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Evaluations of Energy Efficiency Improvement

Master of Science Thesis in Electric Power Engineering

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Abstract

In this master thesis evaluations of energy efficiency based on harmonic impacts and improvement methods in order to obtain better harmonic performance have been investigated. Here, the impact of harmonics at the PCCs according to IEEE is studied.

This work is based on the simulations of industrial furnaces by means of simulation tool PSCAD/EMTDC in order to approach a reliable simulation method and have a better overview of industrial furnaces operational behaviours. By means of these simulation methods, the appropriate harmonic filters for the furnaces can be applied.

Two main industrial furnaces which have been studied here are induction furnaces and resistive heating elements furnaces. In this case the study of industrial furnaces principle works is vital. The related wiring diagrams and actual measuring value are also needed.

This work is focused on investigations and improvements of harmonic impacts at the Company's intern PCCs more than harmonic impacts on the grid. These harmonics lead to the lower energy efficiency at the Company and cause damages on the electric devices. Then by reducing the harmonics under the standard limitations the economical benefits will be emerged.

Evaluations of power factor values for verifying the existing phase compensation capacitors at the Company has been put into action. In this case the available measured and documented data and information have been used.

In this master thesis four numbers induction furnaces and three numbers heating elements group furnaces have been studied. All furnaces had one or some harmonic components over the IEEE limitations. By using passive harmonic filters for induction furnaces and two numbers of heating elements group furnaces, the harmonic performance are improved and all harmonic components and total demand distortions are reduced under the IEEE limitations. One of the heating elements group furnaces (heating elements group furnace 6) is required structural amendment of its drive system, then applications of passive harmonic filters isn't a proper solution for its harmonic performance improvement.

Since the PCCs are on the secondary side of Company's feeding transformers (10.5(kV)), there were some limitations for doing actual measurements. So the studies of previous measurements which are prepared by consultant Companies were another part of this master thesis activities.

Key words: Point of common coupling, harmonic filters, induction furnaces, heating elements furnaces.

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List of abbreviations

AC	Alternating Current
DC	Direct Current
DPF	Displacement Power Factor
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
MF	Medium Frequency
MV	Medium Voltage
PCC	Point of Common Coupling
PF	Power Factor
PFC	Power Factor Correction
PWM	Pulse Width Modulation
SCR	Silicon Controlled Rectifier
TDD	Total Demand Distortion
THD_i	Total Harmonic Distortion for Current
THD_v	Total Harmonic Distortion for Voltage
VFD	Variable Frequency Drive

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Chapter 1

Introduction

This master thesis is based on the evaluations and improvements of power quality investigations by focus on the harmonic performance generated by the electric appliances in the Company. The impacts of harmonic distortions on the power system and the analysis of electric devices operations principles as induction furnaces are the dominant objects in this thesis work. The impact of distortion harmonics on the power factor is studied too.

In this chapter the background of problem and master thesis aim are explained. Here, the structure of thesis work for approaching the stated goals has also been explained.

1.1 Problem overview and the aim of thesis work

As stated above the impact of harmonics generated by the furnaces have been investigated. Harmonics cause damage of the electric components in the Company and leads to the higher maintenance costs. In order to reduce the harmonic impacts, the electric appliances which cause high level of distortion harmonics should be defined and in the next stage the aim is to eliminate or reduce the harmonics under the standard limitations by means of passive filters. Passive filters are more economical solutions compare with active filters and meet the Company's demand.

Measurements of distortion harmonics are normally costly and it doesn't provide any overview of the appliances operations principles. Then for future study, the trustable simulations models of electric appliances are needed. The simulation models enable us to have a better and understandable overview of the operations of electric appliances and it leads to optimize their performance by means of proper solutions. Here, the theoretical study of furnaces and standards for determining the permission value of distortion harmonics are required. In this case the existing wiring diagrams in the Company are utilized for obtaining the electrical construction of furnaces. Then the model of electrical furnaces are approached.

The second stage of the problem is evaluations of existing compensation capacitors related to the consumption power in order to determine the value of power factor at different point of the Company. Here, the impacts of distortion harmonics on the power factor are taken into consideration.

1.2 Outline of the thesis

This master thesis is organized as following chapters:

Chapter 1: Introduction of thesis is presented. An overview of the problem and thesis aim is also stated in this chapter.

Chapter 2: Introduction of induction furnaces and their principles and fundamentals of operations are explained. Structures of Induction furnaces and a simulated model of induction furnace in PSCAD/EMTDC are presented here.

Chapter 3: Introduction of harmonics fundamental and impacts with theoretical analysis of harmonics quantity is presented. Introduction of harmonics level requirements according to IEEE and IEC standards are stated in this chapter. Evaluations of harmonics and improvement methods are also stated here.

Chapter 4: Definitions of PCC1 where five numbers of loads separately have been studied is put into action. The harmonics generated by the loads and reduction of harmonics according to IEEE by means of passive filters are studied. In this chapter the studies of induction furnaces are based on the simulation models.

Chapter 5: Introduction of heating elements furnaces and their principles and fundamentals of operations are explained. Structure of these furnaces and their power control construction are also presented in this chapter.

Chapter 6: Definition of PCC2 where four numbers of loads separately have been studied is put into action. Improvements of harmonics performance according to IEEE in the heating element furnaces by means of simulation models have been implemented.

Chapter 7: Power factor evaluations at different points of headquarter Company by means of previous measurements of THD and DPF and some considerations of these measurements are covering the structure of this chapter.

Chapter 2

Induction heating furnaces

2.1 Introduction of induction heating

The basic principle of induction heating is introduced by Michael Faraday in 1831. Michael Faraday used two windings of copper turned around an iron core which were supplied by a DC switching battery. By closing the switch on the primary side of windings, momentary current generated on the secondary side. But by opening the switch, current flew by inverse direction on the secondary side. Because of no electrical connection between the windings on primary and secondary side, Faraday discovered that these current are caused by induced voltage from the primary side [1].

This was the basic principle for designing of transformers, motors and generators. In order to reduce heating losses, laminated core produced. In the beginning of the 20th century researchers tried to exploit this basic principle for producing induction heating for melting processes in steel industries. The first attempt confronted some barriers as the lack of capacitors in desired size and well performance alternators. However, the first MF (medium frequency) induction melting established in Sheffield in 1927. At the same time investigators at Midvale Steel and the Ohio Crankshaft in the US tried to use MF Current for surface hardening in crankshafts. The easiest frequencies which provided by the equipments and used were 1920 (Hz) and 3000 (Hz). In the World War II induction heating used in the vehicle and munition industry as the many technologies based fields [1].

2.2 Fundamental of induction heating

There are three fundamental factors which cause heating in the induction furnaces.

a) Transferring heat
b) Electromagnetic induction
c) Skin effect

2.2.1 Transferring heat

Induction furnaces functional principle is similar to the transformers. In figure (1) a simple model of a two winding transformer has been illustrated. According to the equation (1) by using the coils by lower turn number, higher current on the secondary side can be generated which leads to have the higher losses with the higher temperature.

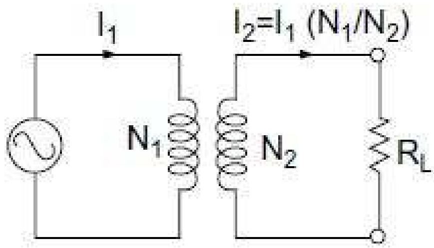


Figure 1 . Equal circuit of transformer

$$\frac{N1}{N2} = \frac{U1}{U2} = \frac{I2}{I1} \quad (1)$$

Secondary coil usually made by low resistance and high permeability, because the use of ferrous material increases energy efficiency [2].

2.2.2 Electromagnetic induction

According to the Ampere's Law, when the AC current flows throw a coil, a magnetic field around the coil will be created.

$$\int Hdl = Ni = F \quad (2)$$

$$\Phi = \mu HA \quad (3)$$

Where,

μ: Permeability,
H: Magnetic field intensity,
φ: Magnetic flux.

By entering an object into the formed magnetic field, the movement velocity of the magnetic field will be changed. According to the Faraday's Law, The generated current on the conductive surface will be in the opposite direction of the induced current. Eddy current will be created by the current on the conductive surface, so the heat energy obtains from the summation of eddy current and induced current [2]. See equations (4) and (5).

$$E = \frac{d\lambda}{dt} = N\frac{d\phi}{dt} \quad (4)$$

$$P = Ri^2 = \frac{U^2}{R} \quad (5)$$

By choosing the object as copper which has conductive properties, the other kind of heating factor (hysteresis losses) due to magnetic field will be emerged. Since the effect of hysteresis losses is so small in induction heating process, this factor is not going to be taken into consideration [2].

2.2.3 Skin effect

By increasing the current frequency in the coil by means of power electronic components, the more induced current will flow on the surface of the load on the secondary side. Current density increases related to the frequency increment [2]. See equations (6) and (7).

$$i_x = i_0 e^{-x/d_0}$$

Where,

x: Distance from the objects' surface,
i_x: Current density at x,
i_0: Current density on skin depth (x = 0),
d_0: Current penetration depth a constant value which determines by the frequency.

$$d_0 = \sqrt{\frac{2\rho}{\mu\omega}}$$

Where,

ρ: Resistivity,
μ: Objects' permeability,
ω: Angular current frequency flowing through the object.

However, heat energy and skin depth are in the reverse relationship. The relation between skin depth and current density is illustrated in figure (2) [2].

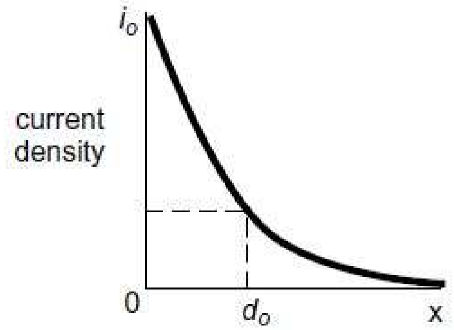


Figure 2 . Skin thickness and current density diagram

High frequency leads to the high current density and the affected heating zone exceeds which cause distortion of the furnaces and high waste of energy. The Current penetration depth and required case depth is illustrated in the figure (3) [1].

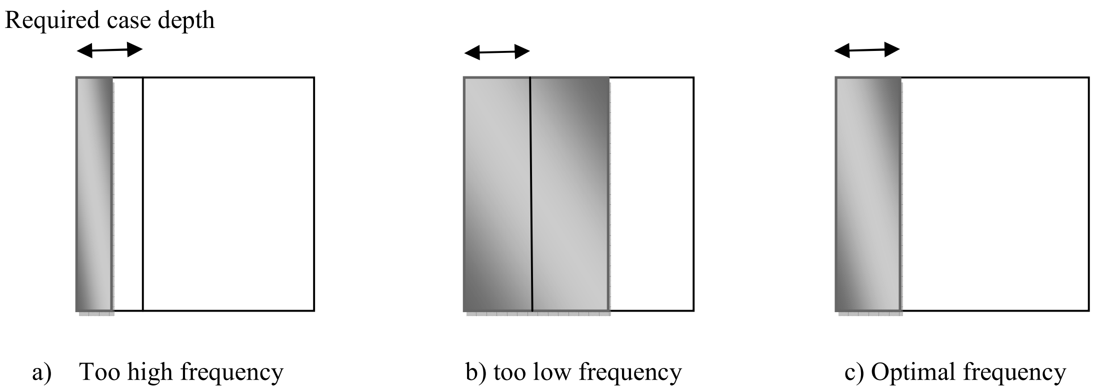


Figure 3. Current penetration depth

Table (1) shows the relevant furnace powers rates (P) and their related frequencies (f), according to the Indoctotherm manual book.

Table 1. Induction furnace powers and related frequencies

kW rating	Frequency
15-100	10 kHz
50-325	3 kHz
150-1500	1 kHz
350-3000	500 Hz
350-4000	100-200 Hz

2.3 Operation overview of induction furnaces

In figure (4) the simple and basic block diagram of one induction furnace is illustrated. Normally the input voltage from the secondary side of the power transformers which feed the induction furnaces are 220V or 575V, this part has been placed in the first block. In the second block, incoming voltage will be converted to the fixed DC voltage it can be a variable DC voltage or variable DC current too. By means of power electronic switching devices, incoming DC current to the third block will be inverted to the one phase AC current. Adoption of the required load and inverters' output will be done in the fourth block. Frequency or phase of inverter or both of them, output of the system and the DC level of converters' output will be adjusted in the control section. [1]

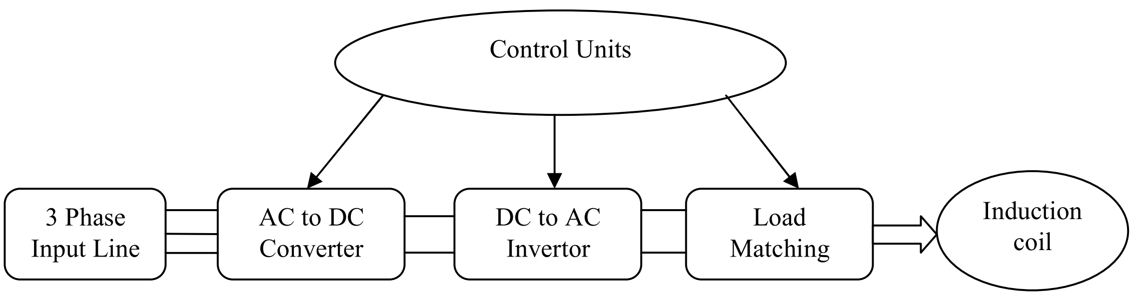


Figure 4. Basic block diagram of induction furnaces

2.3.1 Transformers

Depends on the furnaces' power range, different sizes of transformers should be used. Conventional two winding transformers and three phase three winding transformers are used for different rectification pulse number related to the furnaces nominal power range.

2.3.2 Rectification

The second stage of induction furnaces operation is rectification which is stated above. Induction furnaces use one of three conventional converter methods. The first one is uncontrolled rectifiers which the scheme of it, is illustrated in figure (5). Power will not be reduced in these kinds of converters but in order to control the output level in the furnaces, the regulatable inverters should be used [1]. However, in some cases diodes replace by thyristors but these thyristors don't control the output level. The reason of this replacement is to enable converter to be switched off in the danger by means of a dedicated control system.

The second kinds of converters approach by replacing the phase control thyristors in the figure (5) instead of the diodes. The variable voltage related to the input voltage will be achieved. The cost and control response time increases and on the other hand power can be reduced, so these kinds of converters are not suitable [1]. The third kinds of converters are able to regulate output voltage by means of transistors which will be replaced by the diodes in the figure (5) [1].

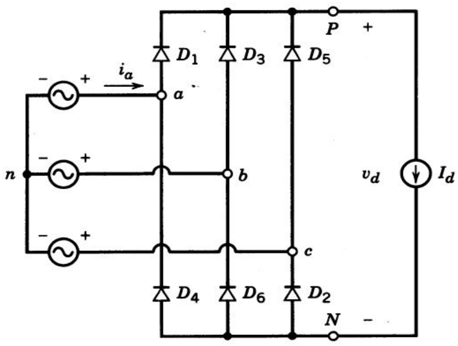


Figure 5. Full bridge converter

The harmonics which caused by converters, should be taken into consideration. For power rates above 600 (kW), the use of 6- pulse converters are not proper [1]. The use of 12- pulse, 18-pulse, 24-pulse and etc. converters will be reduced the harmonics. Three winding transformers are used for this condition.

2.3.3 Inverters

There are two major types of inverters, voltage-fed and current-fed inverters. For more clarity and simplicity, principle design of these different types of inverters has been configured in figure (6) [1].

