LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

Faculty of Technology
LUT Energy
Electrical Engineering

Alexey Khramov

CONVERTER SUPPLY TRANSFORMER FOR LVDC DISTRIBUTION SYSTEM

Examiners	Prof. Juha Pyrhönen
	M.Sc. Vladimir Kuzmichev
Supervisor	M.Sc. Tero Kaipia

Abstract

Lappeenranta University of Technology
Faculty of Technology
Electrical Engineering

Alexey Khramov
Converter Supply Transformer For LVDC Distribution System
Master's thesis
2009
50 pages, 25 pictures, 10 tables.

Examiners: Professor Juha Pyrhönen and M.Sc. Vladimir Kuzmichev

Keywords: Distribution system, low voltage, transformer, harmonics.

This master's thesis is focused on optimizing the parameters of a distribution transformer with respect to low voltage direct current (LVDC) distribution system. One of the main parts of low voltage direct current (LVDC) distribution system is transformer. It is studied from several viewpoints like filtering capabilities of harmonics caused by rectifier, losses and short circuit current limiting

Determining available short circuit currents is one of the most important aspects of designing power distribution systems. Short circuits and their effects must be considered in selecting electrical equipment, circuit protection and other devices.

Table of contents

Abbreviations and symbols

AC	Alternative Current,
DC	Direct Current,
HVDC	High Voltage Direct Current,
LVDC	Low Voltage Direct Current,
MV	Medium Voltage,
RMS	Root-mean-square,
THD	Total Harmonic Distortion,

Φ	magnetic flux,
B	magnetic flux density,
f	frequency
H	magnetic field strength,
I	current,
N	number of turns,
P	losses,
R	resistance,
t	time,
U	voltage,
X	reactance,
Z	impedance,

Subindexis

D	drop,
EC	eddy current,
f	fundamental,
h	number of harmonics,
LL	load losses,
NL	non-load losses,
OSL	other stray losses,
p	resistive component,

q	reactive component,
sc	short circuit
T	total,
TSL	total stray losses,
m	maximum

Acknowledgments

The work was carried out at Lappeenranta University of Technology (LUT) during the period from autumn of 2008 up to spring 2009. I would like to express my sincere appreciation to the people who made this work possible.

At first, I want to thank to supervisors Professor Juha Pyrhbnen and D.Sc. Tero Kaipia for the possibility to work under your leadership, valuable suggestions and your scientific guidance.

I would like to tell thanks to all staff of Department of Electrical Machines of the Moscow Power Engineering Institute and especially to my supervisor Vladimir Kuzmichev for that knowledge, which they gave me.

Special thanks to Julia Vauterin who has made my live and study in Lappeenranta possible.

I am indebted to my and colleges of LUT for uncountable discussions and ideas. Without you the work might not have been finished in time.

I wish to express my thanks to my parents and friends who surround me in Finland and especially from Punkkerikatu 5.

1 Introduction

In present work the transformer is studied as one of the most important components of low voltage direct current (LVDC) distribution system. It is necessary to investigate the transformer behaviour as the transformer influences the work of the whole system. For this purpose a model of LVDC distribution system has been created in the PSCAD-EMTDC program by group of researchers of Lappeenranta University of Technology.

1.1 Main objectives of thesis

The objective of the thesis is to research the parameters of the transformer both for work of the transformer and for work in a LVDC distribution system. Also it is necessary to find out such parameters of the transformer that limit short circuit currents in a LVDC distribution system.

Also it is necessary to find out sources of harmonics in LVDC distribution system and feature of system as loading for the transformer. After that to offer the decision of the problem and to analyze, whether probably to lower level total harmonic distortion (THD) by means of change of parameters of the transformer or it is necessary to create the filter of the higher harmonics separately.

One of the important results will be the level of losses in the transformer as a function of change of transformer parameters.

1.2 LVDC system

LVDC system in general consists of a distribution transformer, a rectifier, a DC link, DC/AC inverter units, filters and customer loads. In a LVDC distribution system the DC connection is used to avoid the need to construct a medium voltage (MV) branch line and traditional AC low voltage (LVAC) network to provide electricity to a group of low power customers. The LVDC distribution network contains only a wide DC connection between mv main line and coupling points of the customers, where the DC voltage is inverted back to AC voltage. The total costs of this kind of structure are lower than in the case of traditional MV/LV AC networks due to lower capital costs. (Lassila 2008) Fig. 1.1 illustrates the main components of a DC delivery system.

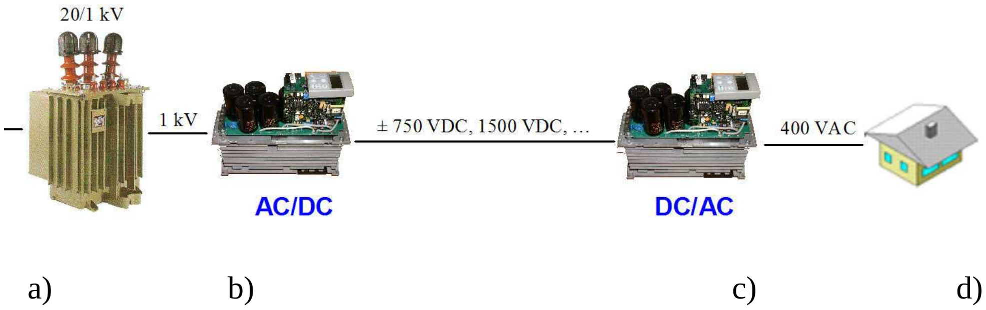


Fig. 1.1. A simplified structure of a low-voltage DC delivery system. a) distribution transformer, b) AC/DC rectifier, c) DC/AC inverter, d) customer. The converters (b and c) may be two or four quadrant converters depending on the need of power flow direction. If there is no generation in the distribution system the AC/DC converter (b) may be a two quadrant converter. If there is generation the AC/DC converter (b) has also to be a four quadrant converter as the customer DC/AC converter (c). (Lassila 2008)

The used DC/AC converter (c) in the studied bipolar ± 750 VDC distribution system is 1-phase full bridge inverter whose nominal power is 10 kVA. The filter uses *LC* topology. The AC/DC conversion (b) is made with two 6-pulse bridges connected in series at the DC side. The LV transformer is a delta-delta and delta-star connected transformer with 30 degree phase shift between secondary voltages which eliminates part of the harmonic content at the primary side in cases of symmetrical loading of the DC-circuits.

One of the main parts of LVDC system is the distribution transformer. The non-linear nature of the load generates harmonic currents which can cause problems in the power system and transformers overheating. Non-linear loads generate harmonic currents which flow from the load toward the power source, following the paths of least impedance. Harmonic currents are currents which have frequencies that are whole number multiples of the fundamental (power supply) frequency. The harmonic currents superimposed on the fundamental current result in non-sinusoidal current waveforms associated with non-linear loads. At transformers, harmonic load currents cause additional heating, primarily in the form of additional winding eddy current losses.

2 Harmonic loading

An important consideration when evaluating the impact of harmonics is their effect on power system component and loads. Transformers are major components in power systems. The increased losses due to harmonic distortion can cause excessive losses and hence abnormal temperature rise. The measurement of iron losses and copper losses of transformers is important in particular for transformers feeding nonlinear loads. This study presents the source of harmonic distortion of load current and shows the existing limits of it.

2.1 Harmonics in general

2.1.1 Definition of harmonics

In AC networks, the currents and voltages are expected to have sinusoidal waveforms. Any deviation leads to the presence of supplementary currents and voltages having a higher frequency, which can lead to rated normal operating conditions alteration, both inside that network, as well as in its neighboring networks.

Throughout the network, the harmonic sources and the harmonic components generated can be the triggering phenomenon for high level over voltages and high currents, which can lead to insulation spark over or breakdown or conductor overheating. And it is to be stressed that all these effects originate in high order harmonic voltages and currents, due to deviations from the expected sine waves.

Power transformers are well known sources for high order harmonics, especially when their core is operating under saturation conditions. Magnetic saturation of the steel core is the main cause for a strong distortion of the magnetizing current waveforms. Under a sinusoidal voltage applied to a winding, the absorbed magnetizing current will have a pointed wave shape, a proof of that is its very rich harmonic content.

2.1.2 Analysing frequency content

The ideal line voltage in power supply grids should be sinusoidal, but through the usage of non-linear consumers, power electronics etc., a distortion and with this a deviation from the sinusoidal shape occurs. This distortion can, through decomposition of the voltage, be characterized and qualified into a fundamental and harmonics. Each periodic function $f(t)$ can, as it is know, be described as a Fourier-series, as sum of trigonometric functions with the fundamental frequency $\omega_1 = 2 \cdot \mathrm{p} \cdot f_1$ and integer multiples of the fundamental frequency. (Renner 2007)

$$f(t) = \frac{A_0}{2} + \sum_{\nu=1}^{\infty} A_\nu \cdot \cos(\nu \cdot \omega_1 t) + B_\nu \cdot \sin(\nu \cdot \omega_1 t) = \sum_{\nu=-\infty}^{\infty} C_\nu \cdot e^{j\nu\omega_1 t} \qquad (2.1)$$

If the positive and the negative half-wave of a signal $f(t)$, except for its sign, hold the same shape the corresponding spectrum contains solely spectral components with odd ordinal number. The mentioned symmetry property is in the stationary case generally given for both, voltage and current. Therefore, in practice primarily current- and voltage spectra with spectral components of odd ordinal number occur.

The classical harmonics-theory encloses a frequency range from 0 Hz to about 2500 Hz. In connection with commutation notches, indirect AC converters and transients, oscillations in the line frequency up to some 10 kHz may occur.

Like the fundamental, each single harmonic in the three-phase-system can, according to the same transformation rules, be disassembled into symmetrical components. For symmetrical voltage relations in three-phase systems, that means that the voltage has the same shape in all three phases, and that the phase shift between the fundamentals of the voltages amounts exactly 120°, the following characteristics can be applied:

- the harmonics of the order $n = 3k$, $k = 1, 2, \ldots$ ($n = 3, 6, 9\ldots$), form a zero sequence system,

- the harmonics of the order $n = 3k+1$, $k = 1.2,..$ ($n = 4.\ 7.\ 10\dots$) form a positive sequence system,
- the harmonics of the order $n = 3k - 1$, $k = 1, 2,..$ ($n = 5, 8, 11\dots$) form a negative sequence system.

Zero sequence systems show the characteristics that they cannot appear in line-line voltages. Therefore, in the majority of cases, they cannot, due to the vector group of the transformers and the neutral point treatment, be transferred into other grid levels.

The above mentioned symmetry properties occur in practice only on a limited extent. Therefore, in the majority of cases the harmonics of every ordinal number can be composed of zero-, positive-, and negative sequence systems. For this reason, also parts of the through 3 divisible harmonics can spread into other grid levels.

