Economic Analysis of distribution transformers under harmonic distortion

Bachelor of Science Thesis in Electric Power Engineering

BEREKET GEBREMESKEL

Department of Energy and Environment
Division of Electric power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010

THESIS FOR THE DEGREE OF BACHELOR OF SCIENCE

Bereket Gebremeskel

Economic Analysis of distribution transformers under harmonic distortion

Supervisor: Eva Palmberg
Radio and Space Science
Chalmers University of Technology

Examiner: Prof. Torbjörn Thiringer
Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2009

Abstract

This thesis's aim is to investigate how much of total transformer losses in the distribution system of Sweden is due to harmonic losses, in comparison to the remaining other losses.

Use of non-linear loads in power systems is increasing, and this has become a power quality problem for both electric companies and customers. Non-linear load not only increase the distribution transformer operational costs, it causes an increase in losses as well also create additional heating in power system components.

Hence, this thesis will cover the basic losses in distribution transformers mainly due to non-linear loads, cost analysis of the total transformer losses and lastly the savings that can be gained respectively. One way to increase the efficiency is to change the transformer to low-loss transformers. Operating losses are less, causing less heat generation and increasing life-time. In conventional loss-analysis, harmonic distortion is not taken into consideration; even though it is of consequence in applications where high harmonic power is observed.

There are a number of ways to decreasing transformer harmonics. In this thesis, an analysis has been conducted relating transformer efficiency to its load; as well as concluding an energy saving of 1.52TWh per year by replacing old equipment sensitive to non-linear loads with better transformers. The calculation and the interview show that the average transformer losses due to harmonics in distribution transformers is lower than 4%.

Acknowledgments

I would like to thank my supervisor Prof. Torbjörn Thiringer and Eva Palmberg for all the support and comments during this thesis. I'd also want to thank Russom Kebedom at Unipower and Sture Englund at Alingsås Energy for contributing with measurements of their distribution transformer. At the same time I would to thank all of the staff at the Alingsås Energy for taking their time to aid me, as well as Göteborg Energi for letting me interview them.

Finally, I would like to thank Arash Ghazinouri and Ragnar Berglund for their invaluable help during this thesis work.

Table of Contents

Chapter 1

Introduction

This chapter will give the background to this project and present the purpose and goals. It will also give the delimitations of the thesis and an outline to this report.

1.1 Background

Distribution transformers are used to deliver electric power as part of an electrical distribution system. From power plants electrical energy is delivered to consumers by transmission and distribution systems. Every year about 150TWh electrical energy is generated from power plants, and 93% of this energy is distributed to the end users. The rest (11TWh) will be lost in the system; out of these losses about 4TWh, or approximately 2000MSEK/year, is dissipated as a loss in the distribution system annually[1][17]. The remaining 7TWh is lost in the transmission (400 kV) and sub-transmission (40-130 kV) net.

The most common type of distribution transformer coupling for low voltage distribution 10/0.4 kV is the Delta-wye. Distribution transformers are designed to operate at frequencies of 50 Hz, but there are loads which also produce currents and voltages with frequency that are integer multiples of the 50 Hz fundamental frequency; this type of distortion is called *harmonics distortion*. Harmonics' effect on transformers leads to increased losses and heating as well as affecting the lifetime of the transformers.

Transformer efficiency has improved steadily since 1960 with the introduction of improved materials and manufacturing methods. Many distribution transformers are generally from 1950 and 1960 and these transformers are oversized and made of conventional material [15]. These are sensitive to non-linear loads. The use of non-linear loads in distribution system is growing and there is a possibility that they increase to 100%. This growth will demand a greater insight into their influence on losses.

1.2 Problem statement

Harmonics distortion has a negative effect on transformer efficiency, in addition to other losses. The loss in a distribution transformer has effect on the price of electricity as well as system losses. The effect on losses has been studied in terms of cost with respect to linear and nonlinear loads.

According to the previous study on Elforsk [1], about 93-95% of the energy generated reaches the end consumer and the rest, 5-7% of the energy, is dissipated as losses in the distribution system. The overall efficiency of the transformer can be affected by high levels of harmonic distortion due to the load. The estimated losses in a distribution system are results of the high voltage cables, low voltage cables, and transformers. From previous studies on losses, 10% of the losses occur in the 10kV high voltage cable, 60% occur in 10/0.4 kV distribution transformer and 30% in 400V low voltage cables.

1.3 Purpose

The purpose of this study is to estimate how much of this 60% losses are due to harmonics effects in distribution transformers and investigating how much can be saved by changing the oversized and high-loss distribution transformers. An economical analysis of the harmonics and losses in transformer is deduced using Total Life Cycle Cost (LCC) and Total Cost of Loss (TCL) evaluations. In addition to this, different materials reducing harmonic distortion are compared.

1.4 Scope and limitation of the study

This thesis covers harmonics distortion on transformers with power ratings 500kVA, 800kVA and 1000kVA, since these are the most common in the distribution system in Sweden. The three different types of transformers analyzed are the existing transformers as well as the newer amorphous metal and silicon-steel transformer. The calculations are carried out on a few selected transformers, and it is not possible to create a general picture of the how old transformers affect the distribution losses. The measurements carried out were used to determine transformer sensitivity to linear and non-linear loads and thus determining the efficiency and the energy which would be saved after an update of the system.

1.5 Methodology

Transformer losses and cost analysis were mainly performed through calculations based on measurements and interviews regarding harmonic distortion. From these, energy- and cost-savings were deduced, in case of replacing transformers with newer ones. A theoretical understanding on harmonics distortion can be helpful in developing suitable analysis for identifying the harmonics content within the total transformer losses.

Chapter 2

Theoretical

This chapter was designed to give the reader a detail insight concept on transformer losses due to harmonics, and cost analysis which has been made theoretically.

2.1 Harmonics phenomenon

The presence of harmonics phenomenon was characterized in beginning of 1800^{th} by a famous mathematician Jean Baptiste Joseph Fourier. Harmonics are multiples of the fundamental frequency which is 50Hz for European and many Asian countries and 60Hz in for instance USA, Canada and other neighboring countries . Harmonics occur mainly due to loads with non-linear characteristics. This results in distorting the applied line current or voltage of the system. The higher order harmonics can be filtered out; the lower order harmonic are usually present and these harmonics have a notable impact on transformers especially when the transformers are under load condition. The total harmonic content THD (Total Harmonic Distortion), of the current or voltage can be calculated as can be seen from eq1and 2.

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

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

where, u_n represents the voltage harmonics and I_n the current harmonic contents of the system. According to Swedish Standard EN 50160,[2], the total harmonic distortion should be maximum 8%, which must be said to be a very high value.

2.1.2 Effect of power system harmonics on transformers

Transformer losses are classified into load and no-load losses. No-load losses are those losses in a transformer whenever the transformer is energized. No-load losses include, eddy current losses, magnetic hysteresis, winding resistance to exciting current, and the losses of dielectric materials. Load losses are those losses that exist with the loading of transformers. Load losses vary with the square of the load current and the dc resistance in the windings(I^2R losses),core clamps, the loss due to leakage fluxes in the windings, parallel winding strands and other parts. For distribution transformers, the major source of load losses is the I^2R losses in the windings[3].