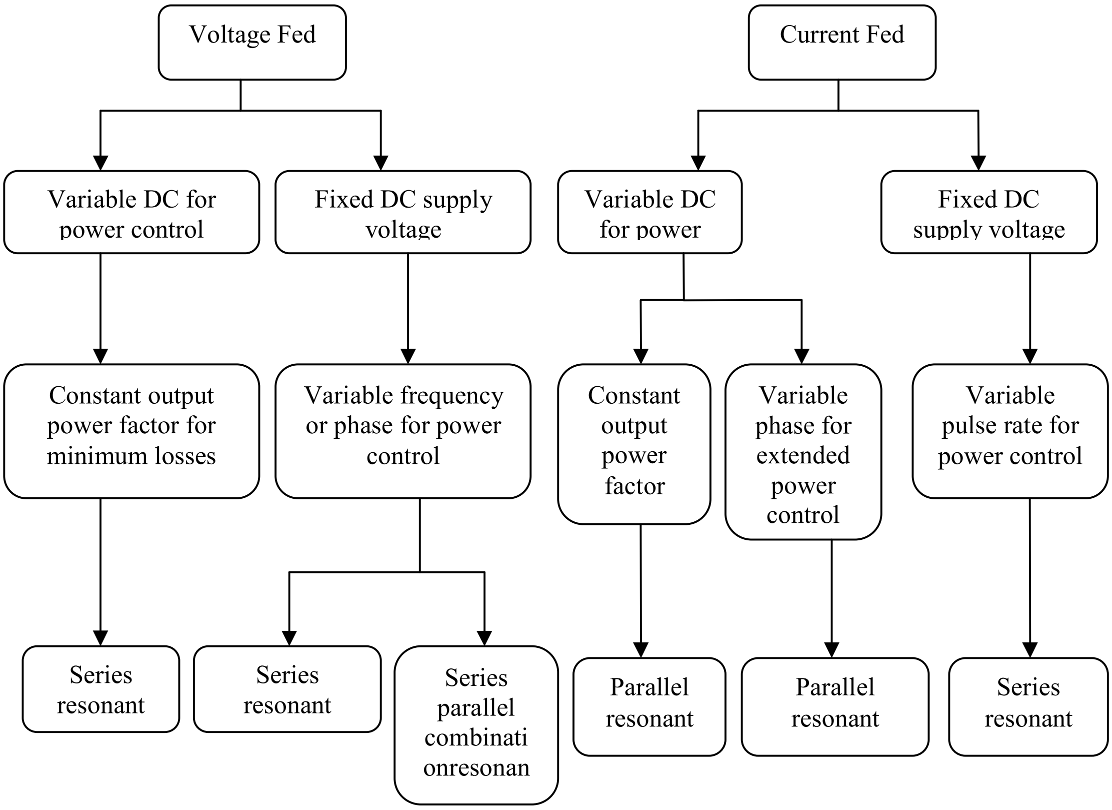


Figure 6. Induction heat inverters

Voltage-fed inverters distinguish by the use of the parallel filter capacitor in the input of the inverter bridge and series connection to the output circuit [1]. In the current-fed inverters, there is a series inductor in the input of the inverter and the connection of the output circuit is parallel [1].

Voltage-fed and current-fed inverters generate frequencies from 90 (Hz) to 1 (MHz) [1]. Different level of frequencies, require different and appropriate power electronic switching devices due to their switching performance and their switching losses. In table (2) the proper switching devices for voltage-fed inverters are shown [ibid]. In the current-fed inverters, thyristors use for the frequencies lower than 10 (kHz) and transistors commonly use for higher level of frequency [1].

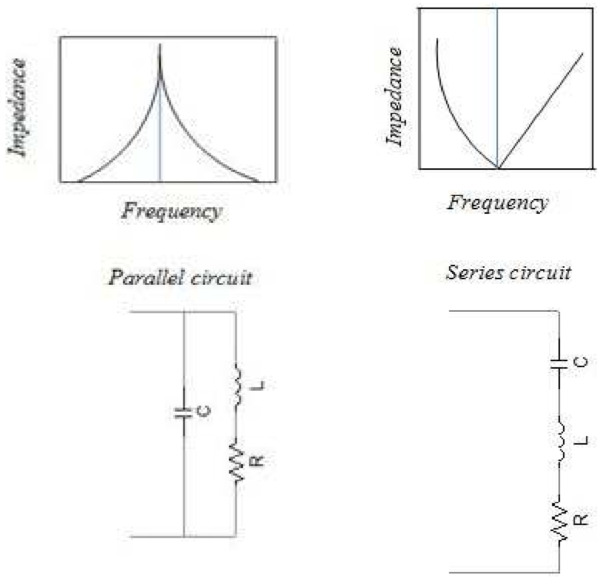
Table 2. Proper switching devices with the applied frequencies

Frequency	**f < 10 kHz**	**f < 50kHz**	**f > 50 kHz**
Switching device	Thyristors or SCRs	IGBTs	MOSFET transistors

Silicon controlled rectifier (SCR) is a type of thyristors. Conventional SCR are not able to turn-off and when they use for variable frequency drives' (VFD) inverters, additional circuits are needed for momentary applying an opposite reverse-bias voltage which able SCRs to be turn-off [3].

2.3.4 Load-matching

The most crucial part of the induction furnaces design is the accurate matching load which leads to the maximum power delivering to the induction furnaces. There are two topologies for matching the load in the induction furnaces; series load-matching and parallel load-matching. In figure (7) these two types of load-matching has been configured regards to the frequency and impedance [1].



a) Parallel resonant b) Series resonant
Figure 7. Resonant circuits

For more clarity in figure (8), the equivalent electrical circuit of an induction heating load form the primary point of view with a series tuning capacitor is illustrated. Equation (8) shows the produced heating power by the induction furnaces. By means of tuning capacitor, the equal capacitive reactance (X_C) to the inductive reactance (X_l) will be generated so their vectors' sum will be zero and a pure resistive circuit will be emerged [1].

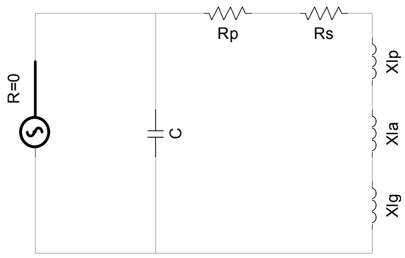


Figure 8. Equivalent circuit for an induction heating load

Where,

X_{lP}: Primary reactance of the coil
X_{ls}: Reflected reactance from the secondary side
X_{lg}: Reflective reactance of the air gap between the coil and workpiece
R_P: Work coil resistance
R_S: Reflective resistance from secondary side (from the workpiece or tank)

$$P = I^2 \times (R_P + R_S) \qquad (8)$$

2.4 Simulation of an induction furnace

After a brief introduction of induction furnaces and their heating theory and principles, a simulation of induction furnace will be presented. By means of this simulation, the harmonic study and electrical performance of the induction furnaces will be simplified. This model is simulated by PSCAD/EMTDC and will be used for different induction furnaces in the Company in order to harmonic study and power factor correction (PFC) which leads to energy efficiency increscent.

In this simulation some assumptions have been taken into considerations:

a) The voltage source is ideal (zero impedance)
b) The steady state condition is considered
c) No losses in the electrical circuit
d) The induction furnace works at the nominal active power
e) The unity power factor in the tank circuit which is prepared by the tuning capacitor

2.3 (MVA), (10.5 (kV)/ 0.575(kV)) three phase three winding transformer is fed the 2 (MW) induction furnace, 12-pulse full bridge rectifier converts the AC voltage to the DC voltage, and there are two current limiter inductors and DC filter capacitors by 12960 (µf) total capacitance. There are four half bridge inverters with SCRs switching devises which invert the DC voltage to the one phase 300 (Hz) AC voltage. 6200 (A) AC current flows to the work coil. Normally, PWM switching method uses for inverters controller. In figure (9) the model of this induction furnace is illustrated.
Load resistance will be calculated from the total active power and flowing current from the work coil by assuming the lossless condition. By considering the actual power factor of the induction furnaces, the amount of load inductance can be calculated too.

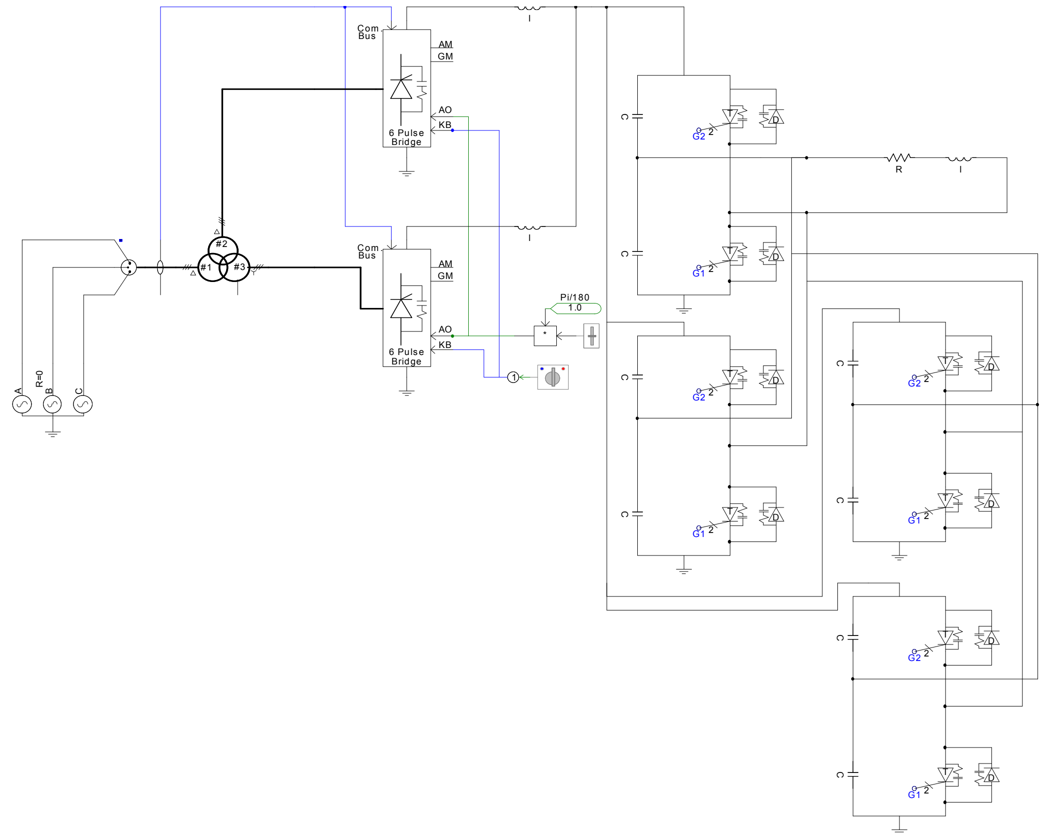


Figure 9. Simulated model of an induction furnace

Chapter 3

Harmonics

3.1 Fundamentals of harmonics

Power quality refers to the sinusoidal current and voltage cure which purely generates and provides by central power station but the impacts of nonlinear loads, lead to the impure sinusoidal voltage and current cure. Non-linear loads are those devises which the current and voltage applied by them are not proportional to each other. These distorted wave form is emerged by summation of the pure sinusoidal waves and by applying the Fourier series, can individually be analyzed [4]. In figure (10) distorted wave form has been presented by Fourier series [ibid].

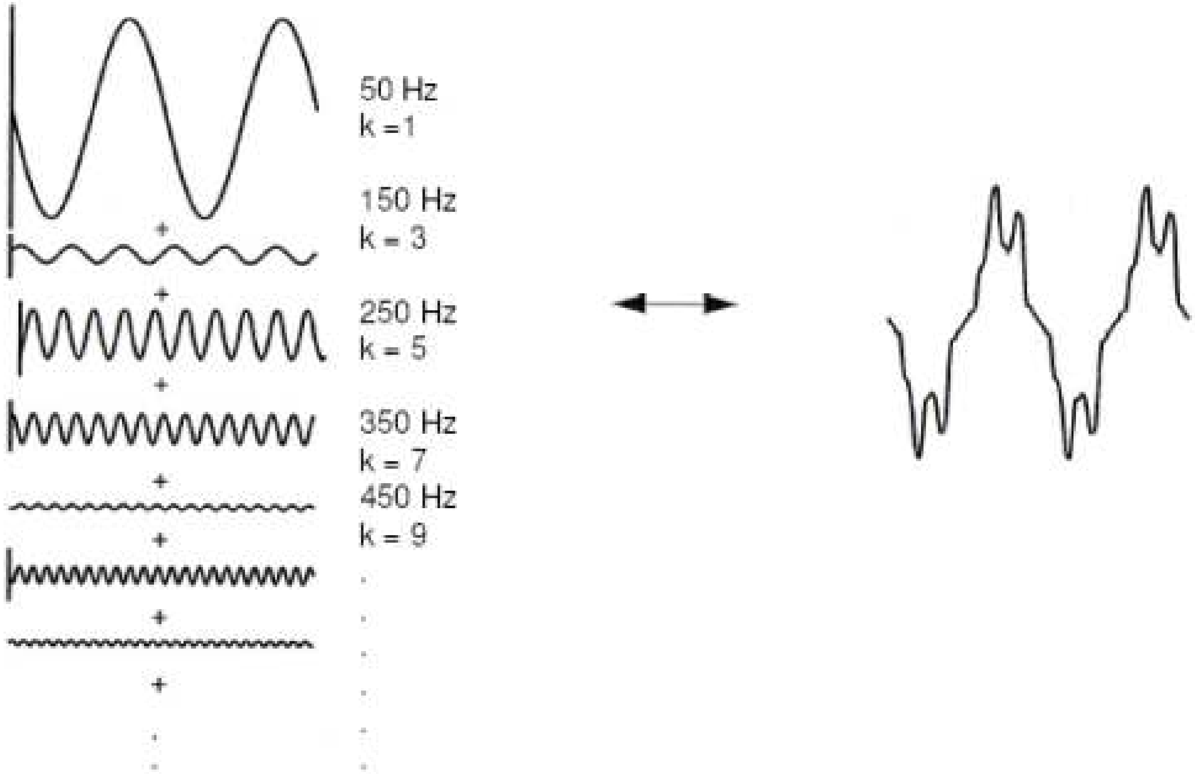


Figure 10. Representation of a distortion waveform by Fourier series

In power systems higher order harmonics are not taken into consideration. It is usually depends on the power system above the 25th up to the 50th [4]. Because of the same identical positive and negative half cycle shape of the curve, Fourier series have only odd harmonics [ibid].

3.1.1 Impacts of harmonics

The impacts of harmonics on the power system and electrical devices are so critical. Table (3) shows the effects of harmonics at different devices [5].

Table 3. Effects of harmonics

Circuit breakers	**Malfunction**
Capacitor banks	Overheating Insulation breakdown Failure of internal fuses
Protection equipments	False tripping No tripping
Measuring devices	Wrong measurements
Transformers, reactors	Overheating
Motors	Increased noise level Overheating Additional vibrations
Telephones	Noise with the respective harmonic frequency
Lines	Overheating
Electronic devices	Wrong pulses in data transmission Over and under voltage Flickering screens
Incandescent lamps	Reduced lifetime Flicker

Harmonics influence the power factor and lead the power system to poor energy efficiency. In steady state condition the quantity of THD can be calculated and it should be taken into consideration in order to approach the reasonable power factor correction.

