,265	0,228	1,288	0,239	6,718

Voltage Drop in Transformers

№	1	6	7	2	3	4
ΔU, V	662,072	11,116	11,084	6,342	11,489	13,840
ΔU, %	3,153	2,711	2,703	1,547	2,802	3,375

ΔU - voltage drop in a network component

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2793,827	248,683	5220,700	3742,315	10458,338	17150,443	10900,509	17875,552	4904,602	3515,728
1	0,220		1,070		13,468		14,167		1,070	
5	0,004	0,635	0,204	8,246	0,248	38,513	0,260	40,495	0,020	8,227
7	0,001	0,137	0,05	1,779	0,06	8,313	0,070	8,742	0,005	1,777
11	0,000	0,066	0,004	0,856	0,043	3,999	0,045	4,205	0,004	0,855
13	0,000	0,051	0,003	0,668	0,036	3,120	0,038	3,282	0,003	0,667
17	0,000	0,035	0,003	0,453	0,027	2,119	0,028	2,229	0,003	0,453
19	0,000	0,029	0,003	0,387	0,024	1,810	0,024	1,904	0,003	0,387
23	0,000	0,022	0,002	0,296	0,018	1,383	0,019	1,455	0,002	0,295
25	0,000	0,020	0,002	0,263	0,016	1,231	0,017	1,295	0,002	0,263
29	0,000	0,016	0,002	0,214	0,013	1,001	0,013	1,052	0,002	0,214
31	0,000	0,015	0,002	0,195	0,011	0,912	0,012	0,959	0,002	0,195
35	0,000	0,012	0,002	0,164	0,009	0,770	0,009	0,810	0,002	0,164
37	0,000	0,011	0,002	0,152	0,008	0,713	0,009	0,713	0,002	0,152
41	0,000	0,010	0,002	0,132	0,007	0,618	0,007	0,650	0,002	0,132
43	0,000	0,009	0,001	0,123	0,006	0,578	0,006	0,608	0,001	0,123
47	0,000	0,008	0,001	0,109	0,005	0,511	0,005	0,537	0,001	0,109
49	0,000	0,008	0,001	0,103	0,005	0,482	0,005	0,507	0,001	0,103
53	0,000	0,007	0,001	0,092	0,004	0,432	0,004	0,455	0,001	0,092

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10019,559	39068,700	17578,484	123780,640	816,769	2665,470	16834,400	117394,015	16771,351	116847,914	31860,219	488814,287
1	3178,352		5620,548		126,181		5620,521		5620,521		6205,007	
5	12,865	80,959	22,831	269,742	0,511	3,782	22,782	269,164	22,779	269,133	25,151	1050,098
7	2,623	17,489	4,657	58,286	0,104	0,818	4,651	58,215	4,652	58,211	5,127	226,741
11	1,208	8,414	2,145	28,041	0,048	0,394	2,143	28,011	2,143	28,009	2,361	109,073
13	0,934	6,565	1,658	21,882	0,037	0,307	1,656	21,859	1,656	21,858	1,825	85,113
17	0,628	4,460	1,115	14,865	0,025	0,209	1,113	14,850	1,114	14,849	1,227	57,819
19	0,535	3,809	0,949	12,697	0,021	0,178	0,948	12,684	0,948	12,684	1,045	49,383
23	0,407	2,912	0,723	9,705	0,016	0,136	0,722	9,696	0,722	9,695	0,796	37,746
25	0,362	2,591	0,643	8,636	0,014	0,121	0,642	8,628	0,642	8,627	0,708	33,588
29	0,294	2,106	0,522	7,020	0,011	0,098	0,522	7,013	0,522	7,013	0,575	27,303
31	0,268	1,919	0,476	6,397	0,010	0,089	0,475	6,391	0,475	6,391	0,524	24,880
35	0,226	1,621	0,402	5,403	0,009	0,075	0,402	5,398	0,402	5,398	0,442	21,013
37	0,209	1,500	0,372	5,001	0,008	0,070	0,372	4,997	0,372	4,996	0,410	19,450
41	0,182	1,301	0,323	4,336	0,007	0,061	0,322	4,332	0,322	4,332	0,355	16,863
43	0,170	1,217	0,302	4,058	0,007	0,057	0,302	4,055	0,302	4,055	0,333	15,782
47	0,150	1,076	0,267	3,586	0,006	0,050	0,267	3,583	0,267	3,583	0,294	13,946
49	0,142	1,015	0,252	3,384	0,006	0,047	0,252	3,381	0,252	3,381	0,278	13,162
53	0,127	0,910	0,226	3,034	0,005	0,042	0,226	3,032	0,226	3,032	0,249	11,801

Voltage Drop in Lines

	Line №									
	12		16		23		33		44	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,849	1,261	47,795	0,228	269,588	1,284	49,027	0,239	13,968	6,718
1	0,217	0,001	0,008	0,000	0,217	0,001	0,008	0,000	0,001	0,000
5	11,172	0,053	1,201	0,006	11,186	0,053	1,202	0,006	0,055	0,026
7	6,339	0,030	0,680	0,003	6,343	0,030	0,681	0,003	0,032	0,018
11	5,701	0,027	0,611	0,003	5,704	0,027	0,611	0,003	0,029	0,015
13	5,525	0,026	0,591	0,003	5,529	0,026	0,592	0,003	0,028	0,014
17	5,269	0,025	0,564	0,003	5,272	0,025	0,564	0,003	0,027	0,014
19	5,168	0,025	0,554	0,003	5,171	0,025	0,554	0,003	0,026	0,013
23	4,996	0,024	0,536	0,003	4,999	0,024	0,536	0,003	0,025	0,013
25	4,921	0,023	0,529	0,003	4,924	0,023	0,529	0,003	0,025	0,013
29	4,789	0,023	0,516	0,003	4,791	0,023	0,516	0,003	0,025	0,013
31	4,729	0,023	0,510	0,002	4,732	0,023	0,510	0,002	0,024	0,013
35	4,621	0,022	0,499	0,002	4,624	0,022	0,500	0,002	0,024	0,013
37	4,572	0,022	0,495	0,002	4,574	0,022	0,495	0,002	0,024	0,013
41	4,482	0,021	0,486	0,002	4,484	0,021	0,486	0,002	0,024	0,013
43	4,440	0,021	0,482	0,002	4,442	0,021	0,482	0,002	0,023	0,013
47	4,363	0,021	0,474	0,002	4,365	0,021	0,474	0,002	0,023	0,013
49	4,327	0,021	0,471	0,002	4,329	0,021	0,471	0,002	0,023	0,013
53	4,260	0,020	0,464	0,002	4,262	0,020	0,464	0,002	0,023	0,013