For sinusoidal magnitudes the definition of active-, reactive- and apparent power offers no problems. For distorted voltages and currents, the connections are more complicated and especially for the reactive power they are not that clear anymore.

2.1.3 Total harmonic distortion

There are several methods of estimating harmonic load content. In this study we will focus on the percentage of Total Harmonic Distortion (%THD). The percentage of total harmonic distortion (%THD) can be defined in two different ways, as a percentage of the fundamental component (the IEEE definition of THD) or as a percentage of the RMS (used by the Canadian Standards Association and the IFC). The first standard is referred in this study.

$$THD = \sqrt{\sum_{h=2}^{N}\left(\frac{I_h}{I_1}\right)^2} \cdot 100 \quad , \qquad (2.2)$$

where I_1 is fundamental harmonic; $I_2, I_3, ...I_h$ are second, third and h harmonics respectively.

Having defined the measurement criteria for distortion, it is useful at this stage to consider the sources of distortion, and how simulating the different transformers could predict the level of distortion. The transformer ferrous core has non-linear characteristics and there is non-linear relationship between *B* and *H* in the core. Figure 2.1 illustrates how the *BH* characteristic changes as the applied field strength (*H*) is increased, introducing non-linear behavior.

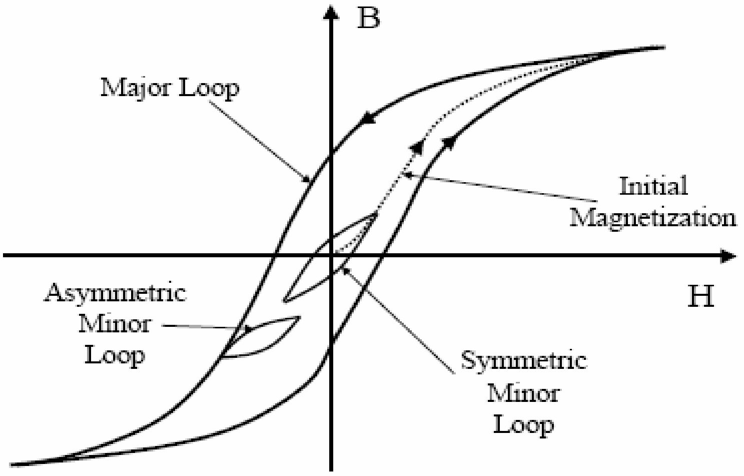


Fig. 2.1. Non-linear B-H behavior in Transformer Core. (Peter 2003)

2.2 Source of harmonics

Basically, the sources of harmonics and inter-harmonics in electric power supply grids can be divided into 3 groups:

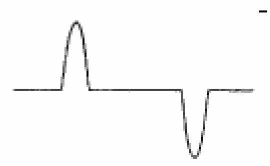
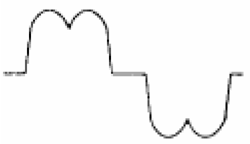
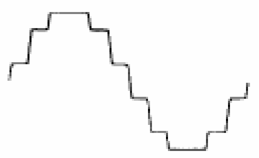
- Non-sinusoidal feeding (harmonic-voltage source)
- Non-linear line impedances or loads (harmonic current sources)
- Current converter, power electronics (harmonic-currents sources)

Especially, the last-mentioned groups are considered to be the main causes for harmonics. Grid elements or consumers are the ones that provoke a non-sinusoidal current on a non-sinusoidal voltage. These harmonic currents cause, in turn, harmonic voltage differences on the network impedances.

2.2.1 Converters especially thyristor and diode bridges

The most important source of harmonic is formed by the group of periodic switched loads. All kind of power electronics are showed in the table 2.1.

Table 2.1. Classification of power converters according to their curve shape. (Renner 2007)

Circuit	Curve shape	Total harmonic distortion, %	Application
single-phase bridge rectifier with smoothing capacitors(2-pulse)		130…160	switching power supply (entertainment and office-electronic, compact fluorescent lamps)
6-pulse rectifier with smoothing capacitor (voltage DC link, V-converters)		70…120	UPS-equipment, variable-frequency inverter for three-phase motors (pumps, ventilators, compressor, mills, crane-chassis, conveyors, stirrers, paper machines)
6-pulse rectifier with smoothing capacitor and inductor		40…70	
6-pulse rectifier with smoothing inductor (current DC. link, I-converter)		30	DC drives (ski lifts, extruders, band-saws) inverter for wind power plants
12-pulse rectifier with smoothing inductor (current DC link. I-converter)		15	DC drives with high performance (roller plants, cableways) DC electric arc furnaces, HVDC-systems
active converter (constant voltage DC link, V-converter)		<10	modern, speed-controlled 4-quadrants-drives

For the calculation of the harmonics of converter bridge circuits, an ideal smoothing inductance in the DC circuit is generally assumed. In the normal case, only "characteristic current converter harmonics" occur in the spectrum of the current.

$$v = 6 \cdot n \pm 1,\ \text{n} = 1, 2, 3\ldots \qquad (2.3)$$

The circuit of a 12-pulse converter bridge results from the parallel connection of two 6-pulse converters on the AC-side, whereas one converter transformer is arranged as a Yy-circuit, and the other in a Yd-circuit. Due to the phase rotation of the vector groups, the harmonics of the order 5, 7, 17, 19 and so on of the bridges cancel out the equivalent harmonics of the second bridge. It remain the harmonics of the orders

$$\nu = 12 \cdot n \pm 1,\ n = 1,2,3\ldots \tag{2.4}$$

Non-characteristic harmonics emerge by unbalanced or unsteady operation. The amplitudes of the harmonic currents obey about the following relation:

$$\frac{I_\mathrm{h}}{I_1} = \frac{1}{n} \cdot \frac{\cos\left(n \cdot \frac{\mathrm{p}}{6}\right) \cdot \sin\left(n \cdot \frac{\alpha}{2}\right)}{\cos\left(\frac{\mathrm{p}}{6}\right) \cdot \sin\left(\frac{\alpha}{2}\right)} \tag{2.5}$$

$$\frac{I_\mathrm{h}}{I_1} = \frac{1}{n} \qquad \text{for } \alpha = 0 \tag{2.6}$$

α is the overlap angle during the commutation, which depends on the value of the commutation reactance - the sum of current converter transformer and grid reactance and on the delay angle. A neglect of the commutation ($\alpha = 0$) results in a decrease of the amplitudes of the harmonics with $1/n$. If you additionally consider the waviness on the DC-side - this means a finite smoothing inductance in the DC circuit - the 5th harmonic accumulates, in comparison to the conventional theory, in the mains current with increasing waviness, the 7th harmonic decreases, while the 11th harmonic stays nearly the same. (Renner 2007)

These circuit have the character of a harmonic current source with a spectrum, which depends on the network impedance only to a minor degree

2.2.2 LVDC system as load of transformer

From the transformer viewpoint the LVDC system looks similar than any other thyristor bridge fed load. Thus, the load currents depend not only from the magnitude of the load at DC side but from overlap angles of the thyristors as well as the characteristics of the DC current. The loading of the supply transformer depend on the harmonic contents of the load current which furthermore depend on the bridge type and used filters both in AC and DC sides of the rectifier. The first assumption in this thesis is that no smoothing inductor in DC or AC side filters are used in the system.

Transformer which used in LVDC distribution system is delta-delta and delta-star connected transformer with 30 degree phase shift between secondary voltages. The initial proposition for the rectifier structure is hence a 12-pulse thyristor bridge, which eliminates part of harmonic content at primary side like described in previous chapter. In normal operation the thyristor bridge in the case of the LVDC system is run like a ordinary diode bridge ($\alpha = 0$). The overlap angle is changed only during the system startup when the DC voltage is ramped from zero to nominal. During the startup the harmonic content of the current is therefore higher than during the normal operation. However, startup situation lasts only very short time and is needed quite seldom.

A very common situation for the LVDC system is the unbalanced loading of the bipolar DC system. This causes the rectifier to be loaded only on one side leading to loading of only one of the two secondaries of the supply transformer. During unbalanced operation of the DC grid, the rectifier looks like a 6-pulse bridge to the transformer. As unbalanced loading is very probable due to random variation in the load of individual end customers, it is seen as the worst case situation in designing of the components. In this thesis the analysis are carried out for totally unbalanced DC loading situation, as the THD of the load current is then double the amount compared to the balanced situation.

2.3 Currents and Voltages distortion limits

There are two distinct thought processes that can be applied to limit the amount of harmonics that are present in power systems. The first, favoured by the International Electrotechnical Commission (IEC), is a series of limits that is appropriate for application at the terminals of any particular nonlinear load. The second, favoured by the IEEE and the basis for IEEE 519-1992, is a series of limits that is appropriate for application at a single more central point of supply to multiple nonlinear loads.

The philosophy of the IEC limits is based on the presumption that limiting harmonic production from every piece of equipment will effectively limit any combined effects. While conceptually effective, the assumptions made in developing the actual limits are quite different from those in IEEE 519-1992 and it has been shown that the IEEE limits are somewhat more restrictive due the use of both voltage and current harmonic limits.

The IEEE limits for voltage and current harmonics shown in Tables 2.2-2.3 are dependent on several variables and concepts defined as follows: I_{sc}- short circuit current; I_f – fundamental harmonic; h – number of harmonics.

Table 2.2. Current distortion limits (in % of fundamental) for distribution system. (IEEE 1993)

I_{sc}/I_f	<11	11<h<17	17<h<23	23<h<35	35<	THD, %
<20	4	2	1,5	0,6	0,3	5
20-50	7	3,5	2,5	1	0,5	8
50-100	10	4,5	4	1,5	0,7	12
100-1000	12	5,5	5	2	1	15
>1000	15	7	6	2,5	1,4	20

Table 2.3. Voltage distortion limits (in % of fundamental) for distribution system. (IEEE 1993)

Voltage, kV	Individual Harmonic Magnitude, %	THDV, %
<69	3	5
69-161	1,5	2,5
>161	1	1,5

The thought processes behind these tables are that 1) the customer should be responsible for limiting harmonic currents in accordance with Tables 2.2 and 2) the utility should be responsible for limiting harmonic voltages in accordance with Table 2.3.

Also EN 50160 standard can be applied at definition voltage limits harmonics. EN 50160 gives the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling in public LV and MV electricity distribution systems, under normal operating conditions. In this context, LV means that the phase to phase nominal RMS voltage does not exceed 1000 V AC and MV means that the phase-to-phase nominal RMS value is between 1 kV and 35 kV AC. The European Union (EU) Low-Voltage Directive (LVD 2006/95/EC) defines the limits for the low-voltage (LV) levels in public distribution systems. It covers equipment designed for use with a voltage rating between 50–1000 V AC and between 75–1500 V DC (LVD 2006/95/EC).