3.1.2 Quantity analysis of harmonic components

By means of Fourier series, the RMS values of current and voltage can be calculated as follows [6]:

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n . \cos nx + b_n . \sin nx) \quad (9)$$

Where, $\frac{a_0}{2}$ is the average value of the function and is expressed as:

$$\frac{a_0}{2} = \frac{1}{T}\int_0^T f(x). dx \quad (10)$$

The coefficient of a_n and b_n can be calculated as:

$$a_n = \frac{2}{T}\int_0^T f(x). \cos nx. dx \quad (11)$$

$$b_n = \frac{2}{T}\int_0^T f(x). \cos nx. dx \quad (12)$$

Developed form of Fourier series can be expressed as:

$$f(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} A_k . \cos(k\omega t - \vartheta_k) \quad (13)$$

Because of the alternating electrical quantities the value of $\frac{a_0}{2}$ is equal to zero. Whereas the voltage and current will be expressed as the multiple frequency of the fundamental harmonic as:

$$V = \sum_{k=1}^{\infty} \sqrt{2}\,.\,V_k.\cos(k\omega t - \vartheta_k) \tag{14}$$

$$I = \sum_{k=1}^{\infty} \sqrt{2}\,.\,I_k.\cos(k\omega t - \vartheta_k - \varphi_k) \tag{15}$$

The RMS value of voltage and current can be calculated as:

$$V = \sqrt{\sum_{k=1}^{\infty} V_k^2} \tag{16}$$

$$I = \sqrt{\sum_{k=1}^{\infty} I_k^2} \tag{17}$$

Total harmonic distortion for voltage is:

$$THD_V = \frac{\sqrt{\sum_{k=2}^{\infty} V_k^2}}{V_1} = \frac{\sqrt{V^2 + V_1^2}}{V_1} \tag{18}$$

Total harmonic distortion for current is:

$$THD_i = \frac{\sqrt{\sum_{k=2}^{\infty} I_k^2}}{I_1} = \frac{\sqrt{I^2 + I_1^2}}{I_1} \tag{19}$$

Total demand distortion for current is:

$$TDD = \frac{\sqrt{\sum_{k=2}^{\infty} I_k^2}}{I_L} \tag{20}$$

Where I_L represents the maximum demand load current.
In order to calculate power factor, the voltage curve is assumed to be pure sinusoidal. It means that the total harmonic distortion for voltage is assumed to be zero and just total harmonic distortion for current is taken into consideration.

$$PF = \frac{P}{S} = \frac{VI_1 \cos \emptyset_1}{VI} \tag{21}$$

In equation (21), $\emptyset_1$ is the phase angle between the fundamental source voltage and fundamental load current and $\cos \emptyset_1$ represents displacement power factor (DPF).

$$\cos \emptyset_1 = DPF \tag{22}$$

Equations (19), (21) and (22) lead to:

$$\mathrm{PF} = \mathrm{DPF}.\frac{1}{\sqrt{1+\mathrm{THD}_i^2}} \tag{23}$$

3.2 Distortion and harmonic level requirements

In the Company there are amount of equipments which cause harmonics due to their operations. Different kinds of drive systems and furnaces which are fed by the numbers of individual or common transformers which lead to harmonic analysis of devises and compare their total and individual harmonics with international standards in the specified level of their voltages.

In table (4), the assumed short circuit powers for different voltage levels according to IEC 61000-3-4 is shown [8].

Table 4. Voltage level at PCC and assumed short circuit power

Voltage level at PCC (kV)	**Assumed short circuit power (MVA)**
132	600
33	400
11	100
0.4	26

Where,
PCC: PCC or Point of Common Coupling is defined as point of utility supplement which can be a common point to equipment with other equipments

Table (5) shows the total harmonic distortion for voltages and individual current harmonic levels at PCC according to IEC 61000-3-4. According to IEC total harmonic evaluation require up to 50th harmonics.

Table 5. $\mathrm{THD_v}$ and contributed current harmonic at selected PCC according to IEC 61000-3-4

Min R_{sc}	**I_5**	**I_7**	**I_{11}**	**I_{13}**	**Voltage %THD**
66	12	10	9	6	2.36
120	15	12	12	8	1.69
175	20	14	12	8	1.25
250	30	18	13	8	1.06
350	40	25	15	10	0.97
450	50	35	20	15	1.02
>600	60	40	25	18	<=0.91

Where,
R_{sc}: Short circuit ratio of the supply at PCC to the nominal equipments' apparent power (S_s/S_n)

Table (6) shows current distortion limits by the percent of the load current (% of IL) according to IEEE Std 519-1992 which covers the power systems from 120 V.

Table 6. Current distortion limits in IEEE Std 519-1992, tables 10.3, 10.4, 10.5

$V_n \leq 69$ kV						
I_{sc}/I_L	h<11	11≤h<17	17≤h<23	23≤h<35	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
69 kV < $V_n \leq$ 161 kV						
<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
V_n > 161 kV						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

I_{SC}: Maximum short-circuit current at PCC
I_L: Maximum demand load current (fundamental frequency component) at PCC
Table (7) shows the total and individual voltage harmonic distortions at PCC point according to IEEE 519-1992.

Table 7. Voltage distortion limits in IEEE Std 519-1992

Bus voltage at PCC, V_n(kV)	Individual voltage harmonic distortion (%)	THD_v (%)
$V_n \leq 69$	3.0	5.0
$69 < V_n \leq 161$	1.5	2.5
$V_n > 161$	1.0	1.5

3.3 Harmonics evaluations

The levels of harmonics distortion which are caused by non-linear loads as motor drives and induction furnaces should be evaluated in order to compare with the standard limitations, and also for reducing or eliminating of harmful harmonics by means of some harmonic eliminations methods. The process of harmonics evaluations has been illustrated in figure (11) [7].

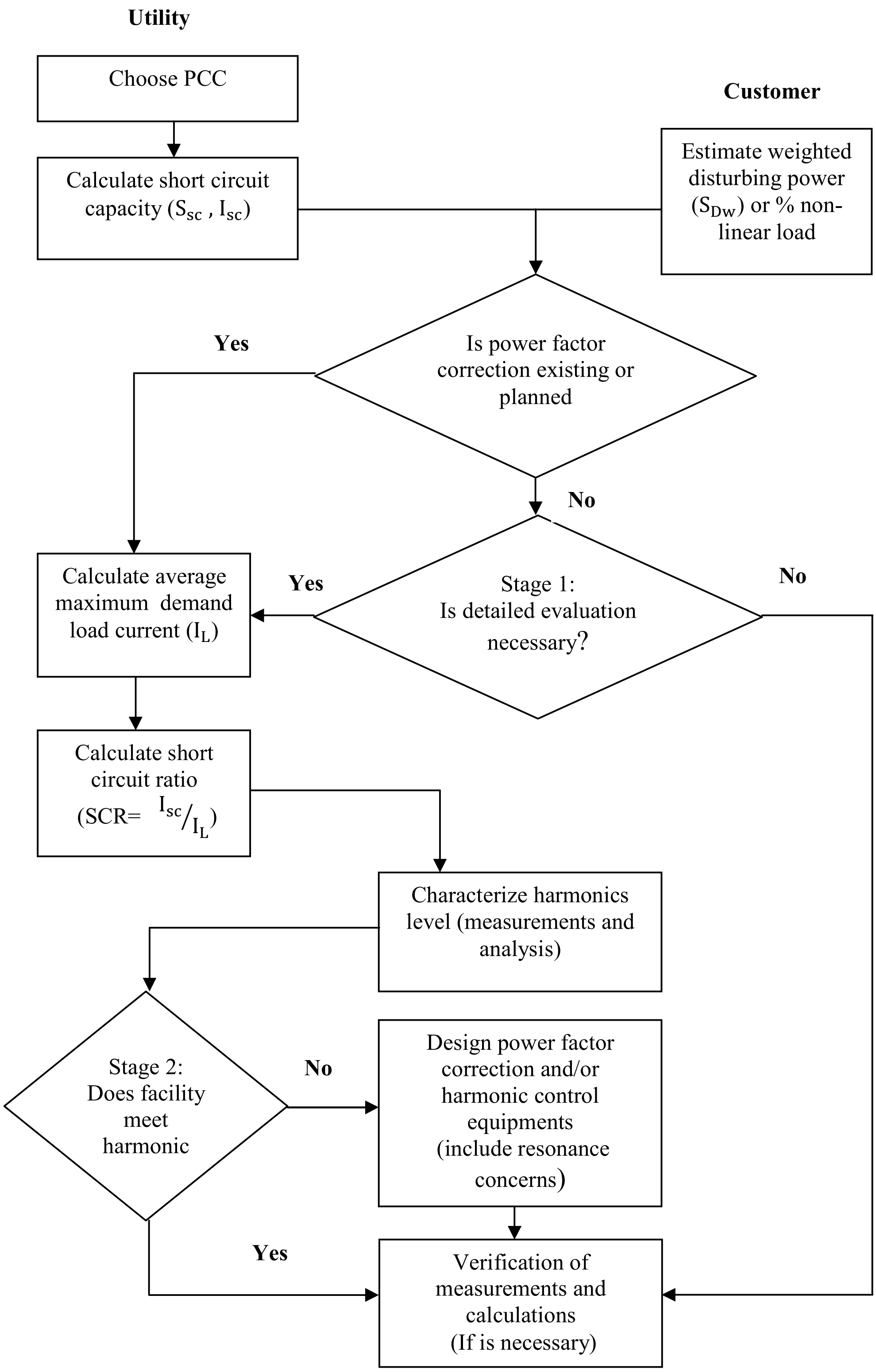


Figure 11. Process of harmonic evaluation

3.4 Harmonics reduction methods

Harmonic reduction methods can be categorized into two fundamental groups. Structural amendments of drive systems by applying proper supply units or structural changes of internal filters and the second method will be implemented by using external filtering equipments [8].

3.4.1 Structural amendments of drive systems

For more clarity one drive system and the factors which influence harmonics has been illustrated in figure (12). The constructions of drive systems influence current harmonics and voltage harmonics emerge due to flowing harmonic currents throw the supply impedance [8].

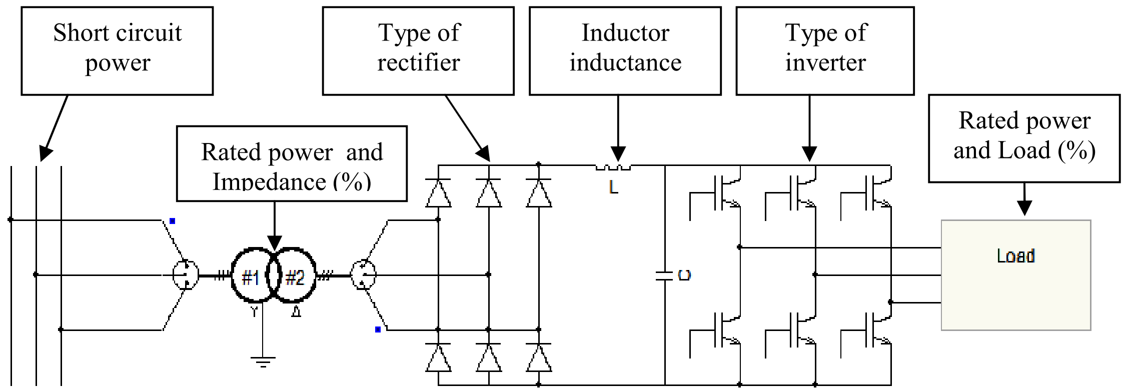


Figure 12. Drive system and affected harmonic factors

Summary of drive system structural factors and their effects is shown in table (8). In the power system industrial plant, the voltage harmonics depend on the system short circuit capacity. Higher the short circuit capacity leads to the lower voltage harmonics [8].

Table 8. Drive system factors and their effects

Cause	Effect
Higher load current	Higher current harmonics
Large AC or DC inductance	Lower current harmonics
Higher number of pulses in the rectifier	Lower current harmonics
Larger transformer	Lower voltage harmonics
Higher short circuit capacity of supply	Lower voltage harmonics

6-Pulse diode bridge rectifiers:

The common rectifier is 6-pulse diode bridge rectifiers. Normally, it contains six uncontrolled diodes rectifier with inductor which by means of DC-capacitors provides the low- pass filter. This possibility leads to the smoother DC current.
But the inductor size is crucial and because of their volumes in some cases they will be totally removed from the internal structures of drive systems. Over size transformer will

be used with 6-Pulse diode bridge rectifier in order to meeting the standard limitations but this is difficult then external harmonic filters will be applied [8].

12- Pulse diode bridge rectifiers:
Principle of 12-pulse diode bridge rectifier is two parallel connected 6-pulse diode rectifiers which supply a common DC bus. In these kinds of rectifiers, three winding transformers supply 12-pulse rectifiers with 30o phase shift on the secondary side. This phase shifting leads to the harmonics elimination on the primary side, because some of the harmonic components on the primary side are in the opposite phase [8].

24- Pulse diode bridge rectifiers:
Two number of parallel connected 12-pulse diode bridge rectifiers create a 24-pluse diode bridge rectifier. In these rectifiers, two numbers of three winding transformers by 15o phase shift on the secondary side will feed the rectifiers and more harmonic frequencies will be eliminated [8].

IGBT- Bridge rectifiers:
By replacing IGBT components with diodes in the conventional 6-pulse diode bridge rectifier, IGBT rectifier will be emerged. These rectifiers are able to control DC-voltage level and displacement power factor (DPF) regardless of each other. The main drawback is the high costs of these kinds of rectifiers. [8].

Very low harmonic frequencies cause by IGBT-bridge rectifiers and nowadays supply units of motor drive systems construction are based on the IGBT-bridge rectifiers. The main drawback is the high manufacturing costs of these kinds of rectifiers. In table (9) the individual current harmonics of different supply units and their manufacturing costs is shown [8]. In table (9) the manufacturing costs for different supply units which are based on the conventional 6-pulse bridge rectifier with no use of inductor is shown [8].

Table 9. Current harmonics and manufacturing costs of different supply units

Supply Unit	**Manufacturing cost**	I_5(%)	I_7(%)	I_{11}(%)	I_{13}(%)	I_{17}(%)	I_{19}(%)
6-pulse rectifier without inductor	100%	63	54	10	6.1	6.7	4.8
6-pulse rectifier with inductor	120%	30	12	8.9	5.6	4.4	4.1
12-pulse rectifier with polycon transformer	200%	11	5.8	6.2	4.7	1.7	1.4
12-pulse rectifier with double wound transformer	210%	3.6	2.6	7.5	5.2	1.2	1.3
24-pulse rectifier with 2 unit 3 winding transformers	250%	4.0	2.7	1.0	0.7	1.4	1.4
IGBT rectifier	250%	2.6	3.4	3.0	0.1	2.1	2.2

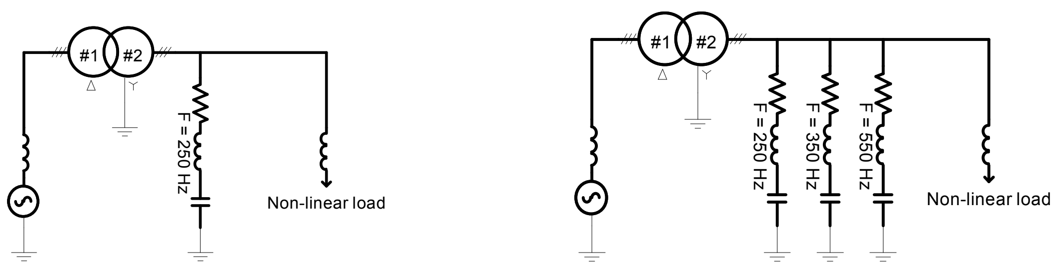
3.4.2 Filtering equipments

By means of filtering equipments the harmful harmonics can be eliminated or reduced to the acceptable limits. There are two fundamental filtering methods which are widely used.

a) Passive filters

Tuned single arm passive filters:
They contain a series inductor with capacitor bank and usually installed close to the harmonic generating loads. They usually tuned for the 5th harmonics in the power systems which supply industrial loads. The harmonic components above the tuned frequency will be absorbed but the lower frequency harmonics may be amplified. These kinds of filters are not so efficient and usually are not applied in the new installations [8]. A single tuned single arm passive filter is illustrated In figure (13, a).

Tuned multiple arm passive filters:
There are two or more tuned passive filters which are tuned for different harmonic components. Every brunch designs for low impedance at the dedicated harmonic current compare to the rest of the system. These kinds of filters have better harmonic performance compare with the single arm passive filters and they are usually applied for large DC drive installations by dedicated feeding transformers [8]. Figure (13, b) shows a tuned multiple arm passive filter.



(a): Single arm passive filter (b): Multiple arm passive filter

Figure 13. Passive filters

b) Active filters

The main problem of passive filters utilization is the appeared resonance which leads to more complicity in some cases and cause extra harmonic problems. Active filter generate the same harmonic components which are caused by the non-linear load but in the opposite phase. These kinds of filters have high effect on the harmonics but their costs compare with the passive filters are so high. They are usually applied for the multiple small drives. A principle diagram of active filter is illustrated in figure (14) [8].

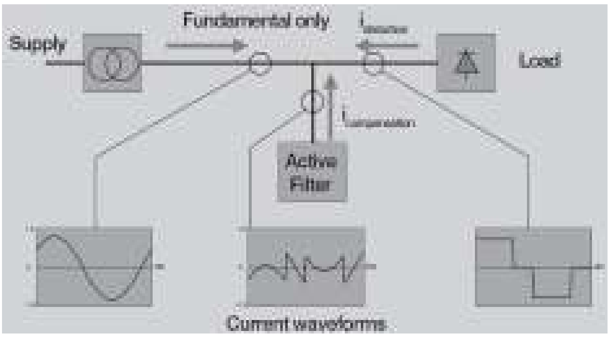


Figure 14. Principle figure of active filter

Active filters unlike to the passive filters are controllable. The over load condition can be eliminated by means of combination control of their active filtering and compensating current which are generated by the capacitors. These kinds of filters are able to eliminate all harmonic currents up to their nominal capacities [9]. There are two installation topologies for active filters; parallel and series, but only parallel topology is considered because of more flexibility, lower losses and higher overload ability [ibid].