2.1.3 Effect of harmonics on no-load losses

According to Faraday’s law the terminal voltage determines the transformer flux level.

$$N\frac{d\phi}{dt} = u(t) \tag{3}$$

Transferring this equation into the frequency domain shows the relation between the voltage harmonics and the flux components.

$$Nj(hw) \times \phi_h = u_h \qquad \text{h=1,3,…} \qquad \text{j= Square root of (-1)} \tag{4}$$

This equation shows that the flux magnitude is proportional to the voltage harmonic and proportional to the harmonic order h [4]. Harmonics affect no-load losses only in relation to voltage distortion and are affected only marginally by voltage harmonic distortion and therefore can be neglected when determining the effect of harmonics on no-load losses. Therefore neglecting the effect of harmonic voltage and considering the no load losses caused by the fundamental voltage component will only give rise to an insignificant error. This is confirmed by measurements[4].

2.1.4 Effect of harmonics on load losses

In most power systems, current harmonics are of significance. Higher frequency components in the load current cause losses because harmonics do not fully penetrate the conductor. They travel on the outer edge of the conductor; this is called skin effect. When skin effect occurs, the effective cross sectional area of the conductor decreases; increasing the resistance and the I^2R losses. This in turn heats up the conductors slightly extra as well as objects in their vicinity. The I^2R losses are affected by harmonics if the rms value of the load current increases due to the harmonic components; then these losses will increase with square of the current[4][7].

$$P_\Omega = R_{dc} \times \sum_{h=1}^{h_{max}} I_{hrms}^2 \tag{5}$$

where: R_{dc}=dc resistance (ohms)

I_h=rms current at harmonic “h” (amperes)

Harmonic currents increase also the eddy current losses in transformers; these increase approximately with the square of the frequency. For linear loads eddy currents are a fairly small component of the overall load losses (approx. 5%). With non-linear loads however, they become a more significant component, sometimes increasing as much as by 15x to 20x. With the eddy current losses known, the eddy current losses due to any non-sinusoidal load current can be calculated[4][7][8].

$$P_{EC} = P_{EC-R} \quad \sum_{h=1}^{h_{max}} h^2 \left(\frac{I_h}{I_R}\right)^2 \tag{6}$$

where: P_{EC}=winding eddy current

P_{EC-R}= Winding eddy-current loss under rated conditions (per unit of rated load I^2R loss)

I_R= rms sine wave current under rated frequency and load conditions (amperes)

h = Harmonic order

The harmonic loss factor for winding eddy current is derived as:

$$F_{HL} = \frac{\sum_{h=1}^{h_{max}} h^2 \left(\frac{I_h}{I_R}\right)^2}{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_R}\right)^2} \tag{7}$$

Therefore under harmonics loads, eddy current losses in winding must be multiplied with the harmonic losses factor .

Harmonics also affect other stray losses due to stray flux. The other stray losses are assumed to vary with the square of the rms current and the harmonic frequency to the power of 0.8.

$$P_{osc} = P_{osc-R} \sum_{h=1}^{h_{max}} h^2 \left(\frac{I_h}{I_R}\right)^{0.8} \tag{8}$$

where: P_{osc}= Other stray loss (watts)

P_{osc-R}= Other stray loss under rated conditions (watts)

The harmonic losses factor for other stray losses is expressed in a similar form as for the winding eddy currents.

$$F_{HL-STR} = \frac{P_{osc}}{P_{osc-R}} = \frac{\sum_{h=1}^{h_{max}} h^{0.8} \left(\frac{I_h}{I_R}\right)^2}{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_R}\right)^2} \tag{9}$$

2.2 Transformer efficiency and losses

Transformer with high efficiency result in significant electricity savings. Transformer efficiency is basically the measure of how much power is transformed from the primary to the secondary side of the transformer[4][9].

$$\eta = \frac{x \times kVA \ \times pf \times 1000}{x \times kVA \times \ pf \times 1000 + noload\ losses + T \times load\ losses \times x\hat{}2} \tag{10}$$

Where x=per unit load relative to nameplate rating, kVA is the nameplate rating in kVA, pf ($\cos\varphi$) is the power factor. The power factor, defined as the ratio of the real power to the apparent power, varies as utility system load change. During high load conditions the power factor ranges from 0.90 to 0.97[18]. T is the load loss temperature correction factor to correct to a specified temperature; i.e. 75^0 C for dry type and 85^0C for oil-filled transformers.

Temperature correction factor[3] (T)= $\frac{Load\ losses\ at\ operating\ temperature}{Load\ losses\ at\ reference\ temperature}$ (11)

$$0.9 \times \frac{R_T - op}{R_T - ref} + 0.1 \times \frac{R_T - ref}{R_T - op}$$

If the operating temperature is 100^o C, $\frac{R_T - op}{R_T - ref} = \frac{234.5+100}{234.5+75} = 1.0808$ and the temperature Correction factor, T= $0.9 \times 1.0808 + \frac{0.1}{1.0808} = 1.0652$
F= temperature coefficient =234.5 for copper and 227 for Aluminum.

2.3 Total cost of the losses and Life cycle cost of distribution transformers

Several methods can be used to calculate the losses of distribution transformers. Total Cost of Losses (TCL) and Total Life Cycle Cost (LCC) are two of the methods used in determining the cost of transformer losses over its life. In purchasing transformers, it is necessary to take into consideration the investment cost and cost of losses.

The relationship of the total cost losses, cost of load and no-load losses from an economic perspective, any reliability criterion, and the resulting design should be based on the cost of providing extra reliability by changing one or more of the system parameters versus the benefits accruing to society from the additional reliability. The basic concept of reliability cost worth evaluation is portrayed graphically in figure2.1.

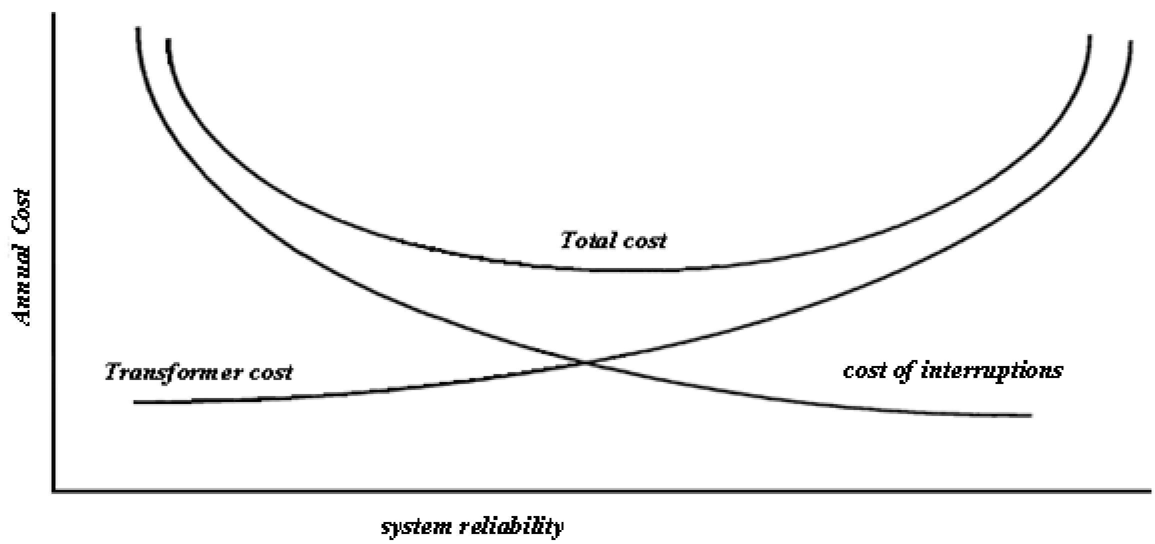

Figure 2.1 concept of reliability cost worth evolution

2.3.1 Total Cost of Losses (TCL)

TCL is the sum of total costs of losses associated with the costs of load and no-load losses. The total cost of losses (TCL) dissipated in a distribution transformer over its life span can be calculated using the following formula [9].