Voltage Drop in Transformers

	Line №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	654,707	3,118	10,925	2,665	10,893	2,657	6,256	1,526	11,304	2,757	13,576	3,311
1	15,263	0,073	0,924	0,225	0,924	0,225	0,622	0,152	0,924	0,225	1,742	0,425
5	48,759	0,232	0,918	0,224	0,918	0,224	0,419	0,102	0,919	0,224	1,038	0,253
7	27,324	0,13	0,516	0,126	0,516	0,126	0,235	0,057	0,516	0,126	0,580	0,141
11	24,376	0,116	0,459	0,112	0,459	0,112	0,209	0,051	0,459	0,112	0,514	0,125
13	23,567	0,112	0,443	0,108	0,443	0,108	0,202	0,049	0,444	0,108	0,496	0,121
17	22,403	0,107	0,421	0,103	0,421	0,103	0,191	0,047	0,422	0,103	0,471	0,115
19	21,952	0,105	0,413	0,101	0,413	0,101	0,187	0,046	0,413	0,101	0,461	0,112
23	21,205	0,101	0,399	0,097	0,399	0,097	0,181	0,044	0,399	0,097	0,445	0,109
25	20,887	0,099	0,393	0,096	0,393	0,096	0,178	0,044	0,393	0,096	0,439	0,107
29	20,333	0,097	0,382	0,093	0,382	0,093	0,174	0,042	0,383	0,093	0,427	0,104
31	20,088	0,096	0,378	0,092	0,378	0,092	0,172	0,042	0,378	0,092	0,422	0,103
35	19,648	0,094	0,370	0,090	0,370	0,090	0,168	0,041	0,370	0,090	0,413	0,101
37	19,449	0,093	0,366	0,089	0,366	0,089	0,166	0,041	0,366	0,089	0,409	0,100
41	19,085	0,091	0,359	0,088	0,359	0,088	0,163	0,040	0,359	0,088	0,401	0,098
43	18,918	0,090	0,356	0,087	0,356	0,087	0,162	0,039	0,356	0,087	0,398	0,097
47	18,608	0,089	0,350	0,085	0,350	0,085	0,159	0,039	0,350	0,085	0,391	0,095
49	18,465	0,088	0,348	0,085	0,348	0,085	0,158	0,039	0,348	0,085	0,388	0,095
53	18,196	0,087	0,343	0,084	0,343	0,084	0,156	0,038	0,343	0,084	0,383	0,093

Following equations was used for calculations (order is remained the same as in main document):

$$\Delta S_{line} = \frac{\mathbf{P_{line}}^2 + \mathbf{Q_{line}}^2}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{line}} + \mathbf{j} \cdot \mathbf{X_{line}}) \cdot \sqrt{3} \quad , \qquad (4.8)$$

where

ΔS_{line} is apparent power losses in a line ($\mathbf{\Delta}S = \mathbf{\Delta}P + j \cdot \Delta Q$),

$\mathbf{P_{line}}$ and $\mathbf{Q_{line}}$ are active and reactive power through a line respectively,

$\mathbf{R_{line}}$ and $\mathbf{X_{line}}$ are resistance and reactance of a line respectively,

U_{fact} is voltage level at the beginning of a line.

$$\Delta U_{line} = \frac{\mathbf{P_{line}} \cdot \mathbf{R_{line}} + \mathbf{Q_{line}} \cdot \mathbf{X_{line}}}{U_{fact}} \quad , \qquad (4.9)$$

where

ΔU_{line} is voltage drop in a line.

$$\Delta S_{tr} = \frac{\mathbf{S_{tr}^2}}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{tr}} + \mathbf{j} \cdot \mathbf{X_{tr}}) \cdot \sqrt{3} \quad , \qquad (4.13)$$

where

ΔS_{tr} is apparent power losses in a transformer ($\mathbf{\Delta}S = \mathbf{\Delta}P + j \cdot \Delta Q$),

$\mathbf{S_{tr}}$ is apparent power through a transformer,

$\mathbf{R_{tr}}$ and $\mathbf{X_{tr}}$ are resistance and reactance of a transformer respectively,

U_{fact} is voltage level at the beginning of a transformer.

$$\Delta U_{tr} = \frac{\mathbf{P_{tr}} \cdot \mathbf{R_{tr}} + \mathbf{Q_{tr}} \cdot \mathbf{X_{tr}}}{U_{fact}} \quad , \qquad (4.14)$$

where

ΔU_{tr} is voltage drop in a transformer.