Table 2.4. Values of individual harmonic voltages at the supply terminals for order up to 21, given in per cent from nominal voltage. (Markiewicz 1999)

Odd harmonics			
Non multiples of 3		multiples of 3	
5	6 %	3	5 %
7	5 %	9	1,5 %
11	3,5 %	15	0,5 %
13	3 %	21	0,5 %

For voltage distortion the limits are defined in EN 50160. In the Finnish national Sener recommendation the limitations are defined also for currents due to following reasons (Sener 2001):

- Harmonic currents cause harmonic voltages.
- Even if the shape of voltage wave is in its limitations at load connection point, it is possible that current harmonics caused by voltage distortion together with current distortion caused by load equipment may lead to voltage distortion over the limitations somewhere else in the same network.
- By setting limits for current harmonics it is possible to divide the total harmonic current tolerance of the network quite evenly between the customers.

The limitations of the current distortion are presented related to the transmission capacity reserved for a customer (short circuit ratio I_{sc}/I_{ref}) with defined reference load current I_{ref}. In the case of single low voltage customer with fuse based distribution tariff the reference current is the size of customer's main fuse. In the case of a customer with power based distribution tariff, the reference current is the active power defined in the service agreement converted into active current with equation (2.7) as follows (Sener 2001),

$$I_{\mathrm{ref}} = \frac{P}{\sqrt{3} \cdot U_{\mathrm{N}}} \tag{2.7}$$

In which P is the active power of defined in service agreement

U_{N} is the nominal voltage at coupling point

The limitations for the current harmonics are based on the limitations set to voltages in EN 50160, that is, the followed standard. Goal is to fulfill the requirements of the voltage standardization by following the recommendations of current wave form.

Table 2.5. Highest allowed harmonic currents caused by a low voltage customer

Reference load current	Recommended limit for distortion	
≤ 25 A	All equipment within EMC standardization allowed	
> 25 – 200 A	THD maximum 10 % of the reference load current	
> 200 A	THD maximum 8 % of the reference load current, if the RMS value of harmonic current is over 20 A. No limitation if the distortion current is less than 20 A. In addition, limitations for individual harmonics are as follows:	
	Harmonic order h	Percents of reference current
	<11	7,0 %
	11-16	3,5 %
	17-22	2,5 %
	23-34	1,0 %
	>34	0,5 %

3 Transformer characteristics

Efficiency is one of the important characteristics of the transformer. To understand, how it depends on what parameters of transformer, it is necessary to understand electromagnetic processes which occur inside it. The big importance is connection of characteristics with the structure of transformer, i.e. what kinds of windings is applied, what materials is used in manufacture of transformers, how harmonic distortion influence for losses.

3.1 Theory of transformers

In transmission and distribution networks transferring large amounts of alternating current electricity over long distances with minimum losses and least cost, different voltage levels are required in various parts of the networks. For example, the transfer of electricity efficiently over a long transmission line requires the use of high voltages. At the receiving end where the electricity is used, the high voltage has to be reduced to the levels required by the consumer. Transformers enable these changes in voltage to be carried out easily, cheaply and efficiently. A transformer used to increase the voltage is called a "step up" transformer, while that used to decrease the voltage is called a "step down" transformer. (Energy Manager Training)

The operation of a transformer is based on two principles:

- A voltage is induced in a conductor when the conductor passes through a magnetic field. The same effect is produced if the conductor is stationary but the magnetic field in which it is located varies; and
- A current passing through a conductor will develop a magnetic field around the conductor.

A transformer consists of two coils electrically separate but linked by a common magnetic circuit of low reluctance formed by a laminated soft iron core. If one coil (the primary coil) is connected to an AC supply voltage u_1, an alternating magnetic flux linkage ψ_1 is set up in the transformer according to

$$\psi_1 = \int (u_1 - i_1 R_1) \mathrm{d}t \tag{3.1}$$

With sinusoidal voltage u_1 and low primary resistance R_1 the primary flux linkage will be sinusoidal and about 90 degrees phase sifted from the primary voltage. In the iron core there will be a corresponding flux Φ. The dependence of the flux and the primary flux linkage ψ_1 may be given as

$$\psi_1 = N_1 (\Phi_\mathrm{m} + \Phi_\mathrm{l}) \tag{3.2}$$

where Φ_m and Φ_l are the mutual and leakage fluxes and N_1 is the number of primary turns. The mutual alternating magnetic flux passes through the secondary coil, forms a secondary flux linkage ψ_2 whose time differential induces and alternating voltage u_2 in the secondary coil, Fig. 3.1. The magnitude of the secondary voltage is directly proportional to the ratio of the number of turns in the secondary and primary windings (N_1 and N_2) and to the primary voltage.

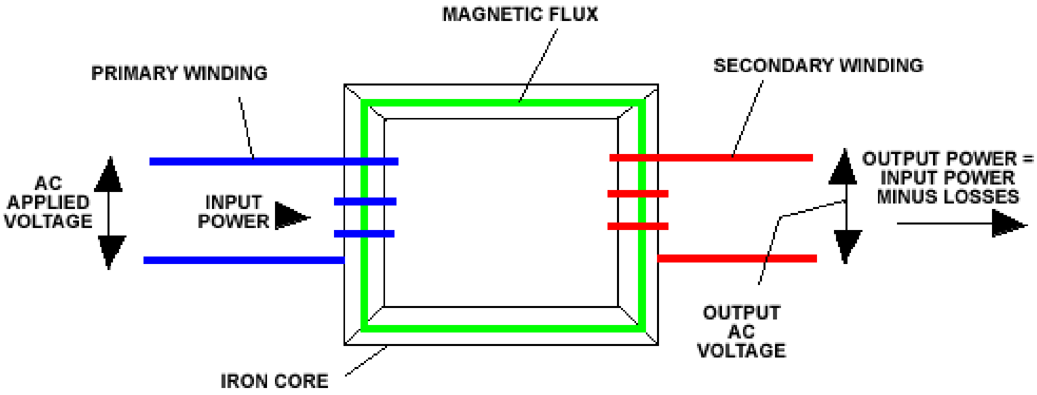


Fig. 3.1. Main principles of a transformer. (Energy Manager Training)

The iron core, which forms a complete magnetic circuit, is made up of laminated strips of special steel having low hysteresis loss and high electrical resistivity. The lamination of the core reduces the eddy-current loss.

For the average transformer used in a power station, the conductor used for the windings consists of paper insulated copper bar or wire. In assembling the transformer, great care is taken to ensure that windings are well insulated both from the iron core and from each other.

The basic construction of a core type transformer consists of the iron core, then a cylinder of insulation, followed by the low voltage winding, then a further insulating cylinder and then the high voltage winding. Clamps are used to hold the assembly in place. These basic components are shown on the attached diagram and are also shown in the attached part cross-section of a very large transformer. (Energy Manager Training)

The assembled transformer has its winding and iron core assembly usually contained in a tank and immersed in transformer oil. The oil is used for further insulating purposes plus the removal of heat from the windings. The assembly of the windings on the core allows gaps to enhance the oil circulation around the windings. The tank is constructed with fins or tubes to allow better circulation of the oil and to provide a greater surface area for contact with the cooling air. Very large transformers have banks of fans to provide greater air-cooling and are operated in conjunction with temperature sensors. Some transformers also have forced oil circulation using a pumping system and an oil cooling circuit. In installations where the use of transformer oil needs to be avoided, the cooling medium used can be gas (nitrogen is often used).

Small transformers are often solely air-cooled. Large transformers that are of open construction so that cooling is provided by direct contact with the surrounding air are being developed for indoor use.

Most distribution type transformers have a tap changer, which is a selector switch that allows the voltage ratio of the transformer to be changed by increasing or decreasing the turns of the winding. The different coils of the transformer winding are brought out and connected to the selector switch to allow the additional turns to be brought into or taken out of circuit. In some distribution transformers, the tap changer switch is an off load manual switch, while in others, the tap changer is an on-load automatic switch. In a generator transformer, the tap changer is a very sophisticated device that is automatically operated on load by the system control.

In the DC-distribution transformer a tap changer is not needed as the DC voltage level ±750 VDC is such a high level that normal consumption voltages 400 VAC and 230 VAC may be easily produced. In principle, voltages of 567 V DC and 325 V DC are needed to produce the desired AC voltages thus leaving a great voltage reserve in the system.

3.2 Typical transformer structures

The transformers as used in the distribution system are normally considered to be the same transformers which provide the transformation from medium-voltage to low-voltage in public distribution networks. In Europe this is 400 V phase to phase, but for the industry 690 V phase to phase is also a common value.

Distribution transformers are usually made in a different factory from larger transformers. There are many more manufacturers that build small transformers than those at the larger end of the scale. The industry is very competitive, and as a result the main consideration in the design of the active part is to achieve the best use of materials and to minimize costs. The one of main characteristics of transformer is efficiency which depends on losses

Nowadays European Harmonization Documents 428 specifies no-load loss levels for three different core types (designated A', B' and C' with C' having the lowest loss and A' the highest). It also gives load losses for three different winding types (designated A. B and C. with C being the lowest loss and B the highest loss). (Hulshorst 2002)

3.2.1 Distribution transformer characteristics

The effects of short-circuit currents in distribution networks for electrical energy are severe, both on the equipment and on the stability of the networks. Since short-circuits occur quite often, the short-circuit withstand capacity must be one of the main characteristics of the equipment.

One of the main parts of the LVDC distribution system is the distribution transformer. Transformers, like other equipment are capable of limiting the short-circuit currents to values predominantly determined by the transformer's impedance. In this way, the design of transformer with respect to short-circuit current withstand capacity is directed towards the limitation of the current values proper as well as towards control of the forces and stresses exerted by the same short-circuit currents inside the transformer.

The following table 3.1 list the current transformer impedances for distribution transformers. This information is necessary for calculating available fault current.

Table 3.1. Three Phase Distribution Transformers. (Siemens)

Three Phase Distribution Transformers			
Size in kVA	Impedance short circuit, %	Efficiency of transformer, %	Weight, kg
50	3 – 3,5	98,0	350 – 500
100	3 – 3,5	98,0	500 – 620
160	3,5 – 4	98,0	620 – 900
315	3.5 – 4	98,5	980 – 1250
500	4 – 6	99,0	1410 – 1860

Nowadays distribution transformers have a very high rated efficiency (typically about 98 – 99%, depending on the size of the transformer). Transformers are, however, seldom operated at their rated load, and hence, an energy efficiency should be defined. The no load power of a transformer is important if the load is low.

3.2.2 Industrial transformer characteristics

Most of the characteristics of industrial transformers are specified in national or international product standards for distribution transformers. Generally, the purpose of standards is to facilitate the exchange of products in both home and overseas markets, and to improve the product quality, health, safety and the environment. International standards are also of importance in reduction trade barriers. The application of standards can be legally required, or by specific reference in the purchase contract.