3.5 Case study at PCC1

Figure (15) shows the incoming transformer from Mälarenergi which feeds five transformers. The short circuit current at PCC1 is 8.4 (kA) and short circuit power at this point is 112 (MVA). T126 individually feeds a 2 (MW) induction furnace, T131 feeds separately two number of 2 (MW) furnaces scheduled at every other week, T128 feeds an ABB 250 (kW) fan motor, T130 and T131 simultaneously feed a 4 (MW) induction furnace.

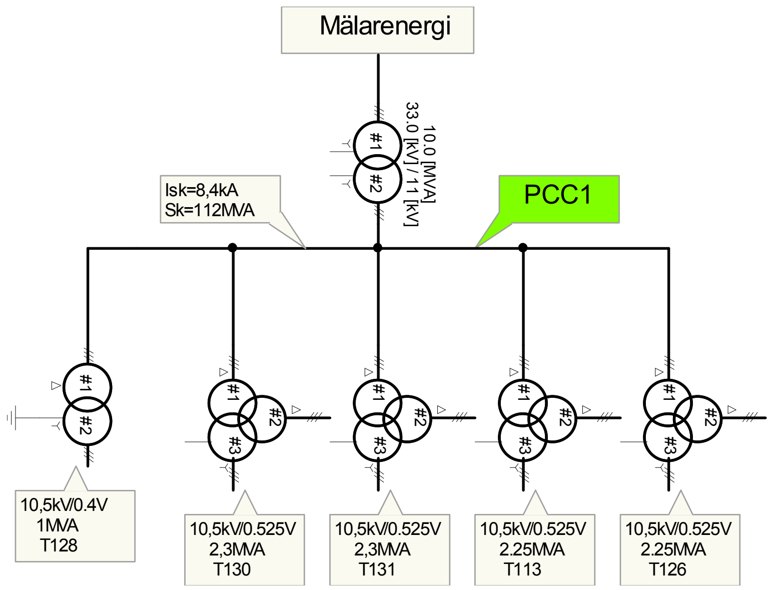


Figure 15. Overview of PCC1

3.5.1 Circulation fan motor

In figure (15), transformer T128, 1 (MVA), (10.5(kV)/0.400(kV)) feeds a 250 (kW), M3BP 355 SMA4 type ABB motor through an ACS 600 type ABB drive system. The load type of the motor is fan. The Motor characteristic is shown in table (10).

Table 10. M3BP 355 SMA4 ABB motor data

Motor type	Process performance
Power [kW]	250
Frequency [f]	50
Voltage [V]	400
Speed [rpm]	1488
Current [A]	436
Torque [Nm]	1604
Power factor	0,86
Efficiency [%]	96,2
Tmax / Tmin	2,7

The actual current is 15.4 (A) and the maximum load current on the primary side of transformer T128 is:

$$S = \sqrt{3}UI \rightarrow 1 \times 10^6 = \sqrt{3} \times 10500 \times I \rightarrow I = 54.9\ (A)$$

The typical individual harmonics and total harmonic distortion generated by ACS 600 type drive systems is exposed in table (11) [10].

Table 11. Typical mains harmonics generated by ABB ACS 600 drive systems

N	**frequency**	**I_n / I_1 (%)**	**I_n /$I_{L(max)}$ (%)**	**IEEE limitation**
1	50	100	100	0.0
5	250	41	11.48	10 %
7	350	17	4.76	10 %
11	550	9	2.52	4.5 %
13	650	5	1.4	4.5 %

Total harmonic distortion for current is 47% which gives 13.16% TDD. Then the individual harmonics and total harmonic distortion for currents are under the standard limitations. But by means of ABB Drivesize software the updated drive system for the motor will be obtained. The new drive system provides better harmonics performance and lower total harmonic distortion. By replacing the new ACS800 ABB multi drive system which includes an ACS800-107-0320-3 inverter and ACS800-307-0280-3 incoming unit instead of the previous one, the individual harmonics distortion and total harmonic distortion will be reduced. Table (12) shows the result from the Drivesize software which illustrates up to 49th individual harmonics distortion compared with the IEEE standard limitations.

Table 12. Result from Drivesize for ACS800 ABB multi drive

n	f [Hz]	Current [A]	In/I1	Voltage[V]	Un/U1	IEEE Currents	IEEE Voltage
1	50	15,4	100,0 %	10493,3	100,0 %	0,0 %/0,0 %	0,0 %/0,0 %
5	250	4,8	30,9 %	40,5	0,4 %	8,7 %/12,0 %	0,4 %/3,0 %
7	350	1,7	11,0 %	20,2	0,2 %	3,1 %/12,0 %	0,2 %/3,0 %
11	550	1,0	6,7 %	19,2	0,2 %	1,9 %/5,5 %	0,2 %/3,0 %
13	650	0,6	3,7 %	12,7	0,1 %	1,0 %/5,5 %	0,1 %/3,0 %
17	850	0,4	2,4 %	10,5	0,1 %	0,7 %/5,0 %	0,1 %/3,0 %
19	950	0,3	1,7 %	8,4	0,1 %	0,5 %/5,0 %	0,1 %/3,0 %
23	1150	0,1	0,9 %	5,3	0,1 %	0,2 %/2,0 %	0,1 %/3,0 %
25	1250	0,1	0,9 %	6,0	0,1 %	0,3 %/2,0 %	0,1 %/3,0 %
29	1450	0,1	0,7 %	5,0	0,0 %	0,2 %/2,0 %	0,0 %/3,0 %
31	1550	0,1	0,7 %	5,5	0,1 %	0,2 %/2,0 %	0,1 %/3,0 %
35	1750	0,1	0,6 %	5,3	0,1 %	0,2 %/1,0 %	0,1 %/3,0 %
37	1850	0,1	0,5 %	4,6	0,0 %	0,1 %/1,0 %	0,0 %/3,0 %
41	2050	0,1	0,4 %	4,0	0,0 %	0,1 %/1,0 %	0,0 %/3,0 %
43	2150	0,0	0,3 %	3,5	0,0 %	0,1 %/1,0 %	0,0 %/3,0 %
47	2350	0,0	0,2 %	2,7	0,0 %	0,1 %/1,0 %	0,0 %/3,0 %
49	2450	0,0	0,2 %	3,1	0,0 %	0,1 %/1,0 %	0,0 %/3,0 %
Cos ø1		0,980		THDCurrent	33,9 %	TDD Current	9,5 %/15%
Tot. power factor		0,928		THDVoltage	0,5 %	THD Voltage	0,5 %/5%

However, the existing drive system can satisfied the standard limitations at the normal cycle operation circumstance and there is no need for updating on the point of harmonic performance view.

3.5.2 Induction Furnaces 1, 2 and 3

As state before and illustrated in figure (15), T113 and T126 feed three induction furnaces, where T126 feeds individually furnace number 3 and T113 feeds separately furnace number 1 and 2. By means of PSCAD/EMTDC these induction furnaces have been simulated (The simulation of induction furnaces is explained in chapter 2). The characteristics of these furnaces are the same. These induction furnaces are manufactured by Inductotherm Group Company located in Britain.

Calculations for induction furnace 1, 2 and 3:

$$\mathrm{I_p} = \mathrm{I}\cos\varphi \rightarrow \mathrm{I_p} = 6500 \times \cos 18.19^{\mathrm{o}} \rightarrow \mathrm{I_p} = 6175\ (\mathrm{A})$$

$$\mathrm{P} = \mathrm{RI_p^2} \rightarrow 2 \times 10^6 = \mathrm{R} \times 6175^2 \rightarrow \mathrm{R} = 0.052\ (\Omega)$$

By considering the power factor of 0.95 in the induction furnace the phase angle will be 18,19o, so the impedance will be calculated as below:

$$\tan\varphi = \frac{\mathrm{X_l}}{\mathrm{R}} \rightarrow \tan(18.19^{\mathrm{o}}) = \frac{\mathrm{X_l}}{0.052} \rightarrow \mathrm{X_l} = 0.017(\Omega)$$

$$\mathrm{Z} = \mathrm{R} + \mathrm{jX_l} \rightarrow \mathrm{Z} = 0.052 + \mathrm{j}0.017\ (\Omega)$$

Since the maximum frequency at the work coil is 300 (Hz) then:

$$l = \frac{X_l}{2\pi f} \rightarrow l = \frac{0.017}{2\pi 300} = 9 \times 10^{-6}(H)$$

Maximum load current on the primary side of transformer T113 and T126 is:

$$S = \sqrt{3}UI \rightarrow 2.25 \times 10^{6} = \sqrt{3} \times 10500 \times I \rightarrow I = 123.7(A)$$

By running the simulation model of the induction furnace, individual harmonics and total harmonic distortions will be obtained. The short circuit current at PCC1 is (Isc=8.4 (kA)) and the maximum load current consumed by the furnace 3, on the primary side of transformer is (ILmax= 123.7(A)). Table (13) shows the result from the furnace 1, 2 and 3 according to IEEEE 519, (see table (6)). The input current to the transformer is about 85 (A).

Table 13. Harmonics generated by induction furnace 3 (ma = 0.9 and mf = 9)

n	frequency	I_n / I_1 (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	0.021	0.0144	10 %
7	350	0.018	0.0123	10 %
11	550	7.76	5.33	4.5 %
13	650	6.16	4.23	4.5 %
17	850	0.011	0.0075	4 %
19	950	0.010	0.0068	4 %
23	1150	2.12	1.45	1.5%
25	1250	1.7	1.16	1.5 %
29	1450	0.002	0.0013	1.5 %
31	1550	0.005	0.0034	1.5 %
35	1750	0.63	0.432	0.7 %
37	1850	0.56	0.384	0.7 %
41	2050	0.0043	0.0029	0.7 %
43	2150	0.0051	0.0035	0.7 %
47	2350	0	0	0.7 %
49	2450	0	0	0.7 %

Total harmonic distortion for current is 10.34% which gives 7.09% TDD (limitation is 12%). Total harmonic distortion for voltage is approximately zero. Figure (16) shows pulse waves from PWM and resulting output current is illustrated in figure (17).

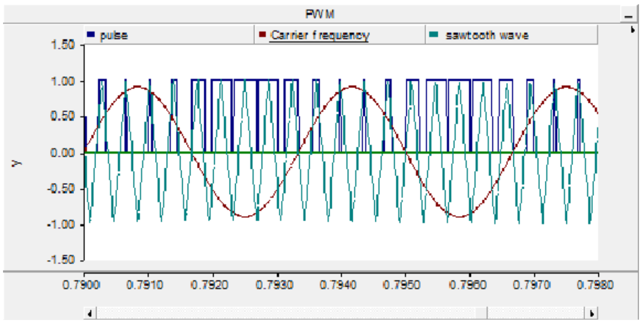


Figure 16. PWM control (ma=0.9 and mf=9)

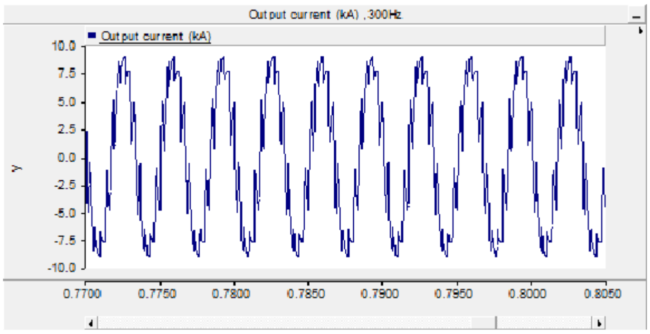


Figure 17. Output current to the work coil by 300Hz frequency

Improvement of harmonic performance in induction furnaces 1, 2 and 3:

According to the simulation results, harmonic 11th is out of limit and harmonics 13th , 23th and 25th are close to the limits. Then in order to reduce the harmonics, the harmonic filters will be applied. For efficient harmonic reduction and for avoiding the increment of the other harmonic components in the circuit which cause by harmonic filters, the harmonics 11th ,13th , 23th and 25th will be filtered. By take the total current harmonic distortion into consideration, the power factor can be calculated as below:

$$\mathrm{PF} = \mathrm{DPF}.\frac{1}{\sqrt{1+\mathrm{THD}_i^2}} = 0.95 \times \frac{1}{\sqrt{1+10.34\%^2}} = 0.944$$

Since the company doesn't have any unwarranted reactive power and in order to prevent over compensation condition in the furnace, 1% increment of power factor is considered.

Calculation of harmonic filter by 1% increasing of DPF compensation,

$$\cos\varphi_1 = 0.95 \rightarrow \varphi_1 = 18.19^o$$

$$\tan\varphi_1 = \frac{Q_c}{P} \rightarrow Q_c = 2 \times 10^6 \times \tan 18.19^o \rightarrow Q_c = 657.179\ \mathrm{kVAr}$$

$$\cos\varphi_2 = 0.96 \rightarrow \varphi_2 = 16.26^o$$

$$\tan\varphi_2 = \frac{Q_{c1}}{P} \rightarrow Q_{c1} = 2 \times 10^6 \times \tan 16.26^o \rightarrow Q_{c1} = 583.325\ (\mathrm{kVAr})$$

$$Q_{c2} = Q_c - Q_{c1} \rightarrow Q_{c2} = 73.857 \text{ (kVAr)}$$

As stated above four numbers of current harmonic components are going to be filtered. Series resonant passive filters are used and the calculated compensative reactive power (73.857(kVAr)) is equally divided between the harmonic filters. Then from the calculated compensation reactive power the value of C can be emerged. The values of inductors at resonant frequency can be calculated as below:

$$f_r = {}^{1}\!/_{2\pi}\sqrt{lC} \tag{24}$$

Where,

f_r: Resonant frequency

The value of filters' resistor in series resonant passive filters can be calculated as below:

$$Q = {}^{nX_l}\!/_{R} \tag{25}$$

Where,

Q: Quality factor of series resonant passive filter
n: Harmonic order
X_l: Inductor reactance at fundamental frequency
R: Resistance of the series resonant passive filter
The quality factor of filter represents sharpness of tuning and is usually between 20 and 100 [12]. The bigger inductor and smaller capacitor leads to steeply raising of the impedance both above and below side the resonant frequency [13]. This provides the higher quality for the filters [13]. There are two alternatives in PSCAD/EMTDC in order to apply harmonic filters. The first option is to apply the values of R, L and C for filter designing and the second alternative is to apply the value of reactive power, resonant frequency and fundamental frequency. Here, the quality factor for the filters is 100.

Table (14) shows the result after harmonic filter application. Total harmonic distortion is reduced to 5.4% which gives 3.7% TDD (<12%) and total harmonic distortion for voltage is still just about zero.

Table (14): Harmonics generated by induction furnace 3, after filtering (ma = 0.9 and mf = 9)

n	frequency	I_n / I_1 (%)	I_n /$I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	0.208	0.142	10 %
7	350	0.233	0.16	10 %
11	550	2.16	1.48	4.5 %
13	650	1.36	0.93	4.5 %
17	850	0.36	0.247	4 %
19	950	0.64	0.439	4 %
23	1150	0.21	0.144	1.5%
25	1250	0.15	0.103	1.5 %
29	1450	0.037	0.025	1.5 %
31	1550	0.05	0.034	1.5 %
35	1750	0.54	0.37	0.7 %
37	1850	0.49	0.336	0.7 %
41	2050	0.029	0.019	0.7 %
43	2150	0.033	0.022	0.7 %
47	2350	0.19	0.13	0.7 %
49	2450	0.18	0.12	0.7 %

The graphical results from the PSCAD/EMTDC for furnace 1, 2 and 3 before and after the harmonic filters application are illustrated in figure (18).