CASE 3A (70% linear load, 30% nonlinear load – 6-pulse rectifier), Iteration 3

Total Power Losses in Lines

№	44	33	23	12	16
ΔP, W	2794,158	5222,277	10476,598	10919,706	4906,170
ΔQ, VAR	258,742	3873,689	17763,290	18519,118	3646,360

Power Losses in Transformers

№	4	3	2	6	7	1
ΔP, W	13330,856	23435,557	948,193	22689,352	22626,04	38325,868
ΔQ, VAR	40353,685	128059,450	2724,767	121650,045	121102,733	505506,163

ΔP - active power losses in a network component, ΔQ – reactive power losses in a network component.

Voltage Drop in Lines

№	12	16	23	33	44
ΔU, V	273,901	48,381	278,525	49,600	13,972
ΔU, %	1,304	0,230	1,326	0,241	6,910

Voltage Drop in Transformers

№	1	6	7	2	3	4
ΔU, V	705,202	12,316	12,289	6,775	12,659	15,061
ΔU, %	3,430	3,004	2,997	1,652	3,087	3,673

ΔU - voltage drop in a network component

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2793,827	248,683	5220,700	3742,315	10458,338	17150,443	10900,509	17875,552	4904,602	3515,728
1	0,216		1,049		13,201		13,885		1,049	
5	0,039	5,861	0,189	76,638	2,299	357,294	2,415	375,288	0,188	76,083
7	0,010	1,251	0,052	16,297	0,614	76,065	0,646	79,950	0,052	16,232
11	0,007	0,601	0,036	7,823	0,391	36,521	0,411	38,390	0,036	7,795
13	0,007	0,468	0,032	6,101	0,332	28,484	0,349	29,942	0,032	6,080
17	0,006	0,318	0,027	4,141	0,248	19,335	0,261	20,326	0,027	4,128
19	0,005	0,271	0,025	3,536	0,217	16,510	0,228	17,356	0,025	3,525
23	0,005	0,207	0,022	2,701	0,168	12,613	0,177	13,259	0,022	2,693
25	0,005	0,184	0,021	2,403	0,149	11,221	0,157	11,797	0,021	2,396
29	0,004	0,150	0,018	1,953	0,118	9,118	0,124	9,586	0,018	1,947
31	0,004	0,136	0,018	1,779	0,106	8,308	0,111	8,734	0,018	1,774
35	0,004	0,115	0,016	1,502	0,086	7,015	0,086	7,015	0,016	1,498
37	0,004	0,107	0,015	1,390	0,077	6,492	0,081	6,825	0,015	1,386
41	0,003	0,092	0,013	1,205	0,064	5,627	0,067	5,916	0,013	1,201
43	0,003	0,086	0,012	1,127	0,058	5,266	0,061	5,536	0,013	1,124
47	0,003	0,076	0,011	0,996	0,049	4,653	0,051	4,892	0,011	0,993
49	0,003	0,072	0,011	0,940	0,045	4,390	0,047	4,616	0,011	0,937
53	0,003	0,064	0,010	0,842	0,038	3,935	0,040	4,138	0,0010	0,840

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10019,559	39068,700	17578,484	123780,640	816,769	2665,470	16834,400	117394,015	16771,351	116847,914	31860,219	488814,287
1	3115,194		5509,284		123,680		5509,047		5509,047		6081,702	
5	118,908	748,251	210,817	2490,737	4,685	34,656	209,379	2473,749	209,302	2472,841	232,956	9726,303
7	23,957	159,684	42,502	531,896	0,949	7,439	42,342	529,896	42,333	529,790	46,870	2072,870
11	11,017	76,696	19,547	255,498	0,437	3,579	19,481	254,637	19,478	254,592	21,549	995,391
13	8,511	59,823	15,102	199,295	0,337	2,789	15,052	198,646	15,050	198,612	16,647	776,366
17	5,719	40,615	10,148	135,309	0,227	1,894	10,117	134,890	10,115	134,867	11,185	527,042
19	4,870	34,681	8,641	115,544	0,193	1,618	8,615	115,193	8,614	115,174	9,524	450,035
23	3,709	26,498	6,582	88,282	0,147	1,236	6,563	88,023	6,563	88,009	7,254	343,827
25	3,297	23,575	5,851	78,546	0,131	1,100	5,834	78,319	5,833	78,307	6,448	305,898
29	2,678	19,158	4,752	63,830	0,106	0,894	4,738	63,651	4,738	63,641	5,237	248,577
31	2,440	17,456	4,329	58,160	0,097	0,814	4,317	57,998	4,317	57,990	4,771	226,488
35	2,060	14,739	3,657	49,109	0,082	0,688	3,647	48,976	3,646	48,969	4,030	191,236
37	1,908	13,642	3,385	45,452	0,076	0,637	3,377	45,330	3,376	45,323	3,730	176,990
41	1,655	11,825	2,937	39,399	0,065	0,552	2,929	39,295	2,929	39,295	3,236	153,414
43	1,549	11,066	2,750	36,871	0,061	0,516	2,742	36,775	2,742	36,770	3,030	143,571
47	1,370	9,777	2,432	32,578	0,054	0,456	2,426	32,495	2,425	32,490	2,680	126,851
49	1,294	9,227	2,296	30,742	0,051	0,430	2,290	30,664	2,290	30,660	2,530	119,702
53	1,161	8,272	2,061	27,562	0,046	0,386	2,056	27,493	2,055	27,489	2,270	107,315