For distribution transformers purchased in the European Union, three levels of standards are applicable:

- World-wide standards (ISO, IEC)
- European standards and regulations (EN, HD)
- National standards (e.g. NBN, BSI, NF, DIN, NEN, UNE, OTEL).

European Harmonization Documents (HD) is initiated if there is a need for a European standard. The draft HD is a compilation of the different national standards on the subject. The HD is finalized by eliminating as many national differences as possible. When a harmonization document has been issued, conflicting national standards have to be withdrawn within a specified period of time, or modified to be compatible with the HD. Usually, the HD is the predecessor of a European standard (EN), which must be adopted as a national standard in the EU member countries. Thus, purchase orders which refer to national standards are compatible with European standards (EN) and/or harmonization documents (HD). (Hulshorst 2002)

Among the many international standards for distribution transformers, two main European Harmonisation Documents specify energy efficiency levels:

- HD 428: Three phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV.

- HD 538: Three phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV.

For the industrial transformers there are also other world-wide standards. These standards are IEC 61378-1: Transformers for industrial applications, and if the transformer is loaded with a non-linear (converter) load IEC 60146-1-2: Semiconductor converters, general requirements and line commutated converters.

The short-circuit impedance of the transformers is 4 % or 6 %, in most cases. This technical parameter is of importance to a utility for designing and dimensioning the low-voltage network fed by the transformer. Transformers with the same rated power but with different short-circuit impedance have a different construction and therefore slightly different losses. For HD 428 / HD 538 compliant distribution transformers, the preferred values for the short-circuit impedance are 4 % for transformers up to and including 630 kVA, and 6 % for transformers of 630 kVA and above.

Based on the HD 538, HD 428 and the interviews the following differences are observed when comparing dry and oil-cooled transformers:

- The purchase price of dry transformers is higher than the purchase price of oil-immersed transformers.
- The no-load losses of a dry transformer are higher, due to their bigger dimensions
- The load losses however, are at full load lower compared to oil-immersed transformers.
- Harmonic pollution of the load causes less heating and ageing in the dry transformers than in the oil-immersed transformers. However, due to epoxy the heat emission of the dry-transformer is weaker than the oil-immersed transformer.
- Dry-type transformers are considered better provided against fire.
- Dry-type transformers do not need an oil-spilling container.
- As a rule of thumb, for a lower loading profile, the oil-immersed transformers are cost effective, sometimes even with an amorphous core, however, if the load is grow-

ing and/or significant harmonic pollution is present, the dry-type transformers are more cost effective.

3.2.3 Analysis of transformer losses

Transformer losses consist of no-load or core losses and load losses. This can be expressed by (3.3). (Sadati 2008)

$$P_{\mathrm{T}} = P_{\mathrm{NL}} + P_{\mathrm{LL}} \tag{3.3}$$

Where P_{T} is total losses; P_{NL} is no-load losses; P_{LL} is load losses.

No-load toss is due to the induced voltage in core. Load losses consist of ohmic loss, eddy current loss, and other stray loss, or in equation form:

$$P_{\mathrm{LL}} = P_{\mathrm{dc}} + P_{\mathrm{EC}} + P_{\mathrm{OSL}} \tag{3.4}$$

Where P_{dc} is loss due to load current and dc resistance of the windings; P_{EC} is winding eddy loss; P_{OSL} is other stray losses clamps, tanks and etc.

P_{dc} as usual is calculated by measuring the dc resistance of the windings and multiplying it by the square of the load current. In that case when it is impossible to measure dc resistance, at first to make calculation of full dc resistance of the transformer using an equivalent circuit, and then approximately divides on resistance of primary and secondary windings. The stray losses can be further divided into winding eddy losses and structural part stray losses. Winding eddy losses consist of eddy current losses and circulating current losses, which are considered to be winding eddy current losses. Other stray losses are due to losses in structures other than windings, such as clamps, tank or enclosure walls, etc. The total stray losses are determined by subtracting dc losses from the load losses measured during the impedance test, as follows

$$P_{\mathrm{TSL}} = P_{\mathrm{EC}} + P_{\mathrm{OSL}} + P_{\mathrm{LL}} - P_{\mathrm{dc}}\,. \tag{3.5}$$

There is no test method to distinguish the winding eddy losses from the other stray losses

There are two effects that can cause increase in winding eddy current losses in windings, namely the skin effect and the proximity effect. The winding eddy current loss in the power frequency Spectrum tends to be proportional to the square of the bad current and the square of frequency which are due to both the skin effect and proximity effect:

$$P_{\mathrm{EC}} = I^2 \times f^2 \tag{3.6}$$

The impact of lower-order harmonics on the skin effect is negligible in the transformer windings.

The equation (3.7) below can be used for calculating the eddy current losses:

$$P_{\mathrm{TSL}} = P_{\mathrm{LL\_R}} - \left[\left(R_1 \cdot I_1^2 + \right) R_2 \cdot I_2^2 \right] \tag{3.7}$$

The winding eddy current loss is then calculated for oil-filled transformers as presented in equation (3.8).

$$P_{\mathrm{EC}} = 0{,}33 \cdot P_{\mathrm{TSL}} \tag{3.8}$$

Each metallic conductor linked by the electromagnetic flux experiences an internally induced voltage that causes eddy currents to flow in that ferromagnetic material. The eddy currents produce losses that are dissipated in the form of heat, producing an additional temperature rise in the metallic parts over its surroundings. The eddy current losses outside the windings are the other stray losses. The other stray losses in the core, clamps and structural pans will increase at a rate proportional to the square of the load current but not at a rate proportional to the square of the frequency as in eddy current winding losses. Experiments were done to find the change of other stray losses with frequency. Results shown that the ac resistance of the other stray losses at low frequencies (0-360Hz) is equal to:

$$P_{\mathrm{OSL}} = 1,29 \cdot \left(\frac{f_{\mathrm{h}}}{f_1} \right)^{0,8} \tag{3.9}$$

Thus this loss is proportional to square of the load current and the frequency to the power of 0.8.

Below equation can be used for calculating the other stray loss:

$$P_{\mathrm{OSL}} = P_{\mathrm{TSL}} - P_{\mathrm{EC}} \tag{3.10}$$

3.3 Electromagnetism

In this part of work it is considered typical core structure in transformer. Also materials which are applied at transformer manufacturing are presented. It is the important part because it influences electromagnetic processes which occur in the transformer. Also influence of the distortion of harmonics on transformer work, on losses which cause an overheat of windings is considering here.

3.3.1 Core structures

Modem core materials comprising laser-scribed cold-rolled grain-oriented silicon steel have been developed and improved substantially to give low core losses but recent history shows that there is still some scope for improvement in core loss reduction (Del Vecchio 2002). In stacked core designs using laminated steel sheets, recent developments in the design and production of the joints has reduced core loss by improving magnetic field continuity at the sheet edges in the yoke sections.

Reducing the lamination thickness will reduce losses by reducing eddy current loss by virtue of an increase in the electrical resistance with the smaller lamination cross-section. However, current lamination thickness is generally considered to be about as low as is consistent with good manufacturing practice for production of stacked layer cores.

An increase in the overall core cross-section would reduce magnetic flux density in the core and thus reduce core loss. This would be at the cost of increased size, weight and cost, however. It would also increase load loss because longer lengths of conductor would be required for the same number of turns and this would increase winding resistance and thus load loss. However, the usable method for decreasing losses is selecting core materials with low losses if it is possible with respect to the increase of the price of the transformer core. Examples of the level of losses for different electrical steels used in transformers are presented in table 3.2.

Table 3.2. Non-oriented fully processed electrical steel. (Surahammars Bruk)

SURA Grade	Thickness mm	Max specific total loss at 50 Hz		Min magnetic polarization at 50 Hz		
		J = 1,5 T W/kg	*LOT** W/kg	H = 2500 T	5000 T	10000A/m T
M210-27A	0,27	2,10	0,85	1,49	1,60	1,70
M235-35A	0,35	2,35	0,95	1,49	1,60	1,70
M250-35A	0,35	2,50	1,00	1,49	1,60	1,70
M270-35A	0,35	2,70	1,10	1,49	1,60	1,70
M300-35A	0,35	3,00	1,20	1,49	1,60	1,70
M330-35A	0,35	3,30	1,30	1,49	1,60	1,70
M700-35A	0,35	7,00	3,00	1,60	1,69	1,77
M250-50A	0,50	2,50	1,05	1,49	1,60	1,70
M270-50A	0,50	2,70	1,10	1,49	1,60	1,70
M290-50A	0,50	2,90	1,15	1,49	1,60	1,70
M310-50A	0,50	3,10	1,25	1,49	1,60	1,70
M330-50A	0,50	3,30	1,35	1,49	1,60	1,70
M350-50A	0,50	3,50	1,50	1,50	1,60	1,70
M400-50A	0,50	4,00	1,70	1,53	1,63	1,73
M470-50A	0,50	4,70	2,00	1,54	1,64	1,74
M530-50A	0,50	5,30	2,30	1,56	1,65	1,75
M530-50HP	0,50	5,30	2,30	1,63	1,71	1,81
M600-50A	0,50	6,00	2,60	1,57	1,66	1,76
M700-50A	0,50	7,00	3,00	1,60	1,69	1,77
M800-50A	0,50	8,00	3,60	1,60	1,70	1,78

* Losses at 1,0 T are given as information only and are not guaranteed.