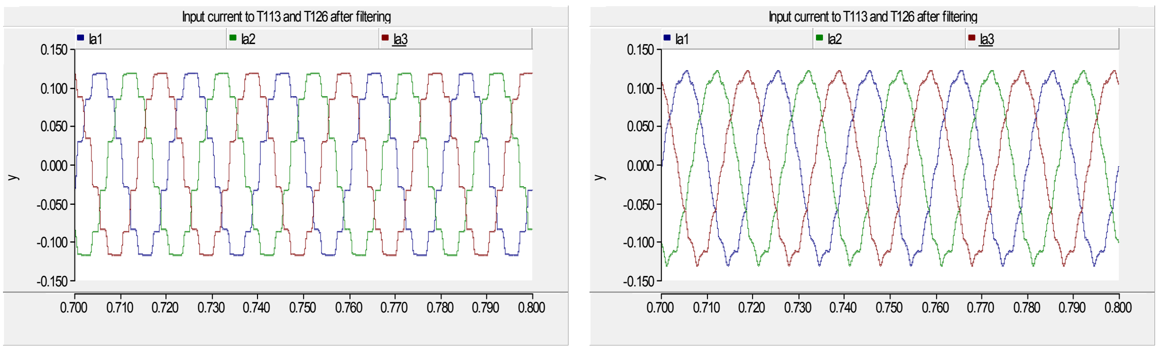


Figure 18. The currents on the primary side of T113 and T126 before filtering (left), and after filtering (right)

3.5.3 Induction furnace 4

Transformer T130 and T131 feed simultaneously a 4 (MW) induction furnaces (see figure (15)). As stated before parallel connection of two transformers by 15o degree phase shifting on the secondary side compare with the primary side, leads to lower harmonic distortion. By means of this connection, 24- Pulse Diode Bridge rectifiers are provided. According to the wiring diagram of the furnace 4, four numbers of full bridge rectifiers convert the AC voltage to the DC voltage. There are two current limiter inductors and DC filter capacitors by 30000 (μf) total capacitance on the DC side of the rectifiers. There are six half bridge inverters with SCRs switching devises which invert the DC voltage to the one phase 300 (Hz) AC voltage. 12500 (A) AC current flows to the work coil. This furnace is able to melt approximately 10 tons scrap.

As stated above, 15o phase shifting on the secondary side compare with the primary side of transformer leads even to the some harmonic cancelations on the secondary side of incoming transformer from Mälarenergi. This prospect gives lower harmonic impacts to the grid.
Figure (19) shows the simulated induction furnace model by means of PSCAD/EMTDC according to the data obtained from the induction furnace wiring diagrams and actual measurements.

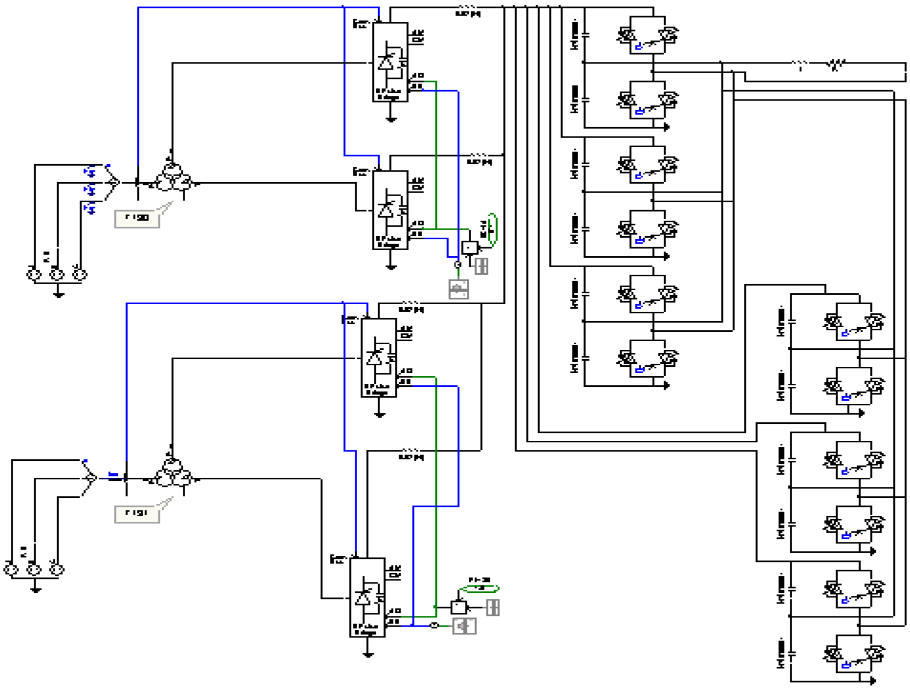


Figure 19. Induction furnace number 4

Calculations of induction furnace 4:

By consider the power factor of 0.95 in the induction furnace the phase angle will be 18,19° .

$$I_p = I\cos\varphi \rightarrow I_p = 12500 \times \cos 18.19^o \rightarrow I_p = 11875\ (A)$$

$$P = RI_p^2 \rightarrow 4 \times 10^6 = R \times 11875^2 \rightarrow R = 0.0283\ (\Omega)$$

So the impedance will be calculated as below:

$$\tan\varphi = \frac{X_l}{R} \rightarrow \tan(18.19^o) = \frac{X_l}{0.0283} \rightarrow X_l = 0.0093(\Omega)$$

$$Z = R + jX_l \rightarrow Z = 0.0283 + j0.0093\ (\Omega)$$

Since the maximum frequency at the work coil is 300 (Hz) then:

$$l = \frac{X_l}{2\pi f} \rightarrow l = \frac{0.0093}{2\pi 300} = 4.933 \times 10^{-6}(H)$$

The short circuit current at PCC1 is 8.4 (kA) and the maximum load current consumed by the furnace 4 on the primary side of transformers is 126 (A).
Table (15) shows the result from the furnace 4 according to IEEE 519, (see table (6)). The input current to the transformer is about 77 (A).

Table 15. Harmonics generated by induction furnace 4 (ma = 0.8 and mf = 9)

N	frequency	I_n / I_1 (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	0.0099	0.006	10 %
7	350	0.0094	0.0057	10 %
11	550	8.1	4.95	4.5 %
13	650	6.5	3.97	4.5 %
17	850	0.0014	0.00085	4 %
19	950	0.00153	0.00093	4 %
23	1150	2.6	1.58	1.5%
25	1250	2.1	1.28	1.5 %
29	1450	0.000093	0.000056	1.5 %
31	1550	0.0034	0.002	1.5 %
35	1750	0.85	0.519	0.7 %
37	1850	0.71	0.43	0.7 %
41	2050	0.0006	0.00036	0.7 %
43	2150	0.009	0.0055	0.7 %
47	2350	0.43	0.26	0.7 %
49	2450	0.43	0.26	0.7%

Total harmonic distortion for current is 11.05 % which gives 6.68% TDD (limitation is 12%) and total harmonic distortion for voltage is approximately zero.

Improvement of harmonic performance in induction furnace 4:

According to the simulation results, harmonic 11th and 23th is out of limit and harmonics number 13th and 25th are close to the limits. Then harmonic filters will be applied. Similar to the previous case, for efficient harmonic reduction and for avoiding the other harmonic components increscent in the circuit which cause by harmonic filters, the harmonics 11th ,13th , 23th and 25th will be filtered. Calculation bellow shows the reduction of power factor affected by total harmonic distortion:

$$PF = DPF.\frac{1}{\sqrt{1 + THD_i^2}} = 0.95 \times \frac{1}{\sqrt{1 + 11.05\%^2}} = 0.944$$

Since the company doesn't have any unwarranted reactive power and in order to prevent over compensation condition in the furnace, 1% increment of power factor is considered.

Calculation of harmonic filter by 1% power factor compensation:

$$\cos \varphi_1 = 0.95 \rightarrow \varphi_1 = 18.19^o$$

$$\tan\varphi_1 = \frac{Q_c}{P} \rightarrow Q_c = 4 \times 10^6 \times \tan 18.19^o \rightarrow Q_c = 1314.358\ (\text{kVAr})$$

$$\cos\varphi_2 = 0.96 \rightarrow \varphi_2 = 16.26^o$$

$$\tan\varphi_2 = \frac{Q_{c1}}{P} \rightarrow Q_{c1} = 4 \times 10^6 \times \tan 16.26^o \rightarrow Q_{c1} = 1166.65\ (\text{kVAr})$$

$$Q_{c2} = Q_c - Q_{c1} \rightarrow Q_{c2} = 147.714\ (\text{kVAr})$$

Series resonant passive filters are used and the calculated compensative reactive power (1166.65 (kVAr)) is equally divided between the harmonic filters. Table (16) shows the result after the application of the filters. Total harmonic distortion is reduced to 8.37% which gives 5% TDD (<12%) and total harmonic distortion for voltage is about zero.

Table 16. Harmonics generated by induction furnace 4, after filtering (ma = 0.8 and mf = 9)

n	Frequency	I_n / I_1 (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	0.0	0.0
5	250	0.14	0.08	10 %
7	350	0.40	0.24	10 %
11	550	1.74	1	4.5 %
13	650	1.15	0.69	4.5 %
17	850	0.15	0.09	4 %
19	950	0.55	0.33	4 %
23	1150	0.21	0.126	1.5%
25	1250	0.53	0.31	1.5 %
29	1450	0.06	0.04	1.5 %
31	1550	0.1	0.06	1.5 %
35	1750	0.76	0.45	0.7 %
37	1850	0.66	0.39	0.7 %
41	2050	0.037	0.02	0.7 %
43	2150	0.03	0.018	0.7 %
47	2350	0.33	0.19	0.7 %
49	2450	0.29	0.174	0.7 %

The graphical results from the PSCAD/EMTDC for furnace 4, before and after the harmonic filters application are illustrated in figure (20).

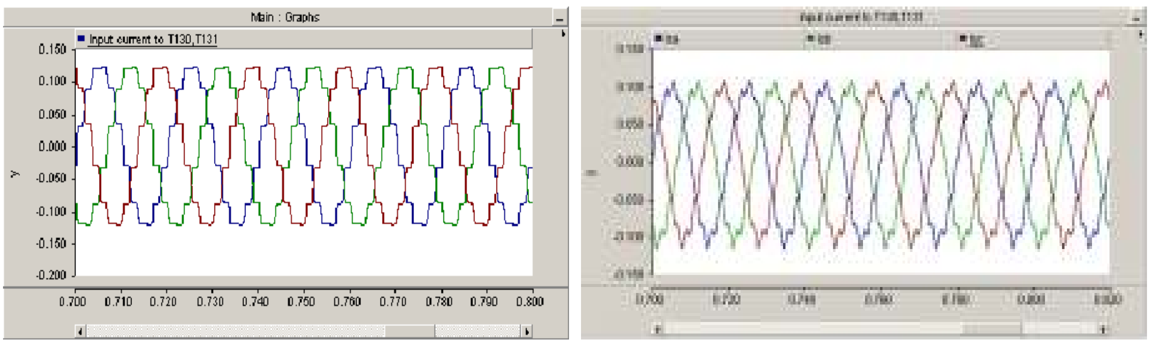


Figure 20. The currents on the primary side of T130 and T131 before filtering (left), and after filtering (right)

Chapter 4

Furnaces by electric heating elements

4.1 Introduction of heating elements principle

The confronted resistivity due to flowing current through the electric heating elements produces significant temperature which can be used in domestic purposes or industrial processes. Resistivity of heating elements varies by temperature variation. The higher resistivity at higher temperature is the principle of heating elements.

Kanthal (renamed to Sandvik Heating Technology) Super is World leader Company which combines the best excellence of both metallic and ceramic materials in order to achieve the best heating performance. Metallic materials provide excellent heat and electric conductivity and the ceramic materials provide low thermal expansion and have high resistivity against oxidation. The resistivity of the elements increases sharply by temperature and on the other hand the higher power at constant voltage will be applied by electric elements and the power will be decreased when temperature of elements increases. This performance of electric heating elements decreases the hazard of overheating [11]. Figure (21) shows a furnace by vertical installed electric heating elements [11].

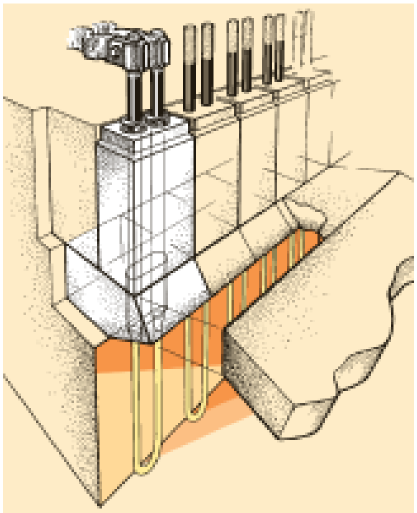


Figure 21. Installation of Sandvik Super elements
with standard package bricks in a brick lined furnace

4.2 Power control of electric heating elements furnaces

Because of the electric heating low cold resistivity, the startup current will be very high and it leads undesired condition. In the past time, tapped transformer was used for voltage reduction when the furnace was cold. But nowadays by means of power electronic and control devises this rushing current in furnace cold condition is managed [11]. There are two main methods in order to control the power of the furnaces; Thyristor control and On/Off control [11].

4.2.1 Thyristor control

a) Phase angle- fired thyristors which can be used with or without the transformers. These transformers located between element loads and thyristors.

b) Burst fired thyristors with phase angle start. This method can also be used with and without transformers.

For more clarity in figure (22), a thyristor control method for one phase is illustrated [11].

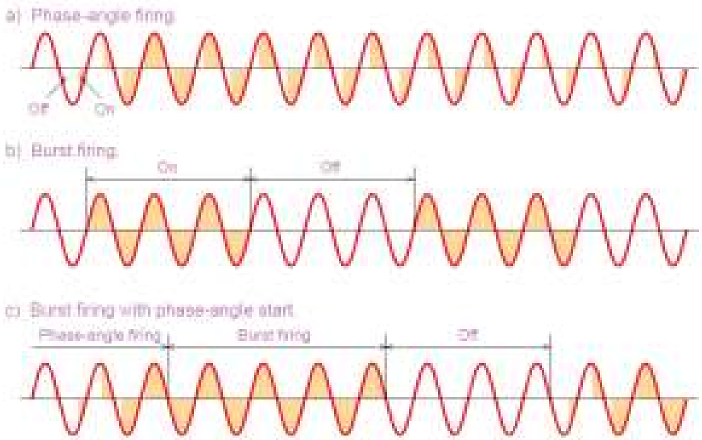


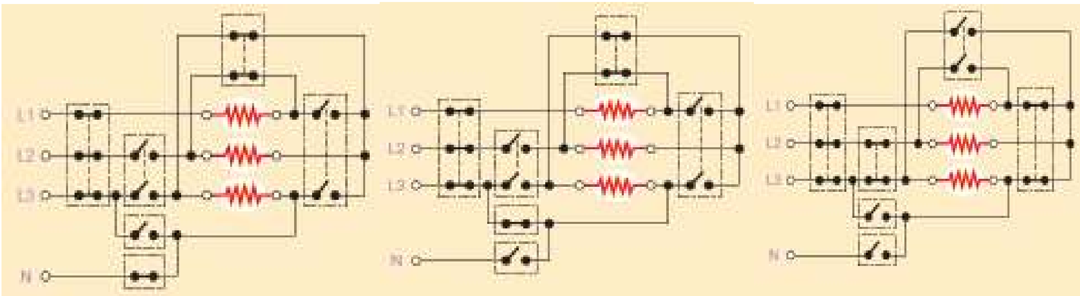
Figure 22. Thyristor control methods

4.2.2 On/Off control

a) Tapped transformers
b) Changing the element connection, contactor switch

Tapped transformers and contactor switch methods have longer on/off periods which lead to poor temperature control. Non-synchronized switching results transient over voltages and contactors mechanical wear [11].

The elements connection by contactor switches will provide the lower current flowing through the furnace in cold condition. At start point all electric heating elements will be in series connection between one phase and neutral which results 33% of full operation voltage. The next step is to connect the electric heating elements in series between two phases which leads to 58 of full operation voltage. By star connection of electric heating elements the full operation voltage will be applied [11]. See figure (23) [11].



First Step b) Second step c) Third step

a) All elements are in series connection between one phase and neutral
b) Elements are in series connection between two phases
c) Star connection of the elements

Figure 23. Changing of elements connection by means of contactor switches

4.3 Case study at PCC2

Figure (24) shows an overview of PCC2 but since there weren't any previous measurements at PCC2 the Short circuit current at PCC2 should be calculated. At PCC1 the previous measurements and calculations of short circuit current by consultant Company Harmonizer is used.