$$TCL_{loss} = E_{loss} \times C_e \times \frac{(1+r)^n - 1}{r \times (1+r)^n} \tag{12}$$

where:

r= the cost of capital
n= the life time of the transformer in years.
C_e = average cost per kWh (SEK/kWh)

Estimation of the total energy loss and can be calculate as:

$$E_{loss} = (P_{NLL} + P_{LL} \times \left(\frac{S_{max}}{S_{rT}}\right)^2) \times 8760 \tag{13}$$

where:

P_{NLL}= is the no-load loss in kW
P_{LL} = is the load loss in kW
$\left(\frac{S_{max}}{S_{rT}}\right)$ = is the average per-unit load on the transformer

2.3.2 Total Life-Cycle-Cost (LCC)

There are several methods used in calculating the purchasing decision of transformers. LCC is one of the most cost- and resource-efficient methods available for calculating the costs of transformers. LCC includes every non-value added activity, in reality just as a transformer purchaser seeks to optimize losses on its power system by purchasing cost effective and energy efficient transformer, manufacturers seek to optimize the losses in transformer design.
The purchase decision for distribution transformer is based on the most economical operation determined by the minimal relative cost per kWh, and on average is given as 5000 yearly full-load hours. However, in many instances transformers may not be operated as full load at all times. Mathematically, LCC can be calculated as follows[10][11].

$$LCC = C_{IV} + C_{P_{NLL}} + C_{P_{LL}} + C_{maintenance} \tag{14}$$

where:
C_{IV} = investment cost
$C_{P_{NLL}}$= cost of no-load losses
$C_{P_{LL}}$= cost of load losses
$C_{maintenance}$= the cost of maintenance per year (correspond to = 1000SEK/year)

$$C_{P_{NLL}} = \frac{(1+r)^n - 1}{r \times (1+r)^n} \times \left(C_p + C_e \times 8760\right) \times P_{NLL} \tag{15}$$

The utilization-time of the load losses (τ_f) can be calculated by the following relationship[7]

$$\varepsilon_f = k \times \varepsilon + (1-k)\varepsilon^2 \text{ and } \tau_f = 8760 \times \varepsilon_f \tag{16}$$

where ε is the utilization factor. Common values for τ_f in Sweden lie between 4000-6000 hours.

The cost of load losses can be calculated by

$$C_{P_{LL}} = \frac{(1+r)^n - 1}{r \times (1+r)^n} \times \left(C_p + C_e \times \tau_f\right) \left(\frac{S_{max}}{S_{rT}}\right)^2 \times P_{LL} \tag{17}$$

where:
C_p= average cost per kW year (SEK/kW year)
C_e= average cost per kWh (SEK/kWh)
$\frac{(1+r)^n-1}{r\times(1+r)^n}$ = called the capital recovery factor and tables for determining it are easily available in most standard engineering economy text and computer software.
S_{max} = yearly peak load
S_{rT} = rated power

Chapter 3

Empirical Data

In this section, the result of the calculations and the measurements will be presented. The current harmonics distortion at different loading is presented, calculations of the cost of different transformers, as well as measurements on transformers.

3.1 Harmonics analysis of electric power companies

In order to understand how harmonics affect different sectors of distribution transformer, like industrial and public distribution, the efficiency of the transformers has been studied. From the previous studies it is shown that the current THD lies between 5-200% and the voltage between 1-6%; this can be seen in table 3.1, from “Elforsk rapport 97:3”[12] and [13], where the values show how harmonics affect different distribution sectors. Harmonics distortion with THD_i= 10% correspond to approximately 10%-15% more losses.

Table 3.1: Showing harmonics affect different sectors.

	Public distribution	Industrial distribution	Medium voltage
Residence, low voltage	I_{THD}:5-30%		
Single larger customer, low voltage	I_{THD}:2-20%		
Single devices (converters)		I_{THD}:25-200%	
Totally for a low voltage transformer	I_{THD}:2-15%	I_{THD}:15-25%	
	U_{THD}:1-6%	U_{THD}:3-6%	
Single customer, medium voltage			I_{THD}: 2-20%
			U_{THD}: 1-5%

<u>Case study- 500kVA Transformer</u>

The transformer in the case study is loaded as shown in table 3.2. It has a rating of 500kVA and it shown how third and fifth harmonics affect the load loss. The objective here is to calculate the load loss.

Load losses harmonics are calculated according to equation (6) to show the losses when loaded with x. The eddy current losses are assumed to be 10% of the total and the copper losses assumed to be 90%.

$$P_{LL} = P_{LL-R} \times x^2[0.9 + 0.1 \times K_h] \quad (18)$$

where: P_{LL}=load losses

P_{LL-R}=load loss under rated conditions

K_h= harmonics factor

x= per unit load

$K_h=\sum_{h=1}^{h_{max}} \frac{I_h^2}{I_1^2} \times h^2$

If THD_i is given, it can be formulated as

$$THD_i = \sum_{h=3,5\ldots}^{h_{max}} \frac{I_h^2}{I_1^2} = \frac{I_3^2}{I_1^2} + \frac{I_5^2}{I_1^2} + \frac{I_7^2}{I_1^2} + \cdots$$

Next step is to assume all THD lie in third harmonics and thus can be calculated as

$$THD_i^2 = \frac{I_3^2}{I_1^2} \quad => \quad I_3^2 = THD_i^2 \times I_1^2 =>$$

$$K_h = 1 + 9 \times \frac{I_3^2}{I_1^2} = 1 + 9 \times THD_i^2$$

Secondly, we assume I_3 and I_5 are equal.

$$THD_i^2 = \frac{I_3^2}{I_1^2} + \frac{I_5^2}{I_1^2} = \frac{2I_3^2}{I_1^2} \quad => \quad I_3^2 = I_5^2 = \frac{1}{2} THD_i^2 \times I_1^2 =>$$

$$K_h = 1 + \frac{I_3^2}{I_1^2} \times 3^2 + \frac{I_5^2}{I_1^2} \times 5^2 = 1 + 34 \times \frac{I_3^2}{I_1^2} = 1 + 34 \times \frac{1}{2} \times THD_i^2$$

Thirdly, we assume all THD_i lie in the 5th harmonics

$$THD_i^2 = \frac{I_5^2}{I_1^2} \quad => \quad I_5^2 = THD_i^2 \times I_1^2 \quad =>$$

$$K_h = 1 + 25 \times \frac{I_5^2}{I_1^2} = 1 + 25 \times THD_i^2$$

The results of these calculations are shown below in table 3.3

Table 3.2 showing losses in the transformer without current THD P_{LL-R}= 6015 and 5100

Load %	***P_{NLL}***		***P_{LL}***		***Total***	***Total***	***Different***
10%	864	240	60.15	51	924.15	291	-633.14
20%	864	240	240.6	204	1104.6	480	-624.6
30%	864	240	541.35	459	1405.35	699	-706.35
50%	864	240	1503.75	1275	2367.75	1515	-852.75
70%	864	240	2947.35	2499	3811.35	2739	-1072.35

Table 3.3 showing losses in transformer with current THD=30%, third and fifth harmonics