3.3.2 Winding structures

For core-form distribution transformers, there are two main methods of winding the coils. These are sketched in Fig. 3.2. Both types are cylindrical coils, having an overall rectangular cross-section. In a disk coil, the turns are arranged in horizontal layers called disks which are wound alternately out-in. in-out, etc. The winding is usually continuous so that the last inner or outer turn gradually transitions between the adjacent layers. When the disks have only one turn, the winding is called a helical winding. The total number of turns will usually dictate whether the winding will be a disk or helical winding. The turns within a disk are usually touching so that a double layer of insulation separates the metallic conductors. The space between the disks is left open, except for structural separators called key spacers. This allows room for cooling fluid to flow between the disks, in addition to providing clearance for withstanding the voltage difference between them. (Del Vecchio 2002)

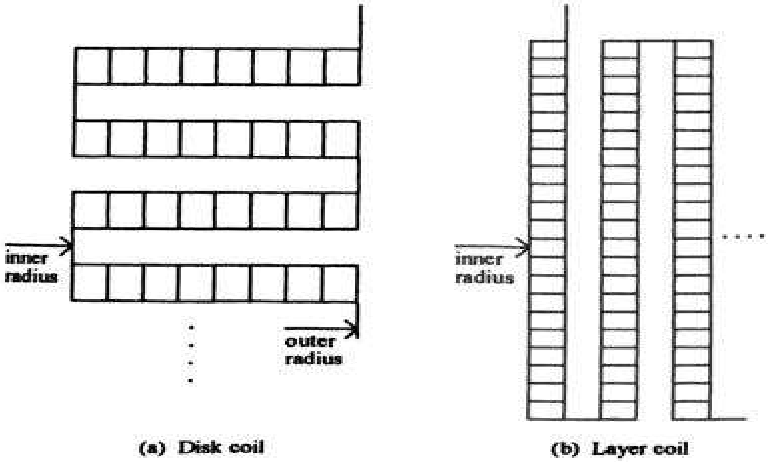


Fig. 3.2. Two major types of coil constructions distributional transformer. (Del Vecchio 2002)

3.3.3 Flux behaviour

In an iron-core power transformer, the flux Φ and the flux density B within the transformer core are proportional to the voltage u_1 applied across the primary winding, according to the Faraday’s law. In the sinusoidal case it can be written : (Hulshorst 2002)

$$U_1 = U_{1\mathrm{m}} \cdot \sin \omega t = \frac{d\Phi}{dt} \qquad (3.11)$$

$$\Phi = \int U_{1\mathrm{m}} \cdot \sin \omega t = \frac{U_{1\mathrm{m}}}{\omega} \cdot \cos \omega t = \Phi_{\mathrm{m}} \cdot \cos \omega t \qquad (3.12)$$

$$B = \frac{\Phi}{S} = \frac{\int U_{1\mathrm{m}} \cdot \sin \omega t}{S} \qquad (3.13)$$

where S is cross-section of the core.

The result magnetizing currant I_m needed to produce this sinusoidal flux is related to the magnetic field strength H by constant value, which is the ratio of number of turns N to the total length of the magnetic flux l:

$$H = NI_{\mathrm{m}}/l \qquad (3.14)$$

The magnetic flux density B is related to the magnetic field strength H by the magnetic permeability of the steel used in the transformer core μ:

$$B = \mu H \qquad (3.15)$$

Equation 3.15 shows that if the magnetic permeability μ is linear and B is sinusoidal, the magnetic field strength H (and what follows, the magnetizing current I_{m}) will be sinusoidal. If the transformer operates in saturation, μ is no longer linear and the magnetic field strength H is non-sinusoidal, because the product of H with the magnetic permeability μ must still produce the sinusoidal flux density B. If the magnetizing current I_{m} is allowed to flow freely (low impedance path Z for all harmonics), after decomposing it to Fourier components, it will contain the fundamental frequency and all the odd harmonics: 3rd, 5th, 7th,9th etc. (Keulenaer 2008).

3.3.4 Impacts of harmonic loading

According to Faraday's law the terminal voltage determines the transformer flux level:

$$N = \frac{d\varphi}{dt} = U(t) \tag{3.16}$$

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

$$N_{\mathrm{j}}(\varphi, \omega) = \frac{d\varphi}{dt} = U_{\mathrm{h}} \tag{3.17}$$

This equation shows that the flux magnitude is proportional to the voltage harmonic and inversely proportional to the harmonic order h. Furthermore, within most power systems the harmonic distortion of the system voltage THD is well below 10 % and the magnitudes of the voltage harmonics components are small compared to the fundamental component, rarely exceeding a level of 2 – 3 %. Therefore neglecting the effect of harmonic voltage and considering the no-load losses cause by the fundamental voltage component will only rise to an insignificant error.

In most power systems, current harmonics are of more significance. These harmonic current components cause additional losses in the windings and other structural parts.

If the RMS value of the load current is increased due to harmonic components, then these losses will increase with the square of the current.

$$P_{\text{Щ}} = P_{\mathrm{dc}} \cdot I^2 = P_{\mathrm{dc}} \cdot \sum_{\mathrm{h=1}}^{\mathrm{h_{max}}} I^2_{\mathrm{h,rms}} \tag{3.18}$$

The eddy current losses generated by the electromagnetic flux are assumed to vary with the square of the RMS current and the square of the frequency (Sadati 2008):

$$P_{EC} = P_{EC\_R} \cdot \sum_{h=1}^{h_{max}} h^2 \cdot \left(\frac{I_h}{I_1}\right)^2 \tag{3.19}$$

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:

$$P_{OSL} = P_{OSL\_R} \cdot \sum_{h=1}^{h_{max}} h^{0,8} \cdot \left(\frac{I_h}{I_1}\right)^2 \tag{3.20}$$

By definition, however, the loss increase due to the presence of harmonics is usually also designated as “extra losses”, see figure 3.3.

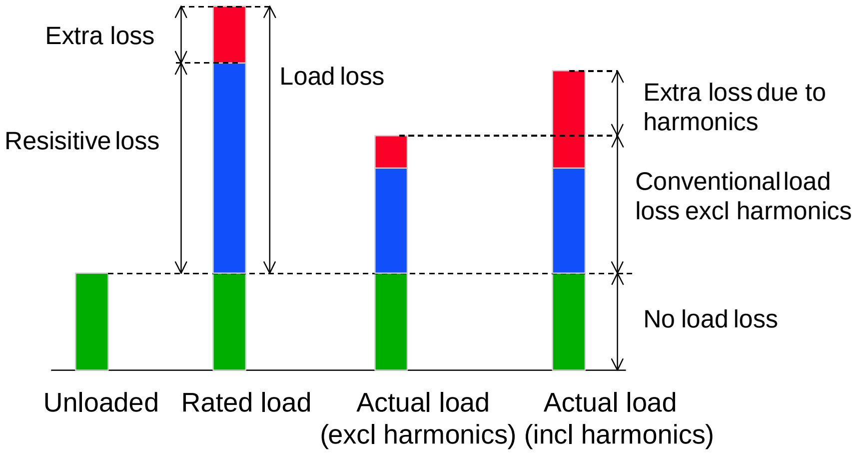


Fig.3.3. Extra losses due to harmonics. (Hulshorst 2002)

There are several approaches to account for the increased losses caused by harmonics in selecting a transformer. The first one, devised by transformer manufacturers in conjunction with Underwriters Laboratories in the United States, is to calculate a factor for the increase in eddy current loss; this is known as ‘K-Factor’. The second method is to estimate by how much a standard dry-transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss; this is known as ‘factor K’. The ‘factor K’ method (used in Europe) is described in the Harmonization document HD 538.3.S1. A third way to calculate the influence of harmonics is described in the IEC 61378-1 “Transformers for industrial applications” (Hulshorst 2002)

4 Optimisation of parameters of LVDC supply transformer

Optimisation of parameters of the transformer is the important problem which the engineer in each specific case should solve contemplating a problem from the different sides. In each specific target it is necessary to pick up those parameters which is better approach for the decision of a problem which is necessary for solving.

4.1 Definition of the objective

In this case it is necessary to pick up parameters which is better approach for the transformer which will be used in LVDC distribution system. First of all it is necessary to look, how to limit short circuit currents by the parameters of transformer. Also it is necessary to look, whether the transformer is used as the filter of the higher harmonics or it is necessary to design the filter separately. Thus the important thing is low losses in the transformer

4.1.1 Model of LVDC distribution system

To look which electromagnetic processes occur in LVDC distribution system model of the LVDC distribution system has been created in Lappeenranta University of Technology by group of researchers. The model has been realised in the PSCAD-EMTDC program.

EMTDC (which stands for Electromagnetic Transients including DC) represents and solves differential equations (for both electromagnetic and electromechanical systems) in the time domain. Solutions are calculated based on a fixed time step, and its program structure allows for the representation of control systems, either with or without electromagnetic or electromechanical systems present. (Wilson 2005)

EMTDC is a class of simulation tool, which differs from phasor domain solution engines, such as load-flow and transient stability programs. These tools utilize steady-state equations to represent electrical circuits, but will actually solve the differential equations of machine mechanical dynamics.

EMTDC results are solved as instantaneous values in time, yet can be converted into phasor magnitudes and angles via built-in transducer and measurement functions in PSCAD - similar to the way real system measurements are performed (Wilson 2005)

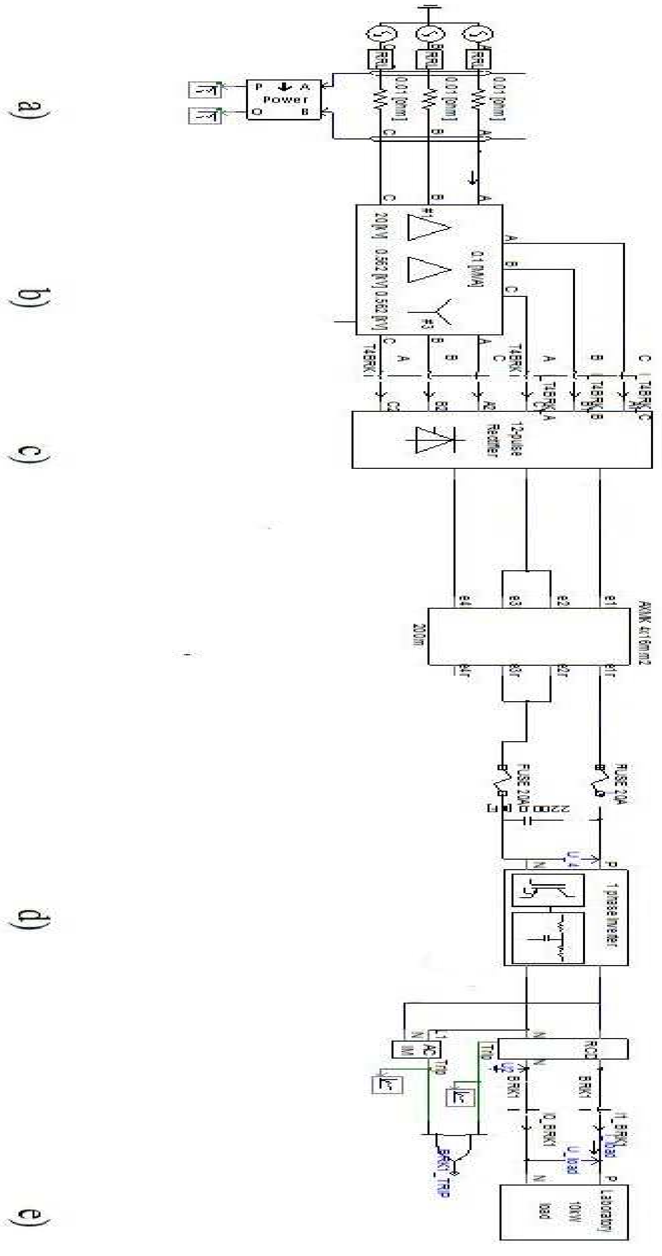


Fig. 4.1. Model of LVDC distribution system which has been created in PSCAD-EMTDC program. a) Source of energy b) distribution transformer, c) AC/DC rectifier, d) DC/AC inverter, e) customer

4.1.2 Characteristics of LVDC supply transformer

Some special design features of the transformer which used at the proposed LVDC distribution system are presented below :

- 3-winding structure;
- 30 degree phase shift between the secondary and tertiary voltages;
- Ddy or Yyd groups, no grounding of star point;
- insulation level for 20/0.56/0.56;
- transformer rated apparent power (S_n) is 100 kVA.