Voltage Drop in Lines

	Line №									
	12		16		23		33		44	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,849	1,261	47,795	0,228	269,588	1,284	49,027	0,239	13,968	6,718
1	0,215	0,001	0,008	0,000	0,215	0,001	0,008	0,000	0,001	0,000
5	35,023	0,167	3,757	0,018	35,155	0,167	3,765	0,018	0,169	0,828
7	19,492	0,093	2,090	0,009	19,534	0,093	2,092	0,010	0,096	0,456
11	17,483	0,083	1,871	0,009	17,516	0,083	1,872	0,009	0,086	0,404
13	16,933	0,081	1,811	0,009	16,964	0,081	1,813	0,009	0,084	0,390
17	16,131	0,077	1,726	0,008	16,159	0,077	1,727	0,008	0,080	0,370
19	15,814	0,075	1,693	0,008	15,841	0,075	1,694	0,008	0,079	0,362
23	15,277	0,073	1,638	0,008	15,302	0,073	1,640	0,008	0,077	0,350
25	15,044	0,072	1,615	0,008	15,069	0,072	1,616	0,008	0,076	0,345
29	14,632	0,070	1,574	0,008	14,655	0,070	1,576	0,008	0,074	0,335
31	14,447	0,069	1,556	0,007	14,470	0,069	1,558	0,008	0,074	0,331
35	14,112	0,067	1,524	0,007	14,134	0,067	1,525	0,008	0,073	0,324
37	13,960	0,066	1,509	0,007	13,981	0,067	1,510	0,007	0,072	0,321
41	13,680	0,065	1,482	0,007	13,700	0,065	1,483	0,007	0,071	0,315
43	13,551	0,065	1,469	0,007	13,571	0,065	1,470	0,007	0,071	0,312
47	13,311	0,063	1,445	0,007	13,331	0,063	1,446	0,007	0,070	0,307
49	13,200	0,063	1,434	0,007	13,219	0,063	1,435	0,007	0,069	0,305
53	12,992	0,062	1,414	0,007	13,011	0,062	1,415	0,007	0,069	0,301

Voltage Drop in Transformers

	Line №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	654,707	3,118	10,925	2,665	10,893	2,657	6,256	1,526	11,304	2,757	13,576	3,311
1	15,111	0,072	0,915	0,223	0,915	0,223	0,616	0,150	0,915	0,223	1,725	0,421
5	157,303	0,749	2,857	0,697	2,856	0,697	1,281	0,312	2,867	0,699	3,226	0,787
7	85,481	0,407	1,580	0,385	1,580	0,385	0,713	0,174	1,583	0,386	1,775	0,433
11	75,936	0,362	1,402	0,342	1,402	0,342	0,632	0,154	1,405	0,343	1,569	0,383
13	73,329	0,349	1,354	0,330	1,354	0,330	0,610	0,149	1,356	0,331	1,514	0,369
17	69,588	0,331	1,286	0,314	1,285	0,314	0,579	0,141	1,288	0,314	1,436	0,350
19	68,140	0,324	1,259	0,307	1,259	0,307	0,568	0,138	1,261	0,308	1,406	0,343
23	65,746	0,313	1,216	0,296	1,216	0,296	0,548	0,134	1,217	0,297	1,357	0,331
25	64,731	0,308	1,197	0,292	1,197	0,292	0,540	0,132	1,199	0,292	1,337	0,326
29	62,961	0,300	1,165	0,284	1,165	0,284	0,525	0,128	1,167	0,285	1,301	0,317
31	62,179	0,296	1,151	0,281	1,161	0,281	0,519	0,127	1,153	0,281	1,285	0,313
35	60,777	0,289	1,126	0,275	1,126	0,275	0,508	0,124	1,127	0,275	1,257	0,307
37	60,142	0,142	1,114	0,272	1,114	0,272	0,503	0,123	1,116	0,272	1,244	0,303
41	58,984	0,281	1,093	0,267	1,093	0,267	0,493	0,120	1,095	0,267	1,221	0,298
43	58,453	0,278	1,084	0,264	1,084	0,264	0,489	0,119	1,085	0,265	1,210	0,295
47	57,469	0,274	1,066	0,260	1,066	0,260	0,481	0,117	1,067	0,260	1,190	0,290
49	57,013	0,271	1,058	0,258	1,058	0,258	0,478	0,116	1,059	0,258	1,181	0,288
53	56,161	0,267	1,042	0,254	1,042	0,254	0,471	0,115	1,044	0,255	1,164	0,284

CASE 3B (70% linear load, 30% nonlinear load – 12-pulse rectifier), Iteration 3

Total Power Losses in Lines

№	44	33	23	12	16
ΔP, W	2794,091	5221,971	10473,380	10916,328	4905,871
ΔQ, VAR	250,768	3769,487	17277,296	18008,901	3542,805

Power Losses in Transformers

№	4	3	2	6	7	1
ΔP, kW	13260,665	23310,369	945,433	22565,826	22091,928	38187,879
ΔQ, kVAR	39335,135	124668,649	2677,892	118278,764	117732,511	492271,966

Voltage Drop in Lines

№	12	16	23	33	44
ΔU, V	268,907	48,057	273,589	49,283	13,970
ΔU, %	1,280	0,229	1,303	0,240	6,777

Voltage Drop in Transformers

№	1	6	7	2	3	4
ΔU, V	685,096	11,577	11,547	6,506	11,937	14,304
ΔU, %	3,262	2,824	2,816	1,587	2,911	3,488

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2793,827	248,683	5220,700	3742,315	10458,338	17150,443	10900,509	17875,552	4904,602	3515,728
1	0,222		1,078		13,574		14,278		1,078	
11	0,008	0,661	0,040	8,610	0,430	40,189	0,452	42,243	0,040	8,577
13	0,007	0,515	0,036	6,713	0,365	31,335	0,384	32,938	0,035	6,688
23	0,005	0,228	0,024	2,972	0,185	13,874	0,195	14,585	0,024	2,962
25	0,005	0,203	0,023	2,643	0,164	12,343	0,172	12,976	0,023	2,635
35	0,004	0,127	0,017	1,652	0,094	7,715	0,099	8,111	0,017	1,647
37	0,004	0,117	0,017	1,529	0,085	7,140	0,089	7,507	0,016	1,525
47	0,003	0,084	0,013	1,096	0,054	5,117	0,056	5,380	0,013	1,093
49	0,003	0,079	0,012	1,030	0,049	4,811	0,051	5,058	0,012	1,027
53	0,003	0,071	0,011	0,927	0,042	4,329	0,043	4,551	0,011	0,923