Load %	***P_{LL}***		All THD lie in third harmonics		I_3 and I_5 assumed equal		All THD lie in fifth harmonics	
10%	60.15	51	65.02	55.13	69.35	58.80	73.68	62.48
20%	240.6	204	260.09	220.52	277.41	235.21	294.74	249.90
30%	541.35	459	585.20	496.18	624.18	529.23	663.15	562.28
50%	1503.75	1275	1625.60	1378.30	1733.80	1470.1	1842.10	1561.90
70%	2947.35	2499	3186.10	2701.40	3398.30	2881.3	3610.50	3061.30

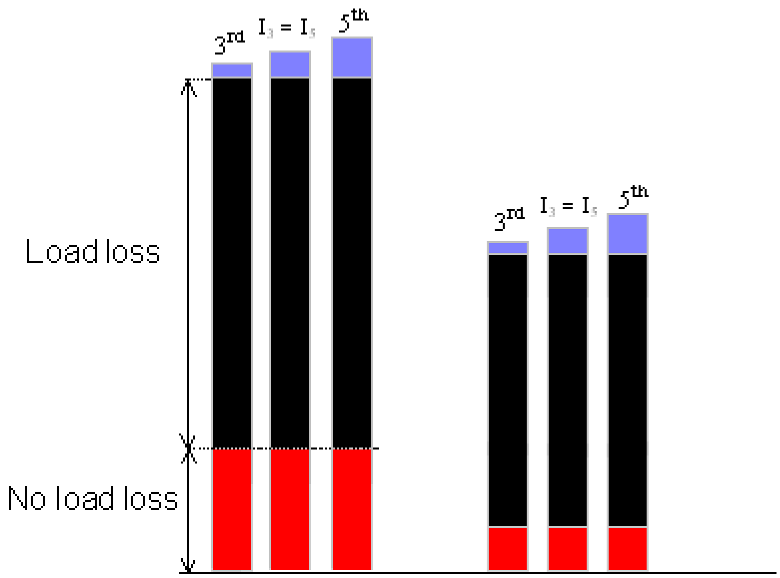

figure 3.1 showing losses in transformer with current THD=30% ,3rd, 5th and 3rd =5th

3.2 Transformer efficiency

Distribution transformer efficiency is steadily improved with losses of less than 0.2% in large units. According to the test report, most distribution transformers convert at least 98% of input power into usable output power. However, when the overall losses of the many transformation steps in a distribution system are considered, these losses can add up. Total transformer losses in percents of kVA load will be minimum when the no-load losses are equal to the load losses. The relationship between load level and efficiency can be seen from figure 3.2. The maximum efficiency is obtained with a loading of 40-70% of the rated apparent power. The figure 3.2 compares the efficiencies of two different transformers affected by linear and non-linear loading.

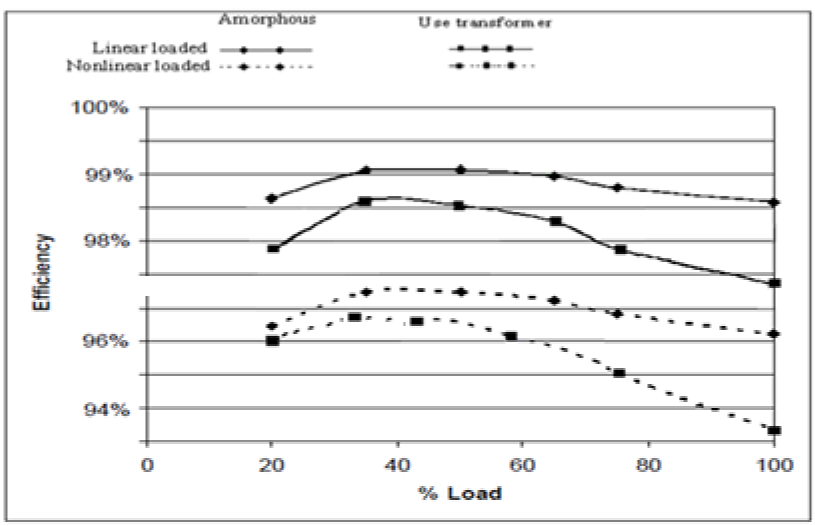

Figure 3.2 Energy efficiencies for various types of 500kVA transformers supplying linear loads and non-linear loads under varying conditions.

3.3 Cost analysis of dry-type and oil-filled transformer

The dry-type and oil-filled distribution transformer are compared based on the transformer investment and cost of the losses. For the expenses it is assumed that the total investment is done the first year, for an interest rate, and then paid back during the lifetime of the system. The parameters in the table 3.4 are used for the calculations. Losses in table 3.5 were calculated with and without current THD_i =30%.

Table3.4: Calculation of the factor A & B.

Oil-filled & dry	r	n (year)	ε_f	T	C_e (SEK/kWh)	A SEK/W	B SEK/W
1	0.08	25	0.5	8760	0.40	37.38	18.69
2	0.06	30	0.4	8760	0.50	60.29	24.11
3	0.04	35	0.2	8760	0.50	54.49	10.89

The average per-unit load (I) is the ratio between the maximum yearly peak load and the transformer rated power (0.85). The maximum demand charge per kWh the energy cost C_e is 0.5SEK/kWh.

$$A = \frac{(1+r)^n-1}{r\times(1+r)^n}\times\left(C_p + C_e\times 8760\right) = \frac{(1+0.06)^{30}-1}{0.06\times(1+0.06)^{30}}\times(0.5\times10^{-3}\times 8760)\text{=60.29SEK/W}$$

$C_{P_{NLL}}$ =60.290×1980= 119.4×10^3 SEK

$$B = \frac{(1+r)^n-1}{r\times(1+r)^n}\times\left(C_p + C_e\times\tau_f\right)\text{=}\frac{(1+0.06)^{30}-1}{0.06\times(1+0.06)^{30}}\times(0.5\times10^{-3}\times 0.4\times 8760\text{=24.1SEK/W}$$

$C_{P_{LL}}$= 24.110×7860×0.85^2=136.9×10^3 SEK

Table3.5: Cost comparison between dry and oil-filled transformer (1000kVA)

	Old transformer(1965)	Oil-filled	Dry
P_{NLL} (W)	1980	420	1800
P_{LL} (W)	7860	10300	8800
$C_{P_{NLL}}$ (k SEK)	119.4	25.3	108.5
$C_{P_{LL}}$ (k SEK)	136.9	179.42	153.3
$C_{P_{LL}}$ THD_i=30%.(3^{rd} or 5^{th})	147.90 (only 3^{rd}) 167.70 (5^{th})	193.95 (3^{rd}) 219.79 (5^{th})	165.72(3^{rd}) 187.79 (5^{th})

3.4 Energy saving by studying difference between transformers

These tables show that the new distribution transformer could reduce these energy losses, depending on the materials used and the loading pattern of the transformer. The typical size of distribution transformers in Sweden is 500kVA, 800kVA and 1000kVA. The industrial sector is a large energy user, covering nearly half of the electricity use annually. Although these enterprises obtain their electricity from the public medium and high voltage networks, much electricity is consumed at low voltage level, so the conversion to low voltage is performed by privately owned distribution transformers. In the Swedish distribution network there are 168000 [1] distribution transformers and their no-load losses can be decreased by changing to amorphous metal core and silicon steel core transformers. This can be seen as follows.

P_{NLL}=168000×600×8760=0.9TWh

Tables 3.6, 3.7 and 3.8 compare the existing transformer with amorphous metal and silicon-steel transformer. The values of efficiency for different transformers were calculated using eq. (11) and the energy saving, E_{saving}using eq.(18).