Short circuit current at PCC2:

In the previous study at PCC1 short circuit current had calculated by consultant company and at different points of the headquarter Company the amount of short circuit current were available. But the short circuit current at PCC2 should be calculated. The incoming short circuit power from Mälarenergi is Ssk= 598 (MVA).

$$S_{ktr} = \frac{S_n}{e_k} = \frac{10\ (\mathrm{MVA})}{8.52\%} = 117.370892\ (\mathrm{MVA})$$

$$S_k = \frac{S_{ktr} \times S_{kn}}{S_{ktr} + S_{kn}} = \frac{117.370892 \times 568}{117.370892 + 568} = 97.27\ (\mathrm{MVA})$$

$$S_k = \sqrt{3}UI \rightarrow 97.27\ (\mathrm{MVA}) = \sqrt{3} \times 10.6\ (\mathrm{kV}) \times I_{sk} \rightarrow I_{sk} = 5.29\ (\mathrm{kA})$$

S_{ktr}: Short circuit power at transformer
S_n : Nominal power of transformer
e_k : Transformer impedance
I_{sk} : Short circuit current on the secondary side of transformer

In figure (24) transformers LT22, LT29 and LT28 individually feed the furnaces which are equipped by several numbers of heating elements. LT26 feeds an ABB, DC motor, this motor is equipped by 1 pc triple-tuned, filter type CHARM-3T which have been tuned to the 5th, 7th and 11th harmonics with total reactive power capacity of 2 (MVAr) at 11(kV).

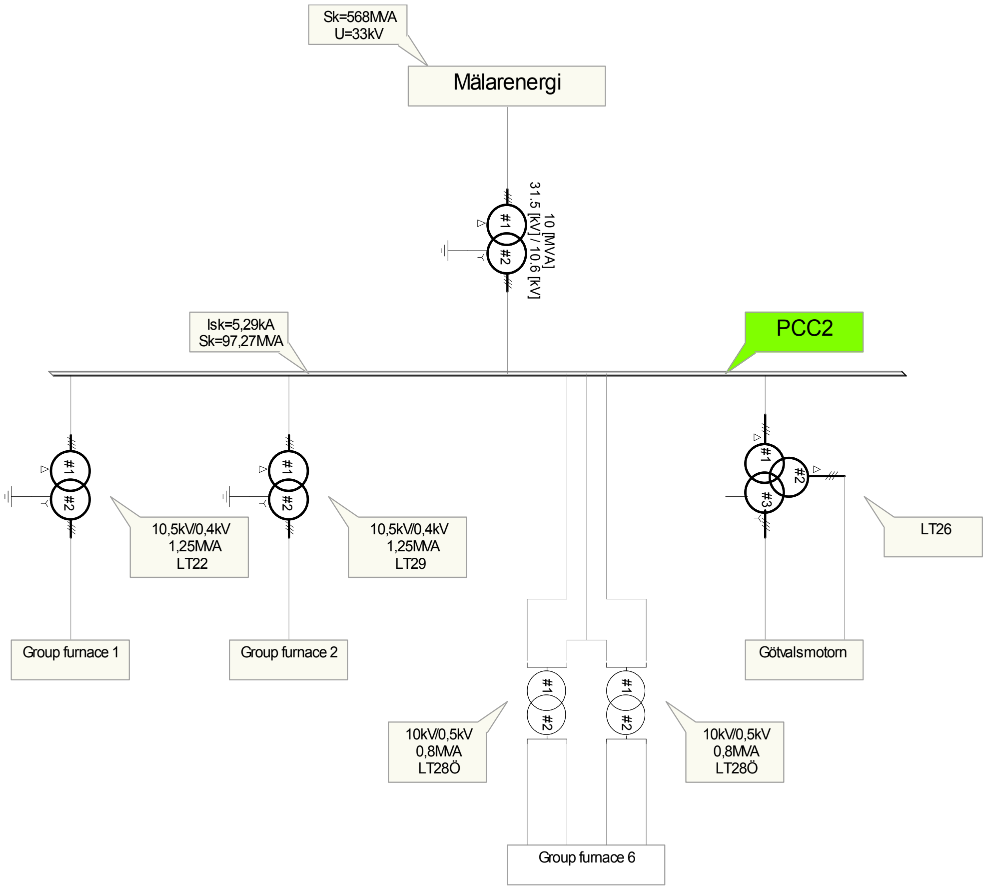


Figure 24. Overview of PCC2

4.3.1 Heating elements group furnace 1

Transformer LT22, 1.25 (MW), feeds group furnace 1. This furnace includes 10 individual cells of furnaces which are fed by 10 thyristors. Totally, 90 numbers of electric heating elements provide high temperature for the furnaces cells. There are 9 numbers of elements in each cell, 3 elements are in series in every phase and Y connected with the other phases. There are YY, (400(V)/133(V)) transformers between thyristors and Y connected load. Figure (25) shows a schematic view of furnace 1.

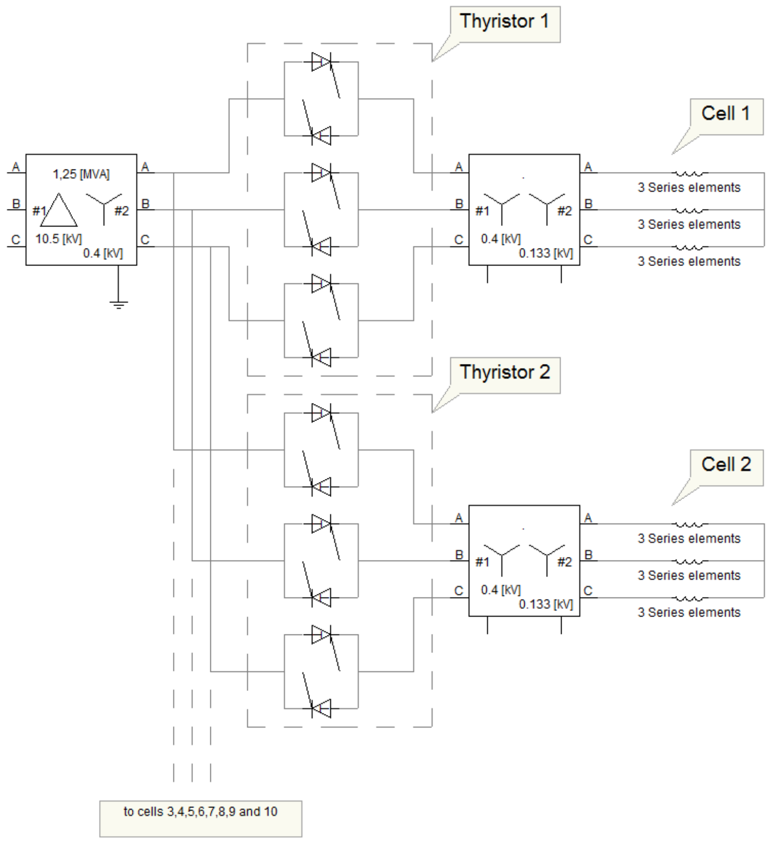


Figure 25. Schematic view of heating elements group furnace 1

Calculations of heating elements group furnace 1:

The maximum power of the furnace is 1000 kW, and then every cell has maximum power of 100 (kW). The furnace maximum load current can be calculated as below:

$$P = \sqrt{3}\,\mathrm{UI}\cos\varphi \rightarrow 1250\ (\mathrm{kVA}) = \sqrt{3}\ \times 400 \times \mathrm{I} \rightarrow \mathrm{I} = 1804\ (\mathrm{A})$$

Maximum load current for each cell is:

$$\mathrm{I}_{\mathrm{Lmax}} = 1804 \div 10 = 180.4\ (\mathrm{A})$$

Maximum current on the primary side of transformer for the furnace is:

$$S = \sqrt{3}\,\mathrm{UI} \rightarrow 1250\ (\mathrm{kVA}) = \sqrt{3}\ \times 10500 \times \mathrm{I} \rightarrow \mathrm{I} = 68.73\ (\mathrm{A})$$

The required current for each cell by resistive heating elements leaves length consideration is 140 (A).

Total current drown from the transformer will be $140 \times 10 = 1400$ (A) and total furnace consumed power is about 1000 kW. Then the input current to the transformer is 53.3 (A).

In order to simulate this furnace, the load impedance should be calculated and in favor of simplicity of simulated model the total impedance at each phase and one couple of thyristor devices can be taken into consideration. This exploitation of the model represents the simple model of furnace without any error. Since the transformers between thyristors and cells don't influence harmonic performance, they can be removed in the model by transmitting the loads to the primary side.

The total power in each cell is the summation of power in each phase. Then, calculation of cells maximum resistance for each phase will be as follows:

$$P_{cell} = P_1 + P_2 + P_3$$

$$P_1 = P_2 = P_3 \text{ (because of semetrical load)}$$

$$P_{cell} = 3 \times P_1 = 125 \times 10^3 \rightarrow P_1 = 41.67 \text{ (kW)}$$

$$P_1 = RI^2 \rightarrow R = 41.67 \times 10^3 \div 180.4^2 \rightarrow R = 1.28\ (\Omega)$$

Total resistance is Rtot =1.28 ÷ 10 = 0.128 (Ω) and by adjusting the thyristors firing angle at 55o, the required load current (140 (A)) for each cell and 1400 (A) for the furnace in one piece will be achieved.

The consideration in this model is, the resistivity of the heating elements vary by variation of temperature. The higher resistivity in the heating elements will be emerged due to the current increment and heating elements don't have constant resistivity. In the simulated model resistivity of the elements has been assumed as constant value but this assumption doesn't have remarkable negative impact on the results.
The ratio of short circuit power to the load current is:

$$\frac{I_{sc}}{I_L} = \frac{5.29 \times 1000}{53.3} = 99.2$$

According to IEEE 519 St, the third row of table (6) will determine the distortion harmonics levels. This value is almost on the border between the third and fourth row of table (6). Then because of the economical reasons and in order to simplify filter designing, the fourth row of table (6) has been selected.

Table (17) shows the result from PSCAD/EMTDC for furnace 1, and is illustrated up to 49th individual harmonics distortion compared with the standard limitations.
Total harmonic distortion for current is 31% which gives 24% TDD (limitation is 15%) and total harmonic distortion for voltage is about zero.

Table 17. Harmonics generated by heating elements group furnace 1

n	Frequency	I_n / I_L (%)	I_n /$I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	24.77	19.19	12
7	350	12.1	9.37	12
11	550	9.15	7.09	5.5
13	650	6.41	4.96	5.5
17	850	5	3.87	5
19	950	4.1	3.177	5
23	1150	3.07	2.37	2
25	1250	2.83	2.19	2
29	1450	2.03	1.57	2
31	1550	2.03	1.57	2
35	1750	1.39	1.077	1
37	1850	1.47	1.139	1
41	2050	1.04	0.8	1
43	2150	1.07	0.82	1
47	2350	0.83	0.64	1
49	2450	0.76	0.589	1

Improvement of harmonic performance in heating elements group furnace 1:

According to the simulation results, harmonics 5th ,11th ,23th ,25th ,35th and 37th are over than standard limitations. Then harmonic filters will be applied. For efficient harmonic reduction and for avoiding the increment of the other harmonics in the circuit which cause by harmonic filters, series RLC tuned filters for harmonics 5th ,7th ,11th ,13th and high pass filter by 850 (Hz) cutoff frequency are applied.

In this case displacement power factor is about unity then this furnace doesn’t need any power compensation capacitors. Since some of the generated harmonics by the furnace are higher than standard limitation, harmonic filters are needed. Active filter harmonic is a proper solution in this case but because of economical considerations the passive filters are demanded. Here, application of passive filters leads to have leading power factor which normally is not desired but total power factor at PCC2 will be improved.

PCC2 is located on the secondary side of T3 (see figure (24)) where the compensation capacitors should be installed in order to obtain the power factor above 0.9.

The total reactive power generated by the filter capacitors is assumed to be 174 (kVAr). In this case the distribution of the filter capacitors capacitance is not equal.

The calculation method for determining the values of R, L and C in series resonant passive filters is explained before.

As stated before there are two alternatives in PSCAD/EMTDC in order to apply harmonic filters. The first option is to apply the values of R, L and C for filter designing and the second alternative is to apply the value of reactive power, resonant frequency and fundamental frequency.

The values of R, L and C in high pass passive filters can be found as below:

$$Q = {}^{R_h}/_{L_h \cdot 2\pi f_k} \tag{26}$$

Q: Quality factor of high pass passive filter
h: Harmonic order
L_h: Inductor of high pass passive filter
R_h: Resistance of high pass passive filter
f_k: Cutoff frequency

Table (18) shows the result after harmonic filters application. Total harmonic distortion for current is reduced to 17.9% which gives 13.8% TDD (<15%) and total voltage distortion is still just about zero.

Table 18. Harmonics generated by heating elements group furnace 1 after filtering

n	Frequency	I_n / I_L (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	13.18	10.21	12
7	350	10.12	7.84	12
11	550	3.48	2.69	5.5
13	650	2.02	1.56	5.5
17	850	0.68	0.52	5
19	950	2.24	1.73	5
23	1150	2.32	1.79	2
25	1250	2.02	1.56	2
29	1450	1.9	1.47	2
31	1550	1.61	0.47	2
35	1750	1.4	1	1
37	1850	1.4	1	1
41	2050	1.06	0.82	1
43	2150	1.02	0.79	1
47	2350	0.83	0.64	1
49	2450	0.74	0.57	1

Figure (26) shows the current wave on the primary side of transformer LT22 in steady-state condition before and after installation of harmonic filters.

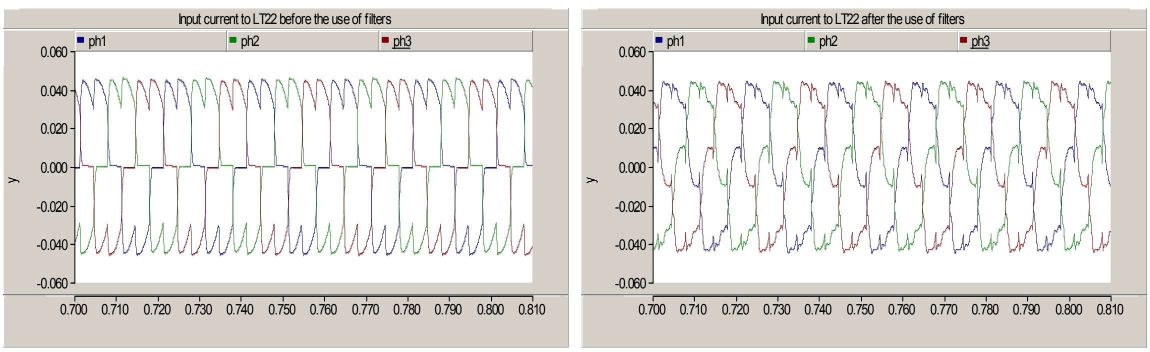


Figure 26. The currents on the primary side of LT22 before filtering (left), and after filtering (right)

For more clarity in figure (27) the single phase view of current on the primary side of LT22 is illustrated.

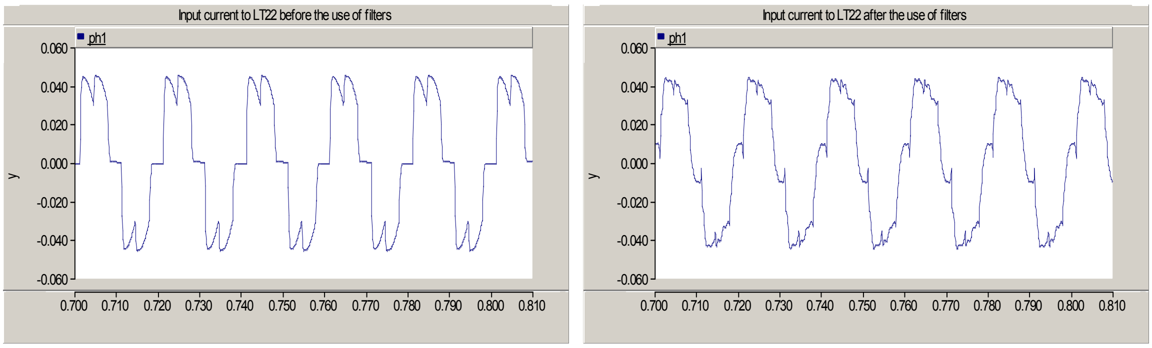


Figure 27. Single phase view of current on the primary side of LT22 before filtering (left), and after filtering (right)

4.3.2 Heating elements group furnace 2

Transformer LT29, 1.25 (MW), feeds group furnace 2. This group furnace has been constructed by six numbers of individual cells which feeds separately by thyristors. There isn't any transformer between the feeding thyristors and electric heating elements in the cells. The number of electric heating elements per cell is the same as group furnace 1 (three elements per phase as series and Y connected three phase load) but the heating elements dimension is not the same as group furnace 1.