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10019,559	39068,700	17578,484	123780,640	816,769	2665,470	16834,400	117394,015	16771,351	116847,914	31860,219	488814,287
1	3203,352		5664,893		127,171		5664,650		5253,812		6253,812	
11	12,121	84,386	21,506	281,110	0,480	3,933	21,430	280,115	21,426	280,063	23,712	1095,294
13	9,362	65,803	16,611	219,210	0,371	3,067	16,554	218,460	16,551	218,420	18,313	854,037
23	4,079	29,144	7,239	97,490	0,161	1,359	7,217	96,795	7,215	96,779	7,979	378,185
25	3,626	25,929	6,435	86,385	0,143	1,209	6,416	86,123	6,415	86,109	7,093	336,461
35	2,266	16,210	4,022	54,008	0,090	0,756	4,010	53,854	4,010	53,846	4,432	210,332

37	2,098	15,003	3,723	49,985	0,083	0,700	3,713	49,845	3,712	49,837	4,103	194,662
47	1,507	10,753	2,674	35,826	0,059	0,502	2,667	35,730	2,667	35,725	2,947	139,511
49	1,418	10,110	2,516	33,686	0,056	0,472	2,509	33,597	2,509	33,592	2,772	131,175
53	1,277	9,097	2,266	30,309	0,050	0,424	2,260	30,230	2,260	30,226	2,497	118,022

Voltage Drop in Lines

	Line №									
	12		16		23		33		44	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,849	1,261	47,795	0,228	269,588	1,284	49,027	0,239	13,968	6,718
1	0,218	0,001	0,009	0,000	0,218	0,001	0,009	0,000	0,001	0,000
11	18,360	0,087	1,964	0,009	18,396	0,088	1,966	0,009	0,091	0,042
13	17,779	0,085	1,901	0,009	17,813	0,085	1,903	0,009	0,088	0,041
23	16,037	0,076	1,720	0,008	16,065	0,076	1,721	0,008	0,081	0,367
25	15,793	0,075	1,695	0,008	15,820	0,075	1,697	0,008	0,080	0,362
35	14,813	0,071	1,599	0,007	14,837	0,071	1,601	0,008	0,076	0,340
37	14,653	0,070	1,584	0,007	14,676	0,070	1,585	0,007	0,076	0,337
47	13,971	0,067	1,517	0,007	13,993	0,067	1,518	0,007	0,073	0,322
49	13,829	0,066	1,503	0,007	13,85	0,066	1,504	0,007	0,073	0,319
53	13,636	0,065	1,483	0,007	13,656	0,065	1,485	0,007	0,072	0,315

Voltage Drop in Transformers

	Line №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	654,707	3,118	10,925	2,665	10,893	2,657	6,256	1,526	11,304	2,757	13,576	3,311

1	15,323	0,073	0,928	0,226	0,928	0,226	0,625	0,152	0,928	0,226	1,749	0,427
11	79,832	0,380	1,472	0,359	1,472	0,359	0,663	0,162	1,475	0,360	1,647	0,402
13	77,073	0,367	1,421	0,347	1,421	0,347	0,640	0,156	1,424	0,347	1,589	0,388
23	69,086	0,329	1,276	0,311	1,276	0,311	0,575	0,140	1,278	0,312	1,425	0,347
25	68,017	0,324	1,257	0,306	1,256	0,306	0,566	0,138	1,258	0,307	1,403	0,342
35	63,853	0,304	1,181	0,288	1,181	0,288	0,533	0,130	1,183	0,289	1,319	0,322
37	63,186	0,301	1,169	0,285	1,169	0,285	0,527	0,129	1,171	0,286	1,305	0,318
47	60,372	0,287	1,119	0,273	1,118	0,273	0,505	0,123	1,120	0,273	1,249	0,305
49	59,780	0,285	1,108	0,270	1,108	0,270	0,500	0,122	1,109	0,271	1,237	0,302
53	58,994	0,281	1,094	0,267	1,094	0,267	0,494	0,120	1,095	0,267	1,222	0,298

Following equations was used for calculations (order is remained the same as in main document):

$$\Delta S_{line} = \frac{\mathbf{P_{line}}^2 + \mathbf{Q_{line}}^2}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{line}} + \mathbf{j} \cdot \mathbf{X_{line}}) \cdot \sqrt{3} \quad , \tag{4.8}$$

where

ΔS_{line} is apparent power losses in a line ($\Delta S = \Delta P + j \cdot \Delta Q$),

$\mathbf{P_{line}}$ and $\mathbf{Q_{line}}$ are active and reactive power through a line respectively,

$\mathbf{R_{line}}$ and $\mathbf{X_{line}}$ are resistance and reactance of a line respectively,

U_{fact} is voltage level at the beginning of a line.

$$\Delta U_{line} = \frac{\mathbf{P_{line}} \cdot \mathbf{R_{line}} + \mathbf{Q_{line}} \cdot \mathbf{X_{line}}}{U_{fact}} \quad , \tag{4.9}$$

where

ΔU_{line} is voltage drop in a line.

$$\Delta S_{tr} = \frac{\mathbf{S_{tr}^2}}{\mathbf{U_{fact}^2}} \cdot (\mathbf{R_{tr}} + \mathbf{j} \cdot \mathbf{X_{tr}}) \cdot \sqrt{3} \quad , \tag{4.13}$$

where

ΔS_{tr} is apparent power losses in a transformer ($\Delta S = \Delta P + j \cdot \Delta Q$),

$\mathbf{S_{tr}}$ is apparent power through a transformer,

$\mathbf{R_{tr}}$ and $\mathbf{X_{tr}}$ are resistance and reactance of a transformer respectively,

U_{fact} is voltage level at the beginning of a transformer.

$$\Delta U_{tr} = \frac{\mathbf{P_{tr}} \cdot \mathbf{R_{tr}} + \mathbf{Q_{tr}} \cdot \mathbf{X_{tr}}}{U_{fact}} \quad , \tag{4.14}$$

where

ΔU_{tr} is voltage drop in a transformer.