The power factor with an average value of 0.90, the average per unit load of the transformer (0.50) and the load loss temperature correction factor to correct to a specified temperature (T=1.065)

$$E_{saving} = \tau_f \times kVA \times pf \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{Amorphous}}\right) \tag{18}$$

$$4000×500×0.90\left(\frac{1}{0.9892} - \frac{1}{0.9929}\right)=6.8 \text{ MWh/year}$$

$$E_{saving} = \tau_f \times kVA \times pf \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{wound\ core}}\right)=4000×500×0.90\left(\frac{1}{0.9892} - \frac{1}{0.9911}\right)=3.5 \text{ MWh/year}$$

Table 3.6: Distribution transformer (500kVA) and 10/0.4 kV distribution transformer.

	Old transformer (A)	Amorphous Metal (B)	silicon-steel (wound core) (C)
Rated load loss	6015	5100	5100
Rated no- load loss	864	240	670
Efficiency	0.9892	0.9929	0.9911
		Compare (A-B)	Compare (A-C)
Energy saved (kWh / year)		6800	3500

$E_{saving} = \tau_f \times kVA \times pf \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{Amorphous}}\right)$= 4000×800×0.90$\left(\frac{1}{0.9898} - \frac{1}{0.9935}\right)$=10.8 MWh/year

$E_{saving} = \tau_f \times kVA \times pf \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{wound\ core}}\right)$=4000×800×0.90$\left(\frac{1}{0.9898} - \frac{1}{0.9918}\right)$=5.87 MWh/year

Table 3.7: Distribution transformer (800kVA) and 10/0.4 kV distribution transformer.

	Old transformer (A)	Amorphous Metal (B)	silicon-steel (wound core) (C)
Rated load loss	6950	7500	7500
Rated no- load loss	1850	350	980
Efficiency	0.9898	0.9935	0.9918
		Compare (A-B)	Compare (A-C)
Energy saved (kWh / year)		10800	58710

$E_{saving} = \tau_f \times kVA \times pf \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{Amorphous}}\right)$=
4000×1000×0.90$\left(\frac{1}{0.9866} - \frac{1}{0.9930}\right)$=23.5 MWh/year

$E_{saving} = \tau_f \times kVA \times pf \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{wound\ core}}\right)$=
4000×1000×0.90$\left(\frac{1}{0.9866} - \frac{1}{0.9914}\right)$=17.7 MWh/year

Table 3.8: Distribution transformer (1000kVA) and 10/0.4 kV distribution transformer.

	Old transformer (A)	Amorphous Metal (B)	silicon-steel (wound core) (C)
Rated no- load loss (W)	1800	440	1150
Rated load loss (W)	16200	10300	10300
Efficiency	0.9866	0.9930	0.9914
		Compare (A-B)	Compare (A-C)
Energy saved (kWh / year)		23500	17700

3.5 How harmonics affect industrial transformer

Figures 3.3-3.8 below illustrate the measurement from one of the distribution transformers owned by Öresundskraft and the effect of harmonics; to eliminate these an active filter is used.

Table 3.9: Distribution transformer (800kVA, 600kVA) and 22/0.42 kV distribution transformer.

	Öresundskraft (A)(800kVA) Dry-type	Amorphous Metal (B) (600kVA) Oil-filled	
Rated no- load loss (W)	1620	840	780
Rated load loss (W)	8988	6200	2788
E_{loss} (MWh/year)	71.34	46.59	24.75
TCL_{loss} (kSEK)	491.0	320.6	170.4
$C_{P_{NLL}}$ (SEK)	97671	50644	47027
$C_{P_{LL}}$ (SEK)	156.6×10^3	108.0×10^3	48600

$$E_{loss} = (P_{NLL} + P_{LL} \times I^2) \times 8760 = (1620 + 8988\times0.85^2) \times 8760 = 71.34\times10^6 \text{Wh/year}$$

$$TCL_{loss} = E_{loss} \times C_e \times \frac{(1+r)^n-1}{r\times(1+r)^n} = 71.34\times10^6\times0.5\times10^{-3}\times\frac{(1+0.06)^{30}-1}{0.06\times(1+0.06)^{30}} = 491\times10^3 \text{SEK}$$

$$C_{P_{NLL}} = 1620\times\frac{(1+0.06)^{30}-1}{0.06\times(1+0.06)^{30}}\times(0.5\times10^{-3}\times8760) = 97671 \text{ SEK}$$

$$C_{P_{LL}} = 8988 \times \frac{(1+0.06)^{30}-1}{0.06\times(1+0.06)^{30}}(0.5 \times 10^{-3} \times 0.4 \times 8760) \times 0.85^2 = 156.6\times10^3 \text{SEK}$$

Measurements on the transformer was done to see how the transformer meets the requirements mentioned with and without filter by the standard, EN 50160,[4]. The measurements include all voltage and current that is connected to frequency converters.

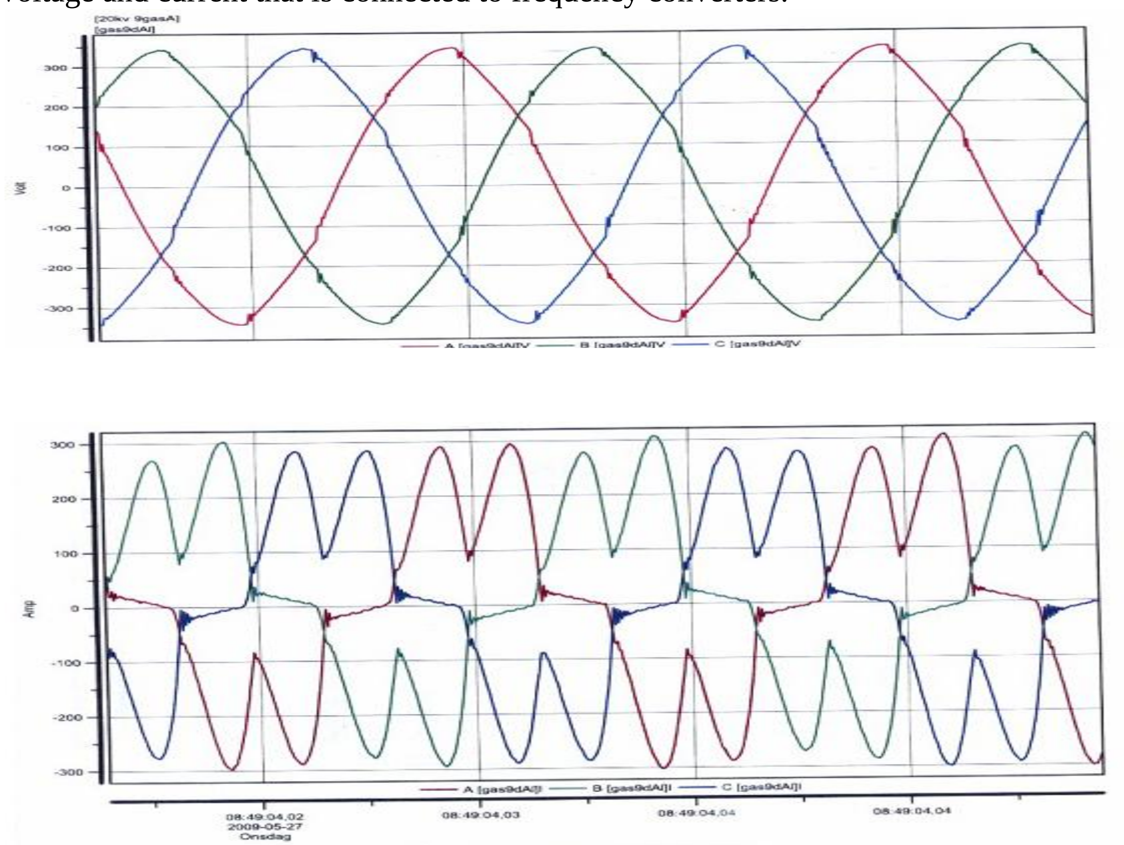

Figure 3.3&3.4: showing the voltage and current curve respectively without filtering. Without the filter connected the voltage THD is 6.68% while the current THD is around 66.95%.