The load of the transformer varies frequently from zero to small occasional overload, but average load is typically between 40 – 60 % of the nominal power. In this connection there is a requirement of good energy efficiency. Transformer can be design as oil immersed or dry type insulation. Physical dimensions standardized, low weight recommended

4.2 Possibilities of limiting short circuit current

The effects of short-circuit currents in transmission and distribution networks for electrical energy are tremendous, both on the equipment and on the stability of the networks. Since short-circuits occur quite often, the short-circuit withstand capacity must be one of the main characteristics of the equipment installed.

Transformers have the quality to limit the short-circuit currents to values predominantly determined by the transformer's impedance. In this way, the design of a power transformer with respect to short-circuit current withstand capacity is directed towards limitation of the current values proper as well as towards control of the forces and stresses exerted by the same short-circuit currents inside the transformer.

Using the model of LVDC distribution system short circuit simulation in the distribution system has been realised with different transformer short circuit impedances. Power supply is rigid and its impedance is kept constant. Thus it is possible to increase only short circuit impedance of the transformer for limit short circuit currents.

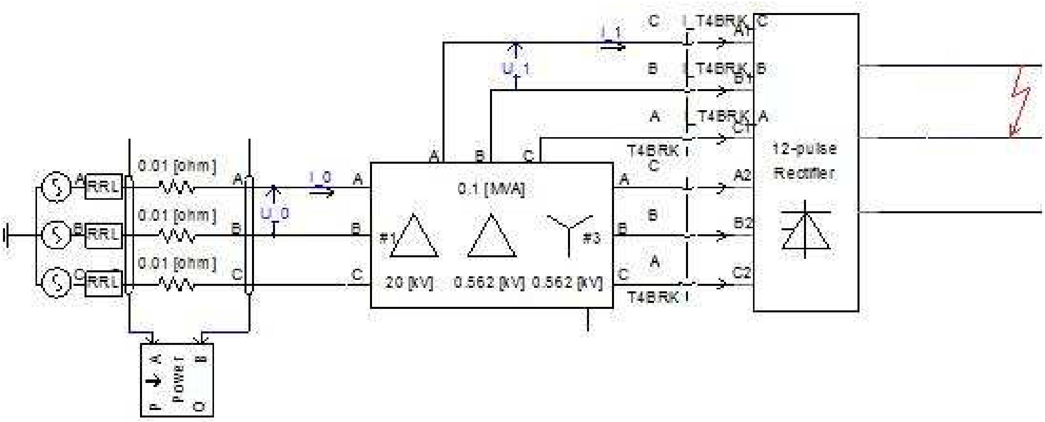


Fig. 4.2. Short circuit realisation in the program.

Figures 4.3, 4.4 and 4.5 show the results of simulation in the PSCAD-EMTDC program:

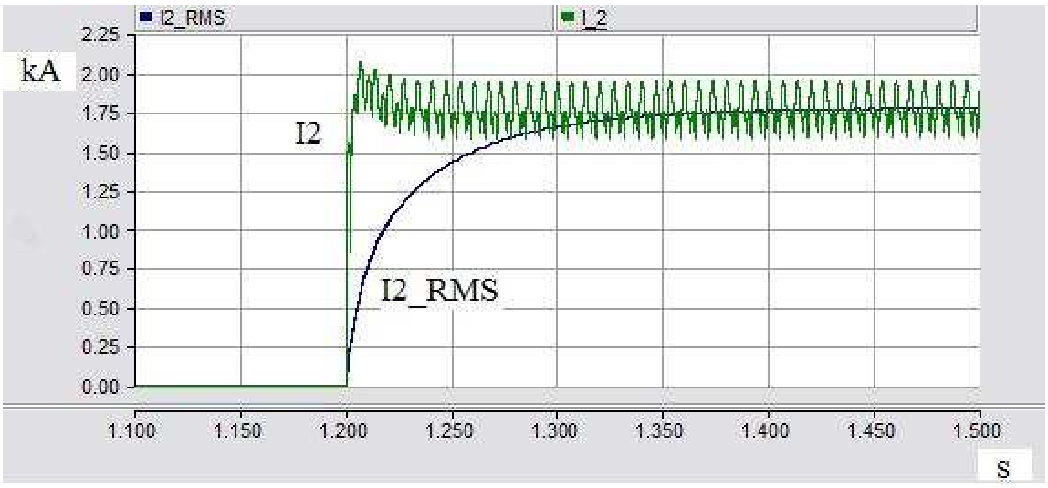


Fig.4.3. Change of DC short circuit current in transformer with short circuit impedance $Z_{sc} = 10\%$.

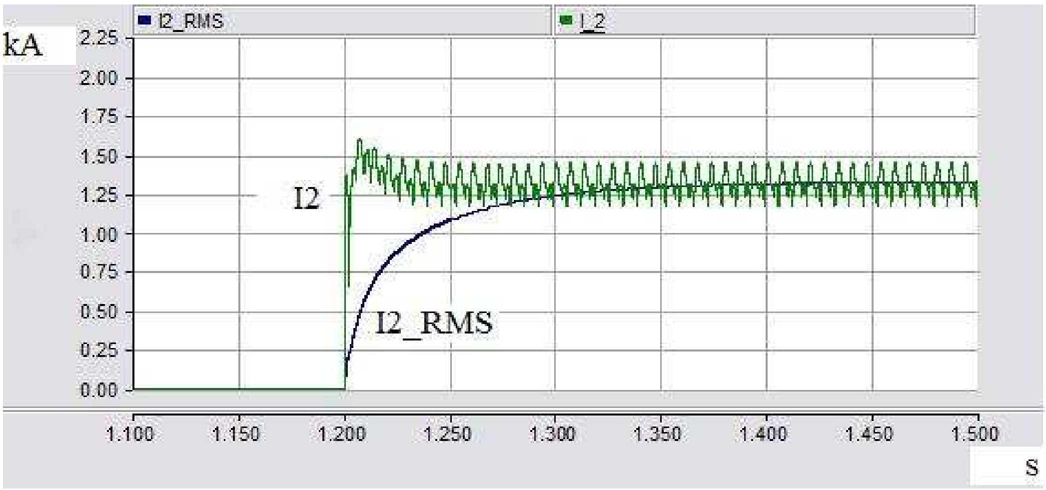


Fig.4.4. Change of DC short circuit current in transformer with short circuit impedance $Z_{sc} = 12\%$.

The results of simulations shows that short circuit current at LVDC distribution system changes inversely proportional to the short circuit impedance. It shows graph at the figure 4.5.

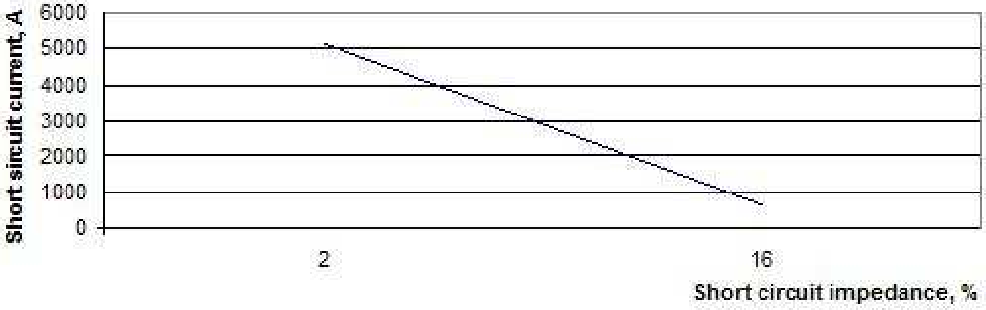


Fig.4.5. Dependence of DC short circuit current on transformer per-unit short circuit impedance.

From the point of view of limiting short circuit currents the transformer should be designed so that the short circuit impedance is very big. But it is necessary to remember that with increasing short circuit impedance the losses also increase in the transformer.

4.3 Reducing of influence of higher harmonics

To compare the influence of parameters of the transformer at 5 kW loading on a spectrum of harmonics between the power supply and the transformer and between the transformer and the rectifier simulation of LVDC distribution system in program PSCAD-EMTDC has been made. Figure 4.6 shows part of model of LVDC distribution system.

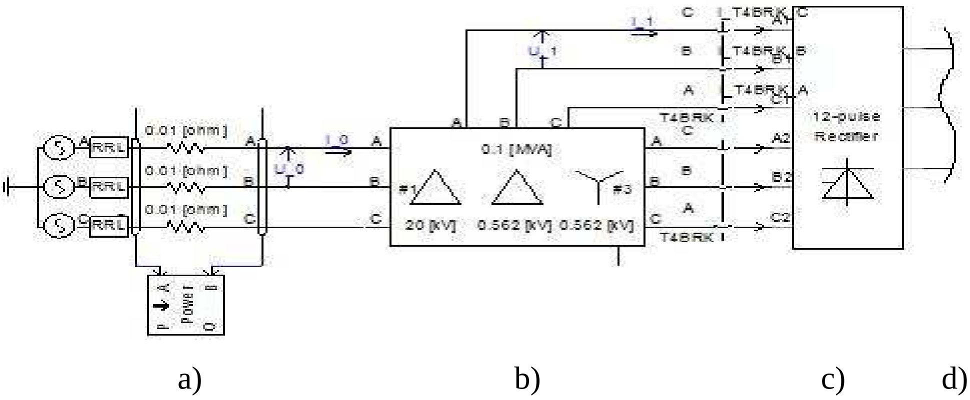
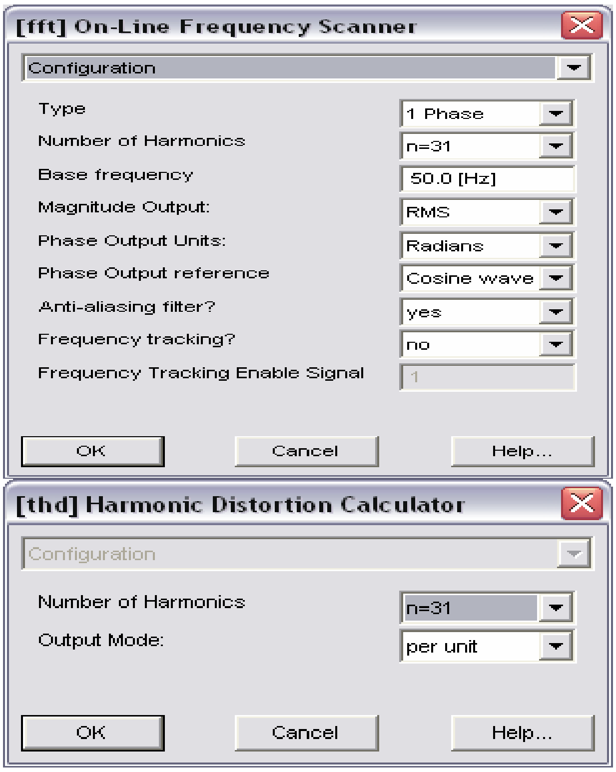


Fig. 4.6. Part of model of LVDC distribution system which has been created in PSCAD-EMTDC program. a) power supply, b) transformer, c) 12-pulse rectifier, d) distribution lines.