Calculations of heating elements group furnace 2:

The nominal power of the furnace is 1000 kW and every cell will have the power of 1000 ÷ 6 = 166.67 (kW). The furnace maximum load current can be calculated as below:

$$S = \sqrt{3}\,UI \rightarrow 1250\ (\mathrm{kVA}) = \sqrt{3}\ \times 400 \times I \rightarrow I = 1804\ (A)$$

Maximum load current for each cell is:

$$I_{Lmax} = 1804 \div 6 = 300.67\ (A)$$

The actual load current for each cell is 235 (A), total power for each cell of furnace will be as follows: (because of the pure resistivity of load, displacement power factor (DPF) can be considered as unity)

$$P = \sqrt{3}\,UI\cos\varphi_1 = \sqrt{3}\ \times 400 \times 235 \times 1 \rightarrow P = 162.8\ (\mathrm{kW})$$

Total current drown from the transformer will be:

$$I_{tot} = I \times 6 \rightarrow 235 \times 6 = 1410\ (A)$$

Simulation method is the same as group furnace 1. In favor of simplicity of simulated model, the total resistance at each phase and a couple of thyristors at each phase can be taken into consideration.

The maximum power per phase by considering of unity displacement power factor is 1250 (kW) / 6 = 208.33 (kW). Then calculation of cells maximum resistivity for each phase is:

$$P_{cell} = P_1 + P_2 + P_3$$

$$P_1 = P_2 = P_3 \text{ (because of semetrical load)}$$

$$P_{cell} = 3 \times P_1 = 208.33 \times 10^3 \rightarrow P_1 = 69.44 \text{ kW}$$

$$P_1 = RI^2 \rightarrow R = 69.44 \times 10^3 \div (300.67)^2 \rightarrow R = 0.768\ (\Omega)$$

Total resistance is R_{tot}= 0.768 ÷ 6 = 0.128 (Ω). Consequently, the result from the simulation for this group furnace is the same as previous group furnace but the results from the cells are different.

Improvement of harmonic performance in heating elements group furnace 2:

Group furnace 1 and 2 has same harmonics performance so the solution for furnace 1 will be also valid for group furnace 2. By applying the same harmonic filters as group furnace 1, the same reduction of individual harmonics and THD will be emerged. Then the shape of current curves will be similar to the previous group furnace.

4.3.3 Heating elements group furnace 6

Transformers LT28Ö, 800 (kVA) and LT28V, 800 (kVA) feed group furnace number 6. These transformers are single phase transformers and connected in special form on the primary side. There are two numbers of cells which separately is fed by transformers and thyristors. There are transformers between thyristors and electric heating elements. The volume of the cells is bigger than two previous group furnaces. In this group furnace, two cells have been combined in order to build a unity cell, so the numbers of elements per cell is double than previous group furnaces. For more clarity the schematic model of this group furnace is illustrated in figure (28). In the figure the resistors represent the resistive loads of heating elements on the primary side of the transformers which are located between heating elements and thyristors.

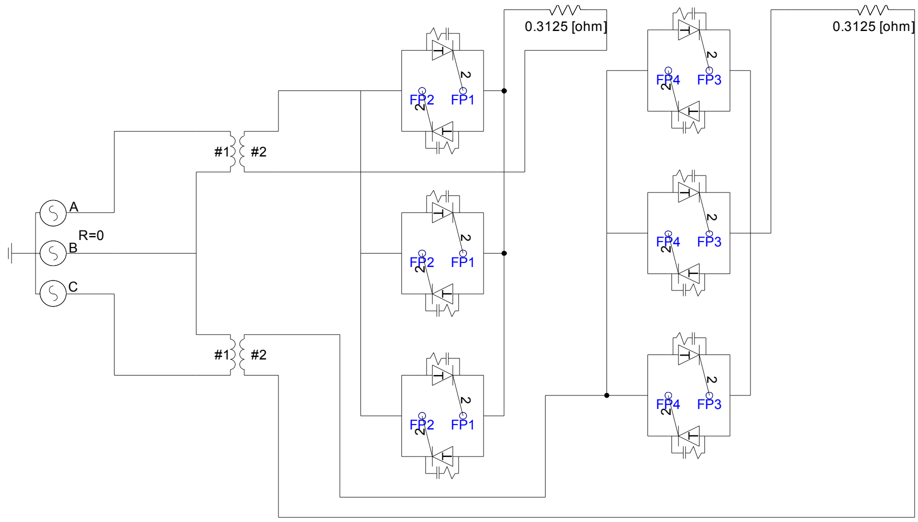


Figure 28. Schematic view of heating elements group furnace 6

Calculations of heating elements group furnace 6:

Two Transformers (LT28Ö and LT28V) transform 10.5 (kV) to 0.5 (kV) on the secondary side. By assuming the pure resistive load (displacement power factor is unity) the maximum load current for each cell will be calculated as bellow:

$$S = UI_{Lmax} \rightarrow 800\ (kVA) = 500 \times I_{Lmax} \rightarrow I_{Lmax} = 1600\ (A)$$

As illustrated in figure (21), there are three parallel couple thyristors which divide the incoming current and feed simultaneously the cells. So the maximum current flowing through each couple of thyristors will be 533.33 (A). The load current for each couple of thyristors is 400 (A).

Total required load current for each cell is:

$$I_{tot} = I \times 3 = 400 \times 3 = 1200\ (A)$$

Calculation of each cell resistivity:

$$P = RI^2 \rightarrow 800 \times 10^3 = R \times (1600)^2 \rightarrow R = 0.3125\ (\Omega)$$

By adjusting the thyristors firing pulse at 48o, the total required load current will be obtained. Total harmonic distortion for current in L1 and L3 is 49.3% which gives 36.9% TDD (limitation is 12%).

Because of the transformers' connection in this group, the third multiple harmonics are generated in L1 and L3e. This group of harmonics will be removed in delta connection on the primary side of incoming transformer from Mälarenergi.

Maximum load current on the primary side of each transformer is:

$$S = UI \rightarrow 800(kVA) = 10500 \times I \rightarrow I = 76.19\ (A)$$

The input current to the transformers in L1 and L3 is about 57 (A) and the current in L2 is 114 (A). In this case at PCC2 the currents from three phase busbar will not be symmetrical. The flowing current through the common phase (L2) is two times more than other phases.

Total harmonic distortion for current in L2 is 22.8% which gives 17.1% TDD (limitation is 8%) and separately has been studied here. The result for individual harmonics in L2 according to IEEE 519 is shown in table (19).

The ratio of short circuit power to the load current in L2 is:

$$\frac{I_{sk}}{I_L} = \frac{5.29 \times 1000}{114} = 46.4$$

The ratio of short circuit power to the load current in L1 and L3 is:

$$\frac{I_{sk}}{I_L} = \frac{5.29 \times 1000}{57} = 92.8$$

Total harmonic distortion for voltage is about zero. The result for Individual harmonics in L1 and L3 is shown in table (20). This table shows the harmonics when both cells are working. Distortion harmonics are compared with IEEE 519.

Table 19. Harmonics in L2 generated by heating elements group furnace 6

n	Frequency	I_n / I_1 (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	16	12	7
7	350	12.1	9.07	7
11	550	6.27	4.7	3.5
13	650	5.86	4.39	3.5
17	850	3.93	2.94	2.5
19	950	2.97	2.22	2.5
23	1150	2.38	1.78	1
25	1250	1.82	1.36	1
29	1450	1.44	1	1
31	1550	1.38	1	1
35	1750	1.05	0.78	0.5
37	1850	1.03	0.77	0.5
41	2050	0.86	0.64	0.5
43	2150	0.71	0.53	0.5
47	2350	0.64	0.48	0.5
49	2450	0.52	0.39	0.5

Table 20. Harmonics in L1 and L3 generated by heating elements group furnace 6

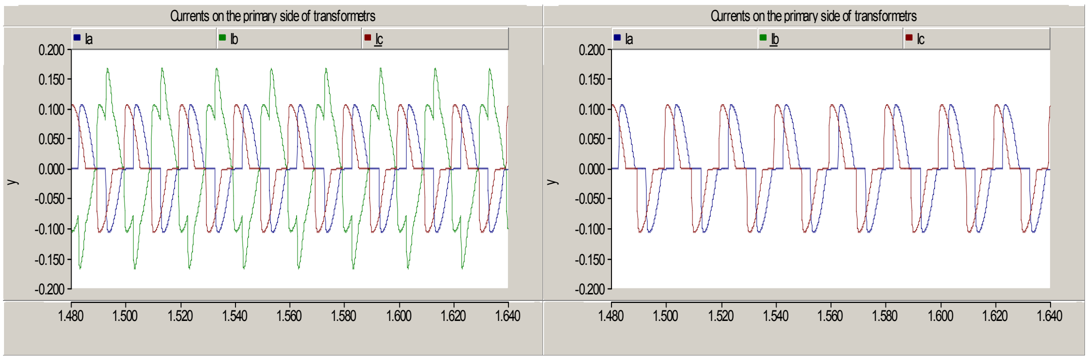
n	Frequency	I_n / I_1 (%)	I_n /$I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0
5	250	15.96	11.97	10
7	350	12.11	9.08	10
11	550	6.15	4.61	4.5
13	650	5.84	4.38	4.5
17	850	3.83	2.87	4
19	950	2.93	2.19	4
23	1150	2.31	1.73	1.5
25	1250	1.78	1.33	1.5
29	1450	1.39	1	1.5
31	1550	1.35	1	1.5
35	1750	1	0.75	0.7
37	1850	1	0.75	0.7
41	2050	0.82	0.61	0.7
43	2150	0.69	0.51	0.7
47	2350	0.62	0.46	0.7
49	2450	0.52	0.39	0.7

Table (21) shows the third multiple current harmonics and the standard limitations value according to IEEE 519.

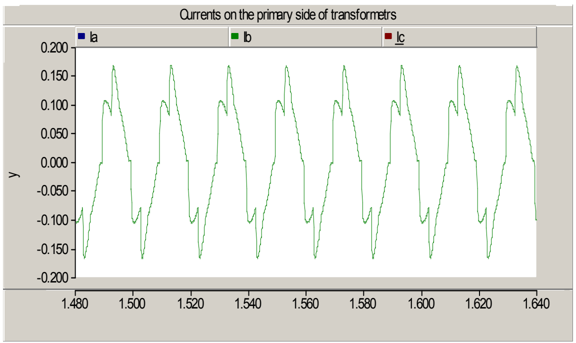
Table (21): Third multiple harmonics in L1and L3 generated by heating elements group furnace 6

n	Frequency	I_n / I_1 (%)	I_n /$I_{L(max)}$ (%)	IEEE limitation
3	150	42.5	31.8	10
9	450	9.14	6.8	10
15	750	3.94	2.9	4.5
21	1050	2.55	1.91	4
27	1350	1.8	1.35	1.5
33	1650	1.18	0.88	1.5
39	1950	0.8	0.6	0.7
45	2250	0.65	0.48	0.7

For more clarity the input currents to the transformers before filtering condition are illustrated in figure (29). Figure (30) shows the voltages on the secondary side of transformers in the phases which thyristors are located and voltages in the phases which are directly connected to the loads.



a) b)



c)

Figure (29): The currents on the primary side of transformers before filtering
a) Three phases b) Two divided phases (L1 and L3) c) The common phase (L2)

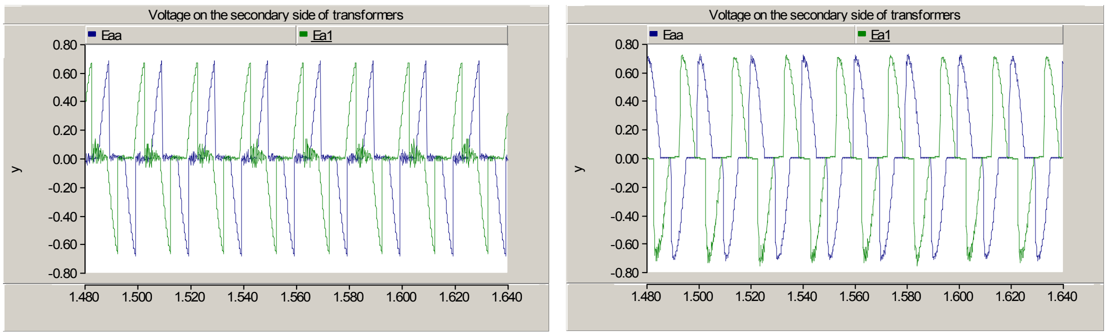


Figure 30. The voltages on the secondary side of transformers
a) Voltages in thyristor control phases b) Voltages in direct load connected phases

Improvement of harmonic performance in heating elements group furnace 6:

Harmonic performance for this group furnace is so critical, the lack of delta connection in transformer or ground connection results third multiple harmonics at PCC2. Here, by means of series RLC tuned filters for 3th , 5th ,7th harmonics and high pass filter by 550 (Hz) cutoff frequency, the amount of individual harmonics and total harmonic distortion for current will be reduced under the standard limitations. The quality factor for series RLC tuned filters is 100 and for high pass filter a value of 20 is considered.

Table 22. Harmonics in L2 generated by heating elements group furnace 6 after filtering

n	Frequency	I_n / I_1 (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0.0
5	250	8.65	6.48	7
7	350	2.14	1.6	7
11	550	0.5	0.375	3.5
13	650	1.01	0.75	3.5
17	850	1.19	0.89	2.5
19	950	1.1	0.82	2.5
23	1150	1.02	0.76	1
25	1250	0.87	0.65	1
29	1450	0.78	0.58	1
31	1550	0.72	0.54	1
35	1750	0.63	0.47	0.5
37	1850	0.59	0.44	0.5
41	2050	0.54	0.4	0.5
43	2150	0.47	0.35	0.5
47	2350	0.44	0.33	0.5
49	2450	0.37	0.27	0.5

Total harmonic distortion for current is 9.41% which gives 7% TDD (<8%) in L2 after harmonic filters application.