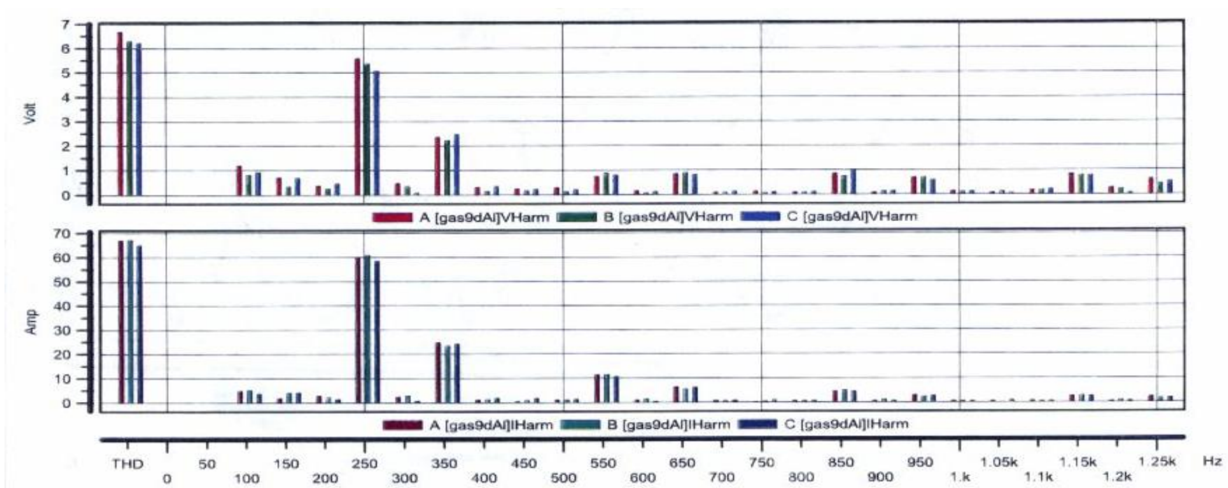

Fig. 3.5 Individual current and voltage harmonic distortion generated by a non-linear load with 50Hz on the transformer’s secondary side.

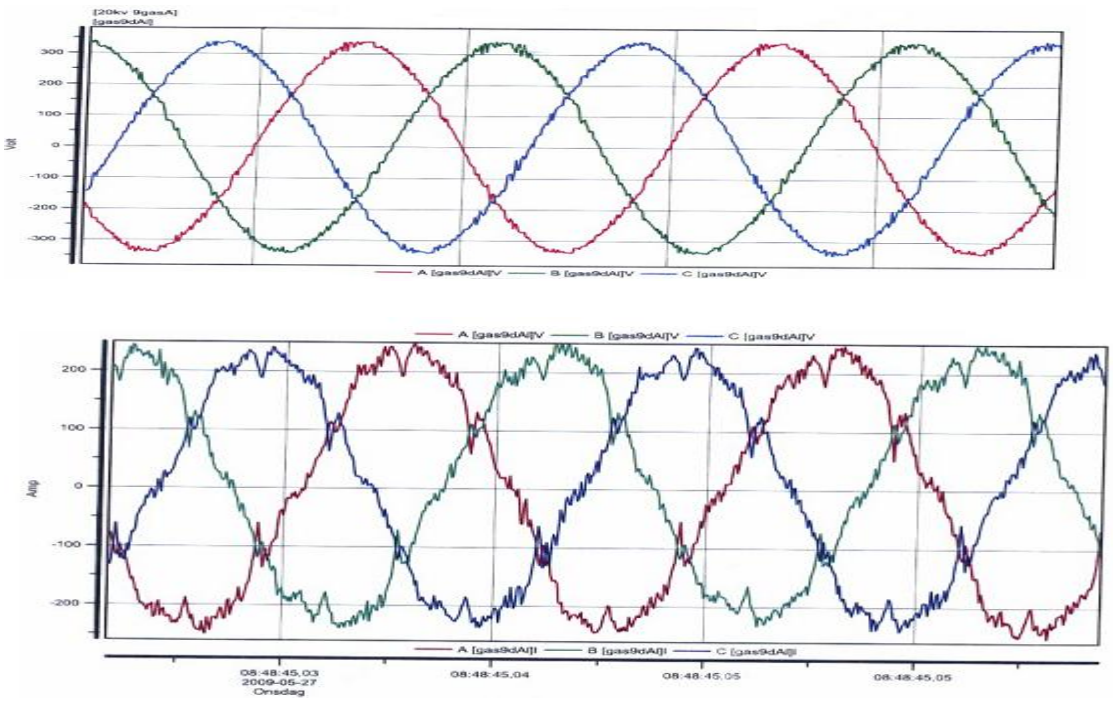

Figure 3.6&3.7: showing the voltage and current curve respectively with filtering.

With the filter connected the voltage distortion is 3.91% and the current distortion is around 16.19%.

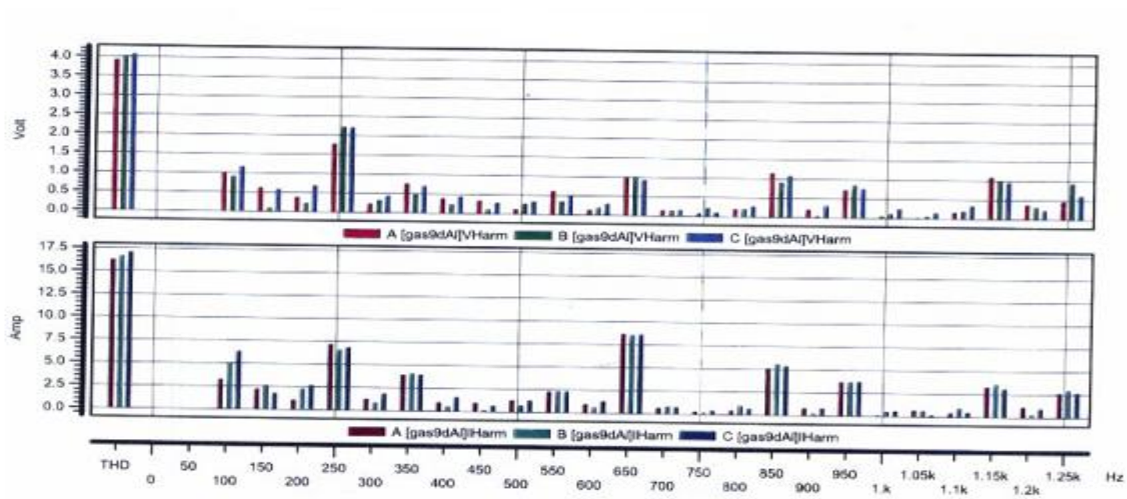

Fig. 3.8: Individual current and voltage harmonic distortion generated by a non-linear load with 50Hz on transformer secondary's side

Chapter 4

4.1 Result and Analysis

The influence of nonlinear load on the transformer has more effect under different loading conditions. Transformers have some optimal loading conditions; they have lower efficiency at low loading as well as overloading. This optimal loading is around 60% for the studied transformers. Moreover for non-linear loads the efficiency is lower compared to linear ones as shown in fig 3.2. In this study the annual load factor of public distribution transformer is assumed to 15%-40% and for industrial users 30-70%. The confidence intervals calculation, different research papers [13][15][16] and interview shows that the average transformer losses due to harmonics in distribution transformer are lower than 4%.