Using the PSCAD-EMTDC program interface it is necessary to set parameters which are applicable to target spectrum of harmonics, particularly quantity of harmonics, base frequency, magnitude output and so on. All parameters which were used for reception of spectrum of harmonics are presented in figure 4.7.

The harmonic computations are based on a standard Fast Fourier Transformation (FFT) technique, used in digital signal processing. The basis function for computation of phase angle can either be a fundamental frequency cosine waveform or a sine waveform starting at time - 0.

The harmonics computed are with respect to a given constant fundamental frequency. For situations where the fundamental frequency is variable, the use of a frequency-tracking device is available to the user. The frequency-tracking unit uses the fundamental component of the input signal corresponding to the previous sampling instance (as computed by the FFT routine), to monitor small changes in the frequency of the input signal. This element is meant to monitor minor fluctuations of frequency. Frequency tracking may be enabled or disabled at users discretion.



[fft] On-Line Frequency Scanner

Type	1 Phase
Number of Harmonics	n=31
Base frequency	50.0 [Hz]
Magnitude Output:	RMS
Phase Output Units:	Radians
Phase Output reference	Cosine wave
Anti-aliasing filter?	yes
Frequency tracking?	no
Frequency Tracking Enable Signal	1

[thd] Harmonic Distortion Calculator

Number of Harmonics	n=31
Output Mode:	per unit

Fig. 4.7. Parameters of output result which has been given in PSCAD-EMTDC program.

Figure 4.8 shows the scheme which were realized in the PSCAD- EMTDC program. It consist of two main parts: on-line frequency scanner and harmonic distortion calculator. Harmonic distortion calculator measures both total and individual harmonic distortion of an input signal according to equation (2.2). This component is optimally designed for use with the on-line frequency scanner component. On-line frequency scanner is an Fast Fourier Transformer (FFT), which can determine the harmonic magnitude and phase of the input signal as a function of time. The input signals first sampled before they are decomposed into harmonic constituents. This component is meant for processing signals consisting of power frequencies (typically 50 Hz and 60 Hz) and its harmonics.

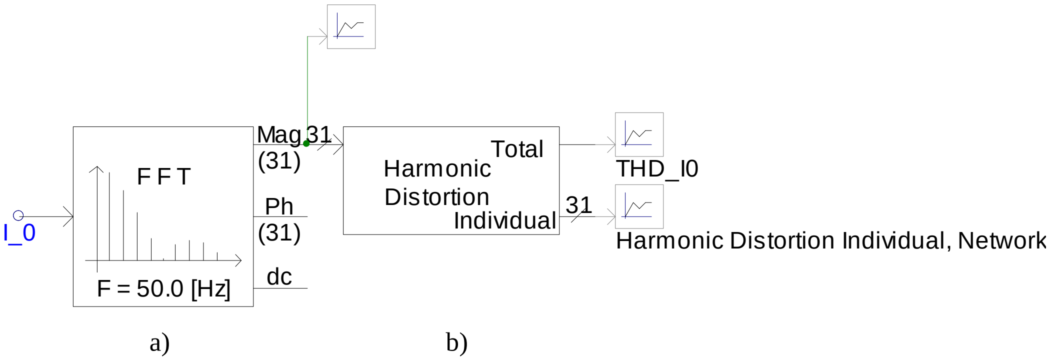


Fig. 4.8. The scheme realised in the program for calculation of THD. a) On-line frequency scanner; b) Harmonic distortion calculator

In figure 4.9 and 4.10 shows the spectrum of harmonics between power supply and the transformer with various short circuit impedance. The given simulations have been made to estimate influence of short circuit impedance on THD.

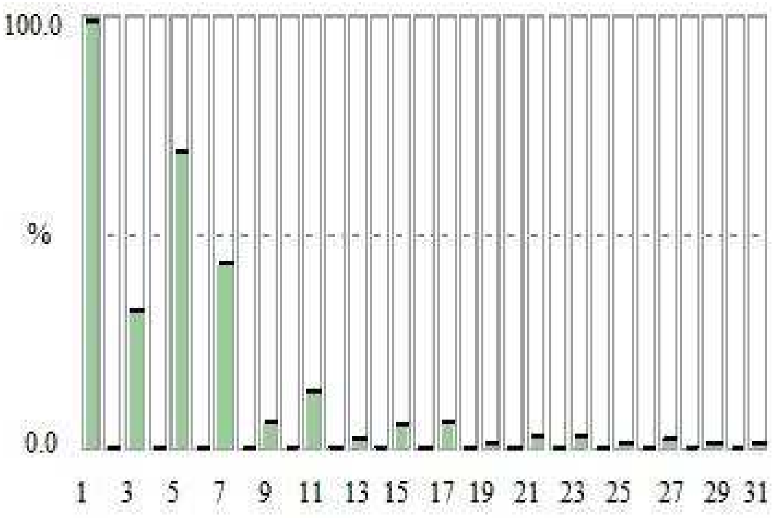


Fig.4.9. Fundamental and harmonics between the power supply and the transformer with short circuit impedance $Z_{sc} = 4\%$.

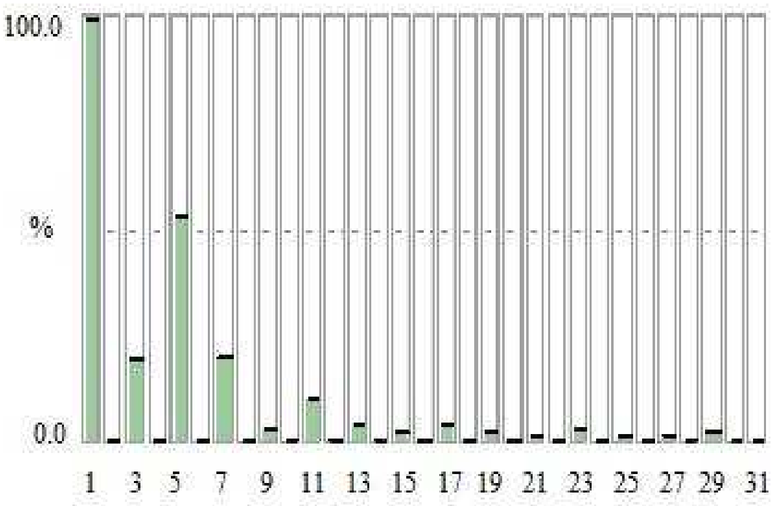


Fig. 4.10. Fundamental and harmonics between the power supply and the transformer with short circuit impedance $Z_{sc} = 16\%$.

Graphs on the figures 4.11 and 4.12 present the dependence THD between power supply and transformer on short circuit impedance and leakage of transformer at use of 6-pulse and 12-pulse rectifier. Obviously that value of THD falls with increase short circuit impedance, but does not reach values of existing standards

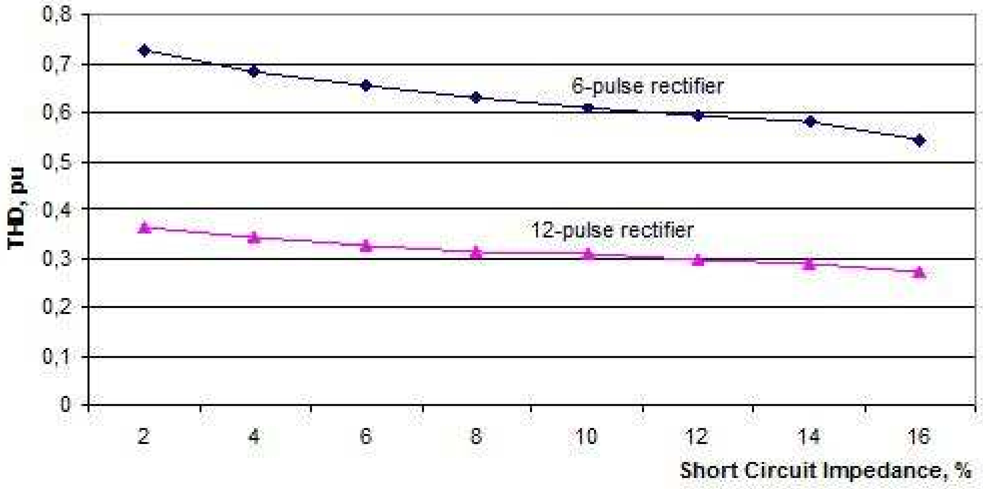


Fig. 4.11. Dependence of THD between the power supply and the transformer on short circuit impedance.

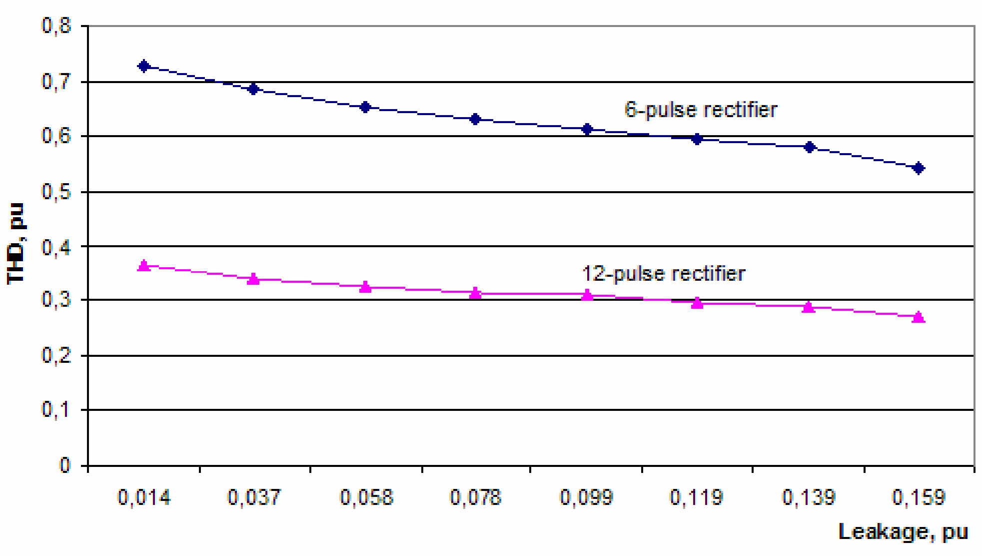


Fig. 4.12. Dependence of THD between the power supply and the transformer on leakage X_L .