CASE 4A (50% linear load, 50% nonlinear load – 6-pulse rectifier), Iteration 3

Total Power Losses in Lines

№	44	33	23	12	16
ΔP, W	2794,363	5223,243	10485,673	10929,222	4907,135
ΔQ, VAR	277,228	4117,550	18903,165	19710,208	3887,200

Power Losses in Transformers

№	4	3	2	6	7	1
ΔP, W	13630,093	23966,092	959,842	23212,301	23149,240	38913,671
ΔQ, VAR	42722,426	135937,159	2833,897	129434,516	132883,844	536347,308

ΔP - active power losses in a network component, ΔQ – reactive power losses in a network component.

Voltage Drop in Lines

№	12	16	23	33	44
ΔU, V	290,520	49,488	295,072	50,686	13,980
ΔU, %	1,383	0,236	1,405	0,247	7,269

Voltage Drop in Transformers

№	1	6	7	2	3	4
ΔU, V	842,926	14,549	14,523	7,596	14,859	17,382
ΔU, %	4,014	3,549	3,542	1,853	3,624	4,239

ΔU - voltage drop in a network component

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2793,827	248,683	5220,700	3742,315	10458,338	17150,443	10900,509	17875,552	4904,602	3515,728
1	0,211		1,028		12,936		13,606		1,028	
5	0,111	16,758	0,546	220,579	6,605	1026,306	6,930	1076,774	0,539	217,729
7	0,030	3,542	0,148	46,297	1,744	215,860	1,832	226,747	0,148	45,978
11	0,021	1,629	0,103	22,091	1,104	103,026	1,160	108,239	0,102	21,955
13	0,019	1,319	0,092	17,219	0,936	84,376	0,984	84,376	0,092	17,117
17	0,016	0,895	0,077	11,678	0,700	54,472	0,736	57,234	0,077	11,612
19	0,015	0,764	0,072	9,968	0,612	46,498	0,643	48,857	0,072	9,913
23	0,014	0,583	0,063	7,611	0,474	35,505	0,499	37,308	0,063	7,570
25	0,013	0,519	0,059	6,769	0,420	31,581	0,442	33,186	0,059	6,734
29	0,012	0,427	0,053	5,498	0,333	25,654	0,350	26,958	0,052	5,470
31	0,011	0,384	0,050	5,009	0,298	23,370	0,313	24,558	0,050	4,984
35	0,011	0,324	0,045	4,228	0,241	20,730	0,244	20,730	0,044	4,207
37	0,010	0,300	0,042	3,912	0,218	18,254	0,222	19,183	0,042	3,893
41	0,009	0,260	0,038	3,390	0,180	15,818	0,189	16,624	0,038	3,374
43	0,009	0,243	0,036	3,172	0,164	14,802	0,173	15,555	0,036	3,157
47	0,008	0,215	0,032	2,802	0,137	13,075	0,144	13,741	0,032	2,789
49	0,008	0,202	0,031	2,643	0,126	12,337	0,133	12,965	0,031	2,631
53	0,008	0,181	0,028	2,369	0,107	11,058	0,113	11,621	0,028	2,359

Appendix D.4

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10019,559	39068,700	17578,484	123780,640	816,769	2665,470	16834,400	117394,015	16771,351	116847,914	31860,219	488814,287
1	3052,716		5399,023		121,206		5398,791		5398,791		5959,752	
5	340,305	2141,428	602,762	7121,436	13,278	98,210	595,464	7035,223	595,078	7030,653	667,912	27886,444
7	67,840	452,187	120,296	1505,459	2,675	20,959	119,515	1495,165	119,473	1495,165	132,887	5876,968
11	31,019	215,948	55,015	719,091	1,225	10,024	54,697	714,930	54,680	714,710	60,742	2805,704
13	23,953	168,358	42,484	560,643	0,946	7,817	42,246	557,509	42,233	557,342	46,900	2187,191
17	16,084	114,221	28,529	380,387	0,636	5,306	28,377	378,364	28,369	378,867	31,488	1483,685
19	13,692	97,508	24,288	324,737	0,541	4,531	24,161	322,047	24,154	322,174	26,524	1266,035
23	10,424	74,468	18,491	248,282	0,412	3,463	18,399	246,023	18,389	246,009	20,254	967,827
25	9,265	66,241	16,436	220,620	0,366	3,079	16,355	219,319	16,833	219,307	18,448	860,898
29	7,522	53,813	13,343	179,232	0,297	2,502	13,279	178,371	13,276	178,325	14,723	698,868
31	6,852	49,025	12,156	163,160	0,271	2,280	12,098	162,510	12,095	162,459	13,412	636,662
35	5,780	41,386	10,265	137,109	0,229	1,925	10,217	137,204	10,217	137,169	11,325	537,423
37	5,354	38,298	9,502	127,452	0,212	1,781	9,456	126,976	9,456	4126,945	10,483	497,325
41	4,645	33,190	8,241	110,550	0,183	1,544	8,204	110,055	8,209	110,086	9,092	430,986
43	4,349	31,058	7,715	103,449	0,172	1,445	7,681	102,990	7,679	102,965	8,511	403,291
47	3,846	27,437	6,823	91,387	0,152	1,277	6,793	90,989	6,791	90,967	7,526	356,254
49	3,630	25,888	6,441	86,230	0,143	1,204	6,413	85,858	6,412	85,837	7,105	336,145
53	3,258	23,272	5,798	77,295	0,129	1,080	5,755	76,968	5,754	76,950	6,368	301,315