From the cases studying of the hospitals distribution transformer is the effect of harmonics is less. According to the measurement from one hospital shows that total harmonics distortion (THD_i) varies about 3-6% and the voltage THD_V variations are lower than 1-2%.

The *THD* with filter and without filter for the transformers studied are shown in table 4.1. The comparison in Table 4.1 shows that the harmonics decrease when a filter is used. We can also see that the cost varies with the loss.

Table 4.1: Showing losses in the transformer with and without filter

	THD_V	THD_i	Loss due to (THD_i)%
Without filter	6.68	66.95	1000-1500W
With filter	3.91	16.19	150-200W

The total harmonic distortion (THD) of the current is 66.95% and any load losses in the windings will be increased very significantly (by more than 66.95%). Thus the transformer would have to be de-rated to prevent overheating. The 800kVA transformer would only be able to supply 82% of its rated capacity, or 656kVA, before overheating if this harmonic content was supplied by the transformer.

4.2 The disadvantage of filter

Many studies show that using harmonic filters in general has less benefit to reduce harmonics losses and the investment cost was not paid back over the estimated lifetime. It is very important to consider this. Instead it is more beneficial to use more efficient transformers in terms of harmonics distortion.

4.3 Energy saving potential

This study shows that several parameters are important; distribution transformers are generally oversized and made of conventional material in order to provide reliability under future anticipated loads, longer life, lower load losses and with low no-load. By replacing 6-8% of the transformers by amorphous metal and silicon-steel transformers energy losses can be decreased by 0.8-1TWh/year. Amorphous metal core transformers have 75% less no-load loss compared to the older ones, while the corresponding reduction value for a silicon steel core transformer is 25%. The energy saving potential by application of energy-efficient transformers differs significantly from company to company. Amorphous metal and silicon-steel distribution transformer can save a substantial amount of energy.

4.4 Cost Of Losses

Transformer losses can be affected by the cost of design and construction of the transformer material. In the last two decades the transformer efficiency have been improved by reducing the transformer losses in the material and size of transformer. The load losses for many of the transformers are low and it is not recommended to replace an existing transformers with the amorphous transformers and /or silicon transformers if the transformer works properly.

The LCC of dry transformers is higher than the LCC of oil-immersed transformers. The no-load losses of a dry transformer are higher, due to their larger dimensions. Dry type of transformer has many advantages over the oil- filled transformers. The load losses of a dry transformer at full load is less compared to oil-filled transformers and dry type of transformers are more safe than oil- filled[17].

Harmonic distortion has less heating and ageing effect on the dry transformer than the oil-filled transformer[17]. However, due to epoxy the heat emission of the dry-transformer is less than the oil-_filled transformers. According to the result gained from the cost and loss analysis of dry and oil-immersed transformer, the purchase price and no-load loss of a dry transformer is relatively bigger than oil-filled.

4.5 Measurement from Öresundskraft

As shown in the previous section there are many evaluation methods used to determine the trade-off between cost of energy losses and initial capital costs in distribution transformer. Öresundskraft has low loading daytime and the economic lifetime is short; one could ask, why would you choose a 600kVA transformer with good efficiency instead of the 800kVA transformer. The loading of the 600kVA transformer will initially be 60%. Table 3.9 gives the calculation for the 800kVA and 600kVA transformers. Changing to a 600kVA transformer gives lowest price, low payback period, and high total life cycle. As the tables show the payback period for investing in amorphous metal and silicon-steel transformer is relatively short, certainly regarding their long life span of 30 years, and can even last longer than this.

Chapter 5

5.1 Conclusion

The aim of this thesis was to investigate how much of the losses in distribution transformers are due to harmonics effects and to investigate the amount that can be saved by changing the oversized and high-loss distribution transformers into more efficient ones. The economical analysis and the measurement, as well as the interview indicates that the average transformer-losses due to harmonics is lower than 4%. Reduction of the harmonic losses with harmonic filters is not worthwhile due to high financial costs for the filters. This is shown in Johan Lundquist's report [13]; as well as in Öresundkraft, where their transformer suffered from high harmonics effects, leading to a decision to apply a filter to decrease them. It was shown that the costs to cool the filter was higher than those gained. From several reports as well as calculations it is shown that losses can be decreased 1.52TWh per year by replacing the old transformers, which are in particular sensitive to non-linear loads, with higher-efficiency transformers.

6.1 Referenser

[1] Elforsk rapport Förluster I local nät. Utkast 2009

[2] Swedich standard SS-EN 50160, Voltage characteristics of electricity supplied by public distribution systems.

[3] Energy efficient transformers Barry W. Kennedy Kennedy, Barry W. 1998

[4] J. Driesen, R. Belmans, K. Hameyer, "Study of Eddy Currents in Transformer Windings caused by Non-Linear Rectifier Load," Proceedings EPNC 98 circuits, Sept. 98, Liege, Belgium, pp.114-117.

[5] A Girgis, E. Makram, J. Nims," Evaluation of temperature rise of distribution transformer in the presence of harmonic distortion," Electric Power Systems Research, vol. 20, no.1, Jan 1990, pp.15-22.

[6] A case study of Power quality improvement and energy saving in textile industry using solid state harmonic filter

[7] IEC 61378-1 Standard Publication: 1997, Transformers for Industrial applications.

[8] IEEE Std C57-110-2008, Recommended Practice for Establishing Transformer Capability when Supplying Non sinusoidal Load currents.

[9] Devki Energy Consultancy Pvt. Ltd., TRANSFORMERS Vadodara 2006

[10] Antonios E Vlastos, "Elanläggningsteknik del 1"

[11] Jurgen Schalbbach, Karl-Heinz Rofalski, " Power system engineering : planning, design, and operation of power systems and equipment,"

[12] Elforsk rapport 97:3, "Begränsning av övertoner i elnät inom tätort"

[13] Johan Lundquist," On Harmonic Distortion in Power Systems " Chalmers2001

[14] Oscar Niklasson "Measuring of harmonics distortions in the current at Preem Raffinaderi Grid, Göteborg"

[15] Leonardo Energy "The Potential for Global Energy Savings from High Efficiency Distribution Transformers" European copper Industry 2005

[16] http://www.energimarknadsinspektionen.se/upload/Rapporter/årsrapporter/EI_2007_webb.pdf

[17] Hans De Keulenaer "Energy Saving Opportunities for Transformers" Energy Efficient Motors & Transformers Workshop May 7, 2002

[18] Johan Fryxell "Reaktiv effekt i elkraftsystem" . Uppsala unviersitet, juni 2009

- Ragnar Berglund " Frequency dependence of transformer Losses" Chalmers 2009
- Thorborg Keld. Kraftelektronik. 1983, Minab/Gotab, Kungälv. ISBN 91-7031-095-0.
- The scope for energy saving in the EU through the use of energy-efficient electricity distribution transformers, European Copper Institute, December 1999.
- Corhodzic and A. Kalam "Assessment of distribution transformers using loss capitalization formulae's"
- Jian Zheng "Transformer ac winding resistance and derating when supplying harmonic-rich current"
- N.R Jayasinghe, J.R Lucas, K.B.I.M. Perera "Power System Harmonic Effects on Distribution Transformers and New Design Considerations for K Factor Transformers"
- I. Zamora1, I. Albizu2, A. J. Mazon, K. J. Sagastabeitia, E. Fernandez **"**Harmonic distortion in a steel plant with induction furnaces"

product specification

- http://www.tradeindia.com/Seller-1954785-2411723-1419 CATALOGS/Transformers.html
- http://www.cee1.org/ind/trnsfm/neep-rpt.pdf

Appendix I product specification

Product Specification

Wound Core Type Oil Immersed Distribution Transformer

This type of transformer adopts high-permeability cold-rolled Silicon-steel sheets as iron core. It is processed with big fill factor and there is no spacing inside the magnetic path. The HV and LV coils are continuously wound around the core with good concentricity and compact winding. The product is of very low consumption and slight noise pollution by combining new generation of technology, good performance and energy saving. It is widely used in power distribution systems.