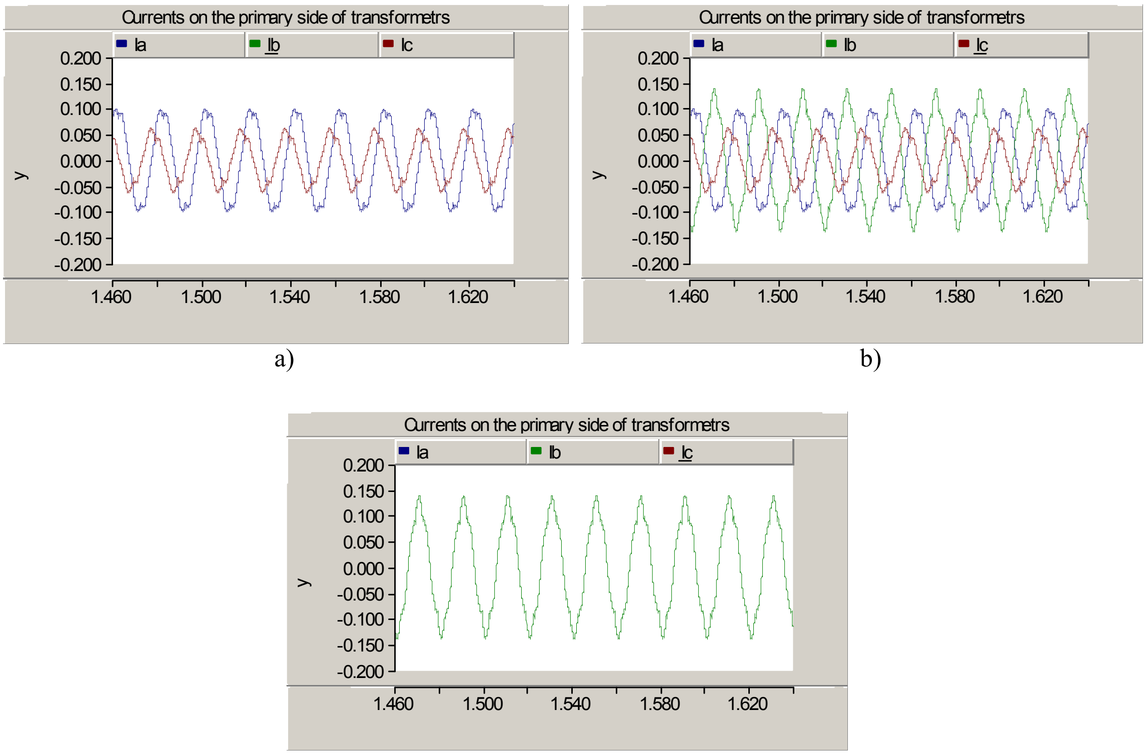
Table 23. Harmonics in L1 and L3 generated by heating elements group furnace 6 after filtering

n	Frequency	I_n / I_1 (%)	$I_n / I_{L(max)}$ (%)	IEEE limitation
1	50	100	100	0
5	250	5.93	4.44	10
7	350	1.33	0.99	10
11	550	0.25	0.18	4.5
13	650	0.59	0.44	4.5
17	850	0.72	0.54	4
19	950	0.68	0.51	4
23	1150	0.63	0.47	1.5
25	1250	0.54	0.4	1.5
29	1450	0.48	0.36	1.5
31	1550	0.44	0.33	1.5
35	1750	0.38	0.285	0.7
37	1850	0.37	0.27	0.7
41	2050	0.32	0.24	0.7
43	2150	0.29	0.21	0.7
47	2350	0.27	0.2	0.7
49	2450	0.23	0.17	0.7

Table 24. Third multiple harmonics in L1 and L3 generated by heating elements group furnace 6 after filtering

n	Frequency	I_n / I_1 (%)	I_n /$I_{L(max)}$ (%)	IEEE limitation
3	150	4.6	3.45	10
9	450	0.83	0.62	10
15	750	0.35	0.26	4.5
21	1050	0.35	0.26	4
27	1350	0.31	0.23	1.5
33	1650	0.25	0.18	1.5
39	1950	0.19	0.14	0.7
45	2250	0.15	0.11	0.7

Total harmonic distortion for current in L1 and L3 is 7.92% after harmonic filters applications which gives 5.94% TDD (<12%). The input currents to the transformers after filtering are illustrated in figure (31).



a) b)

c)

Figure (31): The currents on the primary side of transformers after filtering
a) Three phases b) Two divided phases (L1 and L3) c) The common phase (L2)

As stated above group furnace 6 have significant weight of distortion harmonics and the elimination or reduction of these harmonics is so crucial. In order to approach the harmonics level under the standard limitations, several numbers of passive filters are applied but the solution is not reasonable yet. The applied harmonic filters in this case will generate 3 (MVAr) reactive power and this amount of reactive power indicates the huge capacitance of filter capacitors. Then on the point of economical view this solution is not proper at all.

Since this group furnace is constructed in several decades ago, the substitution of new construction of furnace will lead to the appropriate solution. In group furnace 1 and 2 a proper construction of heating elements furnaces are presented.

Chapter 5

Power factor evaluations

According to the Company's contract with Mälarenergi, the company doesn't pay any reactive power charge on its electricity bill since the consumed reactive power is not exceed 50% of total applied active power. Then the minimum contracted power factor can be calculated as bellow:

$$Q_{cont} = 50\% \times P_{used}$$

$$\tan^{-1} \varphi = \frac{Q_{cont}}{P_{used}} \rightarrow \tan^{-1} \varphi = 50\% \rightarrow \varphi = 26.56^{o}$$

Then the minimum contracted power factor is:

$$PF = \cos \varphi = \cos 26.56^{o} = 0.894$$

5.1 Power factor evaluations in headquarter Company

Headquarter Company is located in Hallstahammar. Here, for more clarity the overview of busbars connection is taken into consideration.

5.1.1 DPF calculations

Power flow and calculated DPF at headquarter Company in Hallstahammar is illustrated in figure (32). This figure is basically illustrated by the consultant Company Harmonizer. Active power and reactive power have been measured by Harmonizer from May 2006 to September 2006 and the average results of the measurements are considered in figure (32).

Measuring of the power and harmonics in MV and HV are so costly and there are usually some economical deliberations for applying it by the Companies.

Calculation of DPF:

KA30:

$$\varphi = \tan^{-1} \frac{Q}{P} \rightarrow \varphi = \tan^{-1} \frac{648}{959} \rightarrow \varphi = 34.04^{o}$$

$$DPF = \cos 34.04^{o} = 0.8285$$

KA21:

$$\varphi = \tan^{-1} \frac{1138}{2888} \rightarrow \varphi = 21.5^{o}$$

$$DPF = \cos 21.5^{o} = 0.93$$

KA22:

$$\varphi = \tan^{-1}\frac{1533}{2460} \rightarrow \varphi = 31.92^{o}$$

$$\mathrm{DPF} = \cos 31.92^{o} = 0.8486$$

KA1:

$$\varphi = \tan^{-1}\frac{858.67}{3432.1} \rightarrow \varphi = 14.04^{o}$$

$$\mathrm{DPF} = \cos 14.04^{o} = 0.97$$

Input busbar from Mälarenergi:

$$\varphi = \tan^{-1}\frac{4180.7}{9742.09} \rightarrow \varphi = 23.22^{o}$$

$$\mathrm{DPF} = \cos 23.22^{o} = 0.9189$$

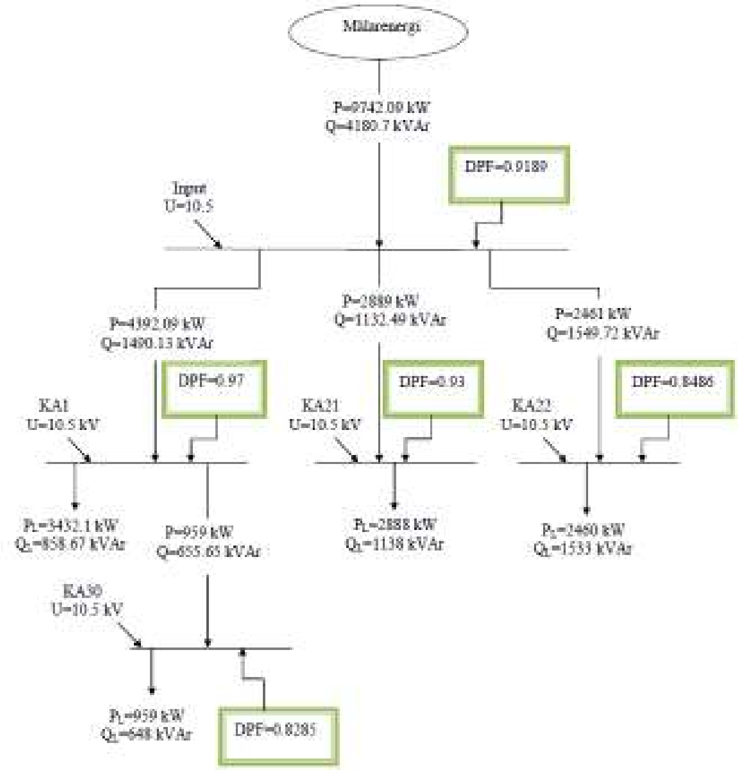


Figure 32. Overview of power flow and DPF at headquarter company

5.1.2 PF calculations

As stated before by assuming that the voltage harmonic distortion is zero, total harmonic distortion for current (THD_i) can be achieved. According to equation (23) THD_i reduces power factor. In figure (33) total harmonic distortion for current and related power factor at headquarter Company is illustrated.

Calculations of PF:

KA30:

$$\mathrm{PF} = \mathrm{DPF}.\frac{1}{\sqrt{1+\mathrm{THD}_i^2}} \rightarrow \ \mathrm{PF} = 0.8285 \times \frac{1}{\sqrt{1+2.51\%^2}} \rightarrow \mathrm{PF} = 0.8282$$

KA21:

$$\mathrm{PF} = 0.93 \times \frac{1}{\sqrt{1+20.63\%^2}} \rightarrow \mathrm{PF} = 0.9108$$

KA22:

$$\mathrm{PF} = 0.8486 \times \frac{1}{\sqrt{1+10.15\%^2}} \rightarrow \mathrm{PF} = 0.8442$$

KA1:

$$\mathrm{PF} = 0.97 \times \frac{1}{\sqrt{1+23.45\%^2}} \rightarrow \mathrm{PF} = 0.9443$$

Input from Mälarenergi:

$$\mathrm{PF} = 0.9189 \times \frac{1}{\sqrt{1+3.01\%^2}} \rightarrow \mathrm{PF} = 0.9184$$

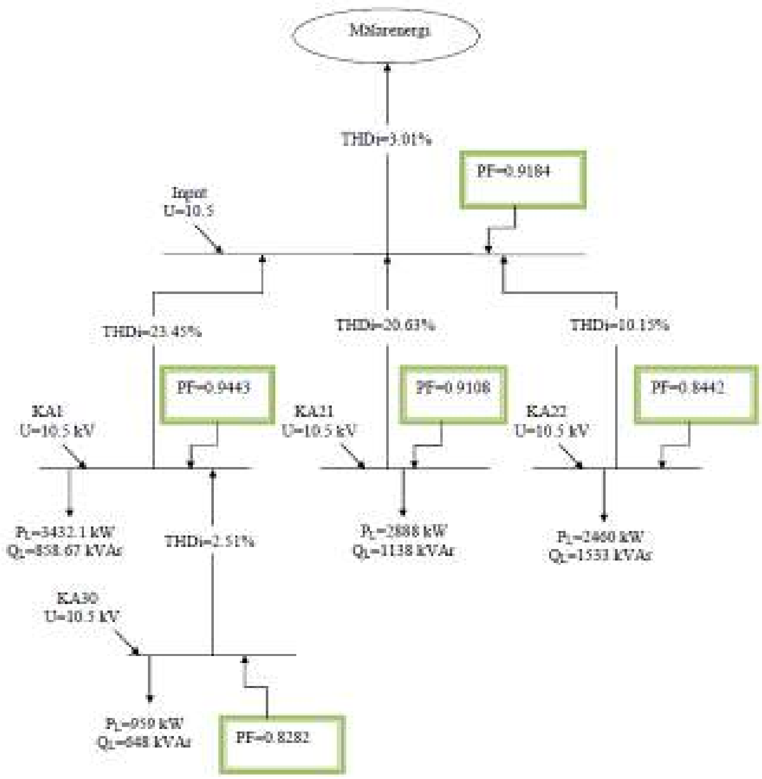


Figure 33. Overview of PF and THD_i at headquarter company

5.1.3 Some considerations

During the study of illustrated power flow by Harmonizer, some inaccuracies were found as bellow:

a) In figure (32) three transformer feed headquarter Company with common busbar connection. But busbar KA1 is separately fed by a transformer (T101). This busbar is studied in this master thesis and is illustrated in figure (15).

b) By means of switch gears, busbar KA30 can be fed by KA1 and KA2 but in normal operation KA30 is fed by KA21.

c) Busbar VV1 which is not shown in figure (32) has own feeder but in these figure it seems, busbar KA22 and VV1 has been taken as unity busbar.

Then the power flow will have small changes. The next consideration is the Company pays individually for two points in headquarter Company the first for the feeder transformer from Mälarenergi to KA1 (T101) and the second for two other incoming feeders from Mälarenergi. This payment is contracted between the Company and Mälarenergi. A simplified overview of the electricity connection in the headquarter Company is illustrated in figure (34).

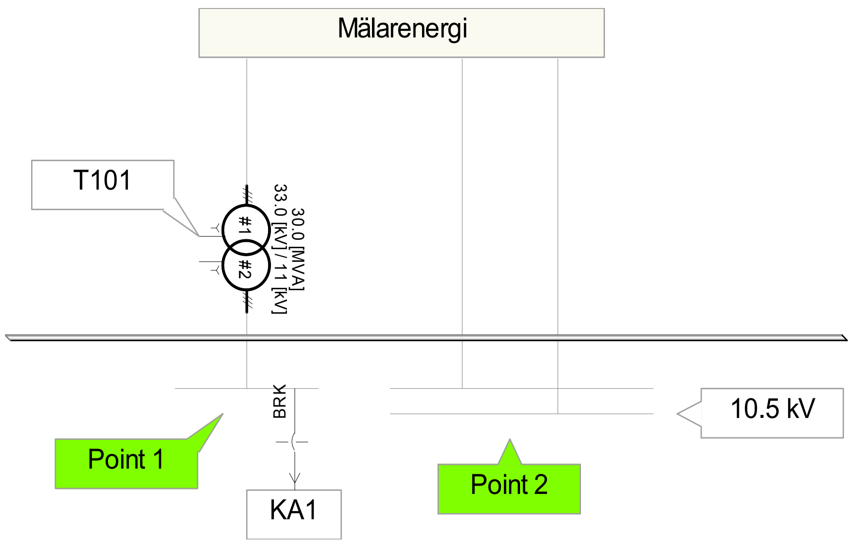


Figure 34. Overview of incoming electricity power to headquarter Company from Mälarenergi

Since the Company doesn't pay any reactive power charge on its electricity bills, no improvements of existing compensation capacitors are required.

5.2 DPF calculations at Bruket

Determination of PF at different points of Bruket required previous or actual measurements of THD_i and power flow in this division. But DPF can be calculated from the Company's electricity bills. Table (25) shows the consumed active and reactive power during three month in the division.

The calculations of DPF for three month are as follows:

$$\mathrm{DPF} = \cos(\tan^{-1}\frac{\mathrm{Q}}{\mathrm{P}}) = \cos\left(\tan^{-1}\frac{1596}{3432}\right) = 0.906$$

$$\mathrm{DPF} = \cos(\tan^{-1}\frac{\mathrm{Q}}{\mathrm{P}}) = \cos\left(\tan^{-1}\frac{1632}{3420}\right) = 0.902$$

$$\mathrm{DPF} = \cos(\tan^{-1}\frac{\mathrm{Q}}{\mathrm{P}}) = \cos\left(\tan^{-1}\frac{1608}{3396}\right) = 0.903$$

Table 25. DPF at division of Bruket

month	Reactive power (kVAr)	Active power (kW)	DPF
1	1596	3432	0.906
2	1632	3420	0.902
3	1608	3396	0.903

However, according to the Company's electricity bills DPF is above than contracted amount (PF=0.894) and no corrections of power factor are needed.

Chapter 6

Conclusion and future work

6.1 Conclusion

According to this study as it was expected passive filters are able to reduce distortion harmonics under the standard limitations but some points should be taken into considerations. The first point is by using the passive harmonic filters for one or some distortion harmonics the quantity of targeted harmonics will be reduced but it can cause increasing the other harmonic components. This phenomenon indicates to have open eyes on the other harmonic components in order to optimize the efficiency of harmonic filters applications. The second consideration is to determine the amount of filters capacitors related to the expected level of power factor and have an economical sight for solving the problems. This study shows the impedances of transformers at PCC and the system short circuit power have a significant role for harmonic evaluations and eliminations or harmonic distortion reduction processes.

The main construction of industrial appliances for example the use of three winding transformers and updated drive systems can reduce the harmonics level properly. In some cases because of the lack of applying the proper construction for industrial appliances, the large numbers of passive harmonic filters are needed which results to the more complicated and costly solutions. Here, on the point of economical view the improvements will not be proper by means of passive harmonic filters applications. Then structural amendments of drive systems by using the proper and updated supply units or the fundamentally changes of construction are needed.

The company doesn’t have any large impact on the grid but it doesn’t mean the intern distortion harmonics have been satisfied the standard limitations.

6.2 Future work

Some works and investigations can be done in the future at the Company. The measurements of power flow and total harmonic distortion for current at division of Bruket for further study of power factor level at different point of the division like the measurements and studies which were done in headquarter Company. There are numbers of industrial furnaces and other electrical appliances in the Company which can be investigated in the future. Other aspects of power quality such as transients over voltages or voltage dips can be studied and investigated in the Company in order to increase the quality and efficiency of electricity power.

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