Voltage Drop in Lines

	Line №									
	12		16		23		33		44	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,849	1,261	47,795	0,228	269,588	1,284	49,027	0,239	13,968	6,718
1	0,213	0,001	0,008	0,000	0,213	0,001	0,008	0,000	0,001	0,000
5	61,082	0,291	6,537	0,031	61,474	0,293	6,566	0,032	0,286	1,432
7	33,382	0,159	3,575	0,017	33,502	0,160	3,582	0,017	0,161	0,777
11	29,798	0,142	3,185	0,015	29,893	0,142	3,191	0,016	0,145	0,685
13	28,838	0,137	3,081	0,015	28,927	0,138	3,087	0,015	0,141	0,661
17	27,441	0,131	2,933	0,014	27,522	0,131	2,938	0,014	0,135	0,627
19	26,890	0,128	2,876	0,014	26,967	0,128	2,880	0,014	0,133	0,614
23	25,959	0,124	2,781	0,013	26,031	0,124	2,786	0,014	0,129	0,592
25	25,056	0,122	2,741	0,013	25,626	0,122	2,747	0,013	0,128	0,583
29	24,844	0,118	2,671	0,013	24,910	0,119	2,675	0,013	0,125	0,657
31	24,525	0,117	2,640	0,013	24,589	0,117	2,643	0,013	0,124	0,561
35	23,947	0,114	2,583	0,012	24,009	0,114	2,587	0,013	0,122	0,548
37	23,684	0,113	2,558	0,012	23,744	0,113	2,561	0,012	0,121	0,543
41	23,202	0,110	2,510	0,012	23,260	0,111	2,514	0,012	0,119	0,533
43	22,979	0,109	2,489	0,012	23,036	0,110	2,492	0,012	0,118	0,528
47	22,567	0,107	2,448	0,012	22,622	0,108	2,451	0,012	0,117	0,519
49	22,376	0,107	2,429	0,012	22,430	0,107	2,432	0,012	0,116	0,515
53	22,018	0,105	2,393	0,011	22,071	0,105	2,396	0,012	0,115	0,508

Voltage Drop in Transformers

	Line №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	654,707	3,118	10,925	2,665	10,893	2,657	6,256	1,526	11,304	2,757	13,576	3,311
1	14,958	0,071	0,906	0,221	0,906	0,221	0,610	0,149	0,906	0,221	1,707	0,416
5	281,660	1,341	4,944	1,206	4,942	1,205	2,181	0,532	4,977	1,214	5,584	1,362
7	148,814	0,709	2,694	0,657	2,694	0,657	1,205	0,294	2,704	0,659	3,026	0,738
11	131,369	0,626	2,381	0,581	2,381	0,581	1,064	0,260	2,389	0,583	2,664	0,650
13	126,71	0,603	2,298	0,561	2,298	0,561	1,027	0,251	2,305	0,562	2,569	0,627
17	120,042	0,572	2,180	0,532	2,180	0,532	0,975	0,238	2,186	0,533	2,435	0,594
19	117,140	0,559	2,134	0,521	2,134	0,521	0,955	0,233	2,140	0,522	2,383	0,581
23	113,216	0,539	2,059	0,502	2,059	0,502	0,921	0,225	2,065	0,504	2,299	0,561
25	111,435	0,531	2,028	0,495	2,027	0,494	0,907	0,221	2,033	0,496	2,263	0,552
29	108,279	0,516	1,973	0,481	1,972	0,481	0,883	0,215	1,978	0,482	2,202	0,537
31	106,509	0,509	1,948	0,475	1,948	0,475	0,872	0,213	1,953	0,476	2,175	0,530
35	104,416	0,497	1,905	0,465	1,904	0,464	0,853	0,208	1,909	0,466	2,126	0,519
37	103,295	0,492	1,885	0,460	1, 885	0,461	0,845	0,206	1,890	0,461	2,104	0,513
41	101,251	0,482	1,849	0,451	1,849	0,451	0,829	0,202	1,853	0,452	2,064	0,503
43	100,313	0,478	1,833	0,447	1,832	0,447	0,822	0,200	1,837	0,448	2,046	0,499
47	98,579	0,469	1,802	0,440	1,802	0,439	0,808	0,197	1,806	0,441	2,012	0,491
49	97,775	0,466	1,788	0,436	1,788	0,436	0,802	0,196	1,792	0,437	1,996	0,487
53	96,275	0,458	1,762	0,430	1,761	0,430	0,790	0,193	1,766	0,431	1,967	0,480

CASE 4B (50% linear load, 50% nonlinear load – 1-pulse rectifier), Iteration 3

Total Power Losses in Lines

№	44	33	23	12	16
ΔP, W	2794,170	5222,323	10476,037	10919,117	4906,223
ΔQ, VAR	254,554	3819,036	17509,807	18250,489	3592,790

Power Losses in Transformers

№	4	3	2	6	7	1
ΔP, W	13324,126	23424,140	947,947	22678,553	22614,908	38312,494
ΔQ, VAR	39816,909	126004,228	2700,423	119876,662	119330,261	498515,400