Features

- The winding iron core is of big fill factor.
- The iron core is annealed.
- There is only one joint in iron core so that to decrease magnetic resistance and to lower down no-load current by 60~80%.
- The no-load capability is decreased by 20~30%.
- The magnetic conductance recovers to the original level before it is processed.
- The compact structure of core lower down noise pollution by 10dB.

Technical Specification

Capacity (kVA)	**Voltage Schedule**		**Vector Group**	**Consumption**		**Short Circuit Impedance (%)**	**No Load Current (%)**	**Outline Dimension mm (+-10%)**			**Weight kg (+-10%)**		**Gauging Distance (mm)**
	HV (kV)	**LV (kV)**		**No Load (W)**	**Load (W)**			**Length**	**Width**	**Height**	**Oil**	**Total**	
30				90	600		0.6	1020	600	1090	95	370	400x550
50				120	870		0.6	1050	620	1120	110	450	400x400
63				140	1040		0.57	1120	650	1150	120	520	550x550
80	6			175	1250		0.54	1160	670	1170	130	570	550x550
100	6.3			200	1500		0.48	1200	700	1210	150	640	550x550
125	11			235	1800		0.45	1250	730	1250	170	750	550x550
160	+-2		Y, d11	280	2200	4	0.39	1290	750	1300	200	860	550x550
200	x 2.5%	0.433	Y, yn0	335	2600		0.36	1330	780	1345	245	990	550x550
250				390	3050		0.33	1370	780	1410	270	1230	660x660
315				465	3650		0.3	1420	800	1470	290	1380	660x660
400				560	4300		0.3	1460	800	1530	320	1760	660x660
500				670	5100		0.27	1505	805	1590	350	1960	660x660
630	5%			840	6200		0.27	1590	850	1650	400	2400	660x660
800				980	7500		0.27	1655	935	1690	550	2530	820x820
1000				1150	10300	4.5	0.27	1755	1035	1750	630	2840	820x820

Note: Dimensions and weights etc. given above are just indicative. We reserve our right for constant improvement / modifications.

Product Specification

Amorphous Metal Distribution Transformer

The ferric core of Amorphous Metal Transformer is amorphous metal material, which is a new type of transformer. This ferric core features with saturate magnetic induction, small coercive force, and litter power loss, low magnetism - excitation current and stable temperature. This transformer is 20%~30% of no-load loss and 50% of no-load current as compared to those normal Silicon Steel based transformers. This is an effective and environmental friendly transformer with distinguished achievement on energy saving.

Features

- The ferric core applies three phase, four case and five post structure.
- The application of D,yn11 connecting series can reduce harmonic wave and improve the power supply.
- The oil tank of transformer applies sealed structure, it performs reliably and is free from maintenance.

Technical Specification

Capacity (kVA)	**Voltage HV (kV)**	**Schedule LV (kV)**	**Vector Group**	**Power Consumption**		**Short Circuit Impedance (%)**	**No Load Current (%)**	**Outline Dimension mm (+-10%)**			**Weight Kg (+-10%)**		**Gauging Distance (mm)**
				No Load (W)	**Load (W)**			Length	Width	Height	Oil	Total	
50				45	870		1	1215	830	1035	175	620	550x660
80				65	1250		0.9	1310	840	1125	210	800	550x660
100				75	1500		0.9	1320	885	1060	210	880	55x660
125	6			85	1800		0.8	1360	890	1100	230	920	550x660
160	6.3			100	2200		0.8	1410	900	1140	255	1095	550x660
200	11			120	2600		0.7	1465	905	1200	295	1240	550x660
250	+-2			140	3050	4	0.7	1540	905	1240	320	1450	550x660
315	x 2.5%	0.433	D, Yn11	170	3650		0.7	1580	910	1300	350	1680	660x660
400				200	4300		0.6	1750	910	1360	430	2130	660x660
500				240	5100		0.6	1820	980	1380	480	2330	660x660
630				300	6200		0.5	1900	1070	1390	540	2800	820x820
800				350	7500		0.5	2020	1170	1400	590	3130	820x820
1000	5%			420	10300		0.4	2110	1250	1420	685	3555	820x820
1250				490	12800		0.4	2200	1320	1460	790	4230	820x820
1600				600	14500	4.5	0.4	2260	1440	1500	870	4910	820x820

Product Specification

Dry Type (Air Cooled) Transformers with varnish / Resin Impregnated or Epoxy Cast coils upto 1000 kVA 3 Phase 11kV Class or below

The Cast Resin Dry Type Transformer applies resin insulated encapsulated winding for HV and LV windings. The product features with low power consumption, zero pollution, heat-proof, cleavage-proof, moisture-proof as well as high mechanical capacity and easy maintenance.

Features

- Strong flame capability, zero pollution, and explosion resistance, it can be installed in the centre of the load.
- Good moisture-proof behavior, safe operation under 100% of humidity.
- Small volume of partial discharge and high electric intensity.
- Good insulating capability well proportioned ampere-turn, strong short circuit resistance and high lighting impulse level.
- Cleavage proof and heat proof, high mechanical capability and long lifetime.
- Winding with temperature automation monitor and protection to ensure longtime safe and reliable performance.
- Low power consumption, strong overload withstand capability, rating capacity rises by 40% - 50% under forced cooling.
- Small volume, lightweight, low noise pollution and easy installation and maintenance.

Application
Power Distribution System in occasions such as High Building Structures, Trading Centers, Powerhouses, Substations and Airports.

Technical Specification

Model	Capacity (kVA)	Voltage Schedule			Vector Group (%)	No Load Consumption (%)	Load Consumption (%)	No Load Current (%)	Short Circuit Impedance (%)	Body Weight (kg)	Gauge (mm)
		HV (kV)	Tap Range (%)	LV (kV)							
JB-30	30					220	700	2.3		500	550
JB-50	50					300	1000	2.2		570	550
JB-80	80					400	1400	2.1		650	550
JB-100	100	6				450	1600	2.0		800	550
JB-125	125	6.3				520	1900	1.9		950	660
JB-160	160	6.6				600	2200	1.8		1060	660
JB-200	200	10	+-5			700	2600	1.7		1180	660
JB-250	250	10.5				800	2900	1.6		1420	660
JB-315	315	11		0.433	D, yn11	950	3500	1.6		1600	660
JB-400	400					1100	4200	1.5	6	1810	660
JB-500	500		+-2 x 2.5			1300	5200	1.5	6	2200	660
JB-630	630					1500	6500	1.4		2530	660
JB-800	800					1600	7500	1.4		2840	820
JB-1000	1000					1800	8800	1.2		3290	820