Voltage Drop in Lines

№	12	16	23	33	44
ΔU, V	276,505	48,535	281,105	49,750	13,973
ΔU, %	1,316	0,231	1,338	0,242	6,957

Voltage Drop in Transformers

№	1	6	7	2	3	4
ΔU, V	740,956	12,647	12,619	6,884	12,981	15,392
ΔU, %	3,526	3,087	3,080	1,680	3,167	3,754

Power Losses in Lines

	Line №									
	44		33		23		12		16	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	2793,827	248,683	5220,700	3742,315	10458,338	17150,443	10900,509	17875,552	4904,602	3515,728
1	0,222		1,077		13,554		14,257		1,077	
11	0,023	1,862	0,113	24,322	1,216	113,418	1,277	119,150	0,113	24,165
13	0,021	1,451	0,101	18,956	1,031	88,403	1,083	92,875	0,101	18,838
23	0,015	0,642	0,071	8,377	0,522	39,874	0,546	41,585	0,069	8,962
25	0,014	0,571	0,065	7,451	0,462	34,757	0,486	36,520	0,065	7,410
35	0,011	0,356	0,049	4,653	0,266	21,715	0,278	22,111	0,049	4,647
37	0,011	0,330	0,046	4,329	0,240	20,140	0,252	21,507	0,046	4,525
47	0,009	0,236	0,036	3,096	0,151	14,517	0,159	14,380	0,036	3,093
49	0,009	0,223	0,034	2,930	0,139	14,211	0,146	14,258	0,034	2,827
53	0,008	0,200	0,031	2,607	0,118	12,329	0,124	12,551	0,031	2,595

Power Losses in Transformers

	Transformer №											
	4		3		2		6		7		1	
Harmonic №	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR	ΔP, W	ΔQ, VAR
DC	10019,559	39068,700	17578,484	123780,640	816,769	2665,470	16834,400	117394,015	16771,351	116847,914	31860,219	488814,287
1	3198,618		5656,522		126,983		5656,279		5656,279		6244,555	
11	34,141	237,677	60,506	791,402	1,347	11,023	60,430	786,115	60,426	786,063	66,712	3088,294
13	26,361	185,286	46,753	616,987	1,040	8,599	46,478	613,358	46,464	613,166	51,622	2407,407
23	11,079	81,144	20,239	272,49	0,453	3,859	20,217	271,795	20,215	271,779	22,979	1064,185
25	10,195	72,929	18,435	242,385	0,403	3,387	17,990	241,123	17,415	241,109	19,093	946,461
35	6,266	45,210	11,022	151,008	0,253	2,112	11,010	150,854	11,010	150,846	12,432	591,332

37	5,898	42,003	10,723	140,985	0,233	1,959	10,713	139,845	10,712	139,837	11,103	547,662
47	4,507	30,753	7,674	100,826	0,167	1,502	7,667	100,730	7,667	100,725	8,947	391,511
49	3,918	28,110	7,516	94,686	0,158	1,325	7,109	94,597	7,109	94,592	7,772	369,175
53	3,584	25,097	6,266	85,309	0,141	1,187	6,260	84,230	6,260	84,230	7,060	331,226

Voltage Drop in Lines

	Line №									
	12		16		23		33		44	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	264,849	1,261	47,795	0,228	269,588	1,284	49,027	0,239	13,968	6,718
1	0,218	0,001	0,009	0,000	0,218	0,001	0,009	0,000	0,001	0,000
11	31,319	0,149	3,348	0,016	31,424	0,150	3,354	0,016	0,152	0,720
13	30,308	0,144	3,238	0,015	30,406	0,145	3,244	0,016	0,148	0,694
23	27,275	0,130	2,922	0,014	27,354	0,130	2,927	0,014	0,135	0,622
25	26,793	0,128	2,880	0,014	26,928	0,128	2,884	0,014	0,134	0,612
35	25,813	0,120	2,713	0,013	25,837	0,120	2,701	0,013	0,128	0,576
37	24,880	0,118	2,584	0,013	24,676	0,119	2,585	0,013	0,127	0,570
47	23,971	0,113	2,517	0,012	23,993	0,113	2,518	0,013	0,123	0,545
49	23,529	0,112	2,503	0,012	23,85	0,112	2,504	0,012	0,122	0,519
53	23,136	0,110	2,483	0,012	23,156	0,110	2,485	0,012	0,121	0,533

Voltage Drop in Transformers

	Line №											
	1		6		7		2		3		4	
Harmonic №	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %	ΔU, V	ΔU, %
DC	654,707	3,118	10,925	2,665	10,893	2,657	6,256	1,526	11,304	2,757	13,576	3,311
1	15,312	0,073	0,927	0,226	0,927	0,226	0,624	0,152	0,927	0,226	1,748	0,426
11	138,321	0,659	2,502	0,610	2,501	0,610	1,117	0,272	2,510	0,612	2,799	0,683
13	133,397	0,635	2,414	0,589	2,414	0,589	1,078	0,263	2,422	0,591	2,699	0,658
23	119,141	0,567	2,163	0,528	2,163	0,527	0,967	0,236	2,169	0,529	2,415	0,589
25	117,240	0,558	2,130	0,519	2,129	0,519	0,952	0,232	2,136	0,521	2,377	0,580
35	109,850	0,523	2,003	0,488	2,003	0,488	0,895	0,218	2,004	0,489	2,233	0,545
37	108,186	0,501	1,969	0,485	1,969	0,485	0,867	0,216	1,971	0,486	2,205	0,539
47	103,372	0,494	1,899	0,473	1,898	0,473	0,855	0,207	1,890	0,463	2,113	0,515
49	102,780	0,490	1,878	0,458	1,877	0,458	0,842	0,205	1,882	0,459	2,096	0,511
53	101,259	0,481	1,850	0,451	1,850	0,451	0,794	0,202	1,855	0,453	2,066	0,504