The figures 4.13, 4.14 and 4.15 shows the same results of simulations but only between transformer and rectifier. If to consider the difference between the values of THD between of power supply and rectifier and between transformer and rectifier that it is only 3 percent.

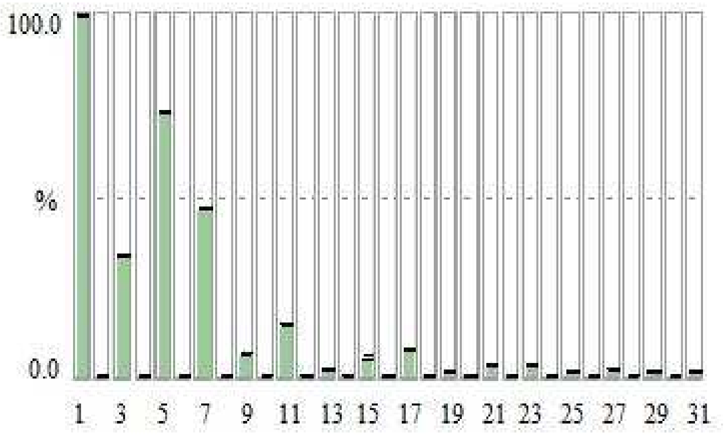


Fig.4.13. Fundamental and other harmonics between the transformer with short circuit impedance $Z_{sc} = 4\%$. and the rectifier.

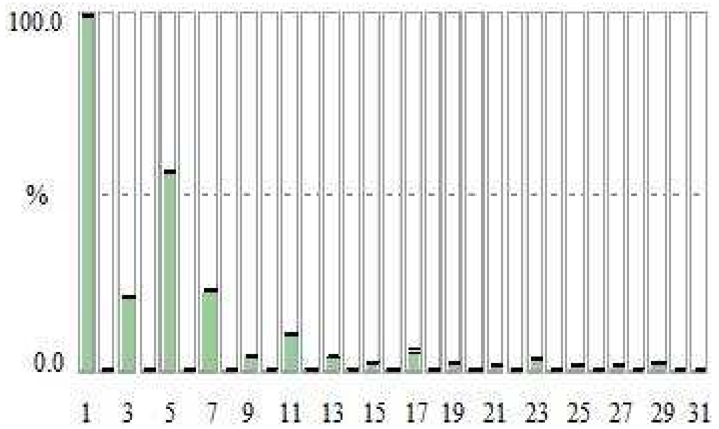


Fig. 4.14. Fundamental and other harmonics between the transformer with short circuit impedance $Z_{sc} = 16\%$. and the rectifier.

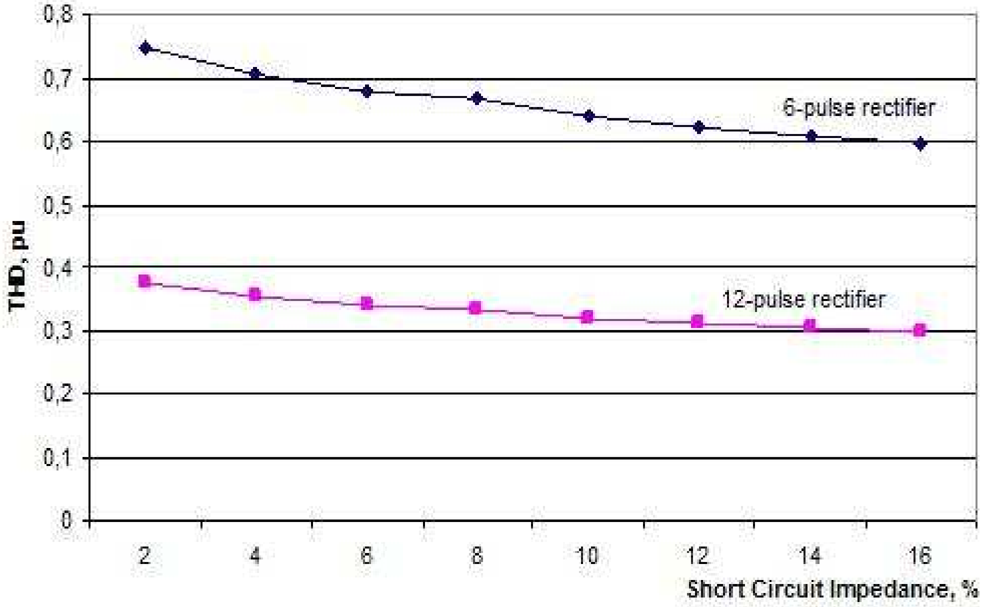


Fig.4.15. Dependence of THD between transformer and the rectifier on short circuit impedance.

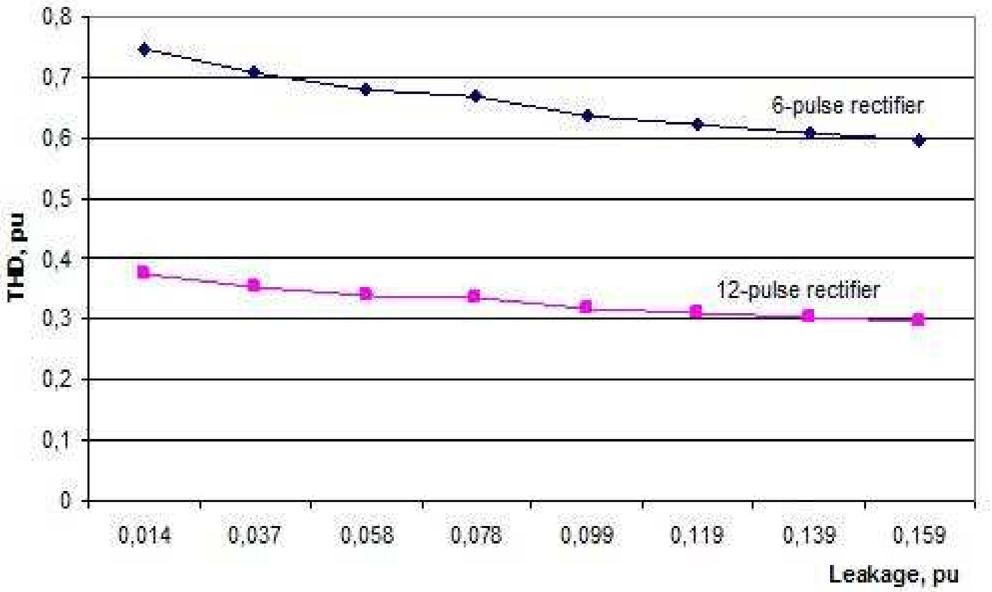


Fig. 4.16. Dependence of THD between transformer and the rectifier on leakage X_L .

The results of simulations showed that THD between the power supply and the transformer and between transformer and the rectifier is higher than it is specified in the IEEE Standard 519-1992 (IEEE 1993) at various values of short circuit impedance of transformer. For this reason changes of existing LVDC distribution system should be made.

One of the ways to reduce THD at LVDC distribution system is to use 12-pulse rectifier instead of 6-pulse, which helps to reduce THD by 50 %. The next way is to use harmonics filters. In some cases, reactors alone will not be capable of reducing the harmonic current distortion to the desired levels. In these cases, a more sophisticated filter will be required. The common choices include shunt connected, tuned harmonic filters {harmonic traps) and series connected low pass filters (broad band suppressors). They consist of a capacitor and an inductor which are tuned to a single harmonic frequency.

4.4 Calculation of losses under harmonic loading

In this section the main result of calculation of losses of transformer with different short circuit impedance under harmonic loading will perform in the table 4.3.

The general parameters of a 100 kVA three phase transformer with different short circuit impedance are summarized in the table 4.1. The values of load and non-load losses were calculated approximately by the linear model of transformer for transformers with different short circuit impedance.

Table 4.1. Transformer parameters.

Parameter	U_1, V	I_1, A	U_2, V	I_2, A	$P_{NL,}$ W	$P_{LL,}$ W
Transformer with Z_{sc}= 4 %	20000	2.89	562	103	220	1475
Transformer with Z_{sc}= 16 %	20000	2.89	562	103	610	2228

Table 4.2. Harmonic specification for first 11 harmonics.

Harmonic order	3	5	7	9	11
Magnitude(Transformer with Z_{sc}= 4 %)	0.33	0.69	0.44	0.059	0.14
Magnitude(Transformer with Z_{sc}= 16 %)	0.20	0.52	0.21	0.035	0.11

Table 4.3. Losses under harmonic load.

	Transformer with Z_{sc}= 4 %		Transformer with Z_{sc}= 16 %	
Type of losses	Rated losses, W	Losses under RMS harmonic load current, W	Rated losses, W	Losses under RMS harmonic load current, W
Non-load	220	220	610	610
dc	987	1779	1491	2052
Winding eddy current	161	10330	243	10210
Other stray	326	2499	494	2627
Total load	1474	14608	2228	14889
Total	1694	14828	2838	15499

The increase in losses under loading is connected with big values of THD. But the purpose of the given research was to understand on how many percent every component of load losses will increase under harmonic load if short circuit impedance of transformer will increase. As we see, the greatest change occurs with eddy currents which have increased by a factor of 2 and become the greatest losses in the transformer. Thus, it is possible to assume that at level of THD which corresponds to standards, it is possible to expect the same percentage change of each of a component of load losses.

4.5 Voltage Drop in supply transformer

One of the most important constraints on distribution system design is the voltage level at the customer intake point. This is particularly important for the vast majority of customers taking supplies at low voltage with no means of adjusting the voltage received. A knowledge of the voltage at different locations can indicate the strong and weak parts of a network.

The voltage-drop phasor U_{d} for a section of line having an impedance Z and carrying current I is given by

$$U_{\mathrm{d}} = \underline{Z} \cdot \underline{I} \tag{4.1}$$

In distribution systems it is the arithmetic difference between the sending- and receiving-end voltages which is the more useful voltage-drop value. A close approximation to this can be obtained from the simplified equivalent circuit shown in figure 4.17. The circuit has resistance R, reactance X, sending-end voltage U_{s}, and receiving-end voltage U_{r}. It carries current I lagging on U_{r}. The equivalent phasor diagram is given in figure 4.18.

During normal load-flow conditions the angle between the receiving- and sending-end voltages U_r, and U_{s} is only a few degrees. For most practical cases the approximation $\varphi = \varphi^{/}$ is acceptable, so that the scalar relationship can be written as:

$$U_{\mathrm{s}} = U_{\mathrm{r}} + I \cdot R \cdot \cos\varphi + I \cdot X \cdot \sin\varphi \tag{4.2}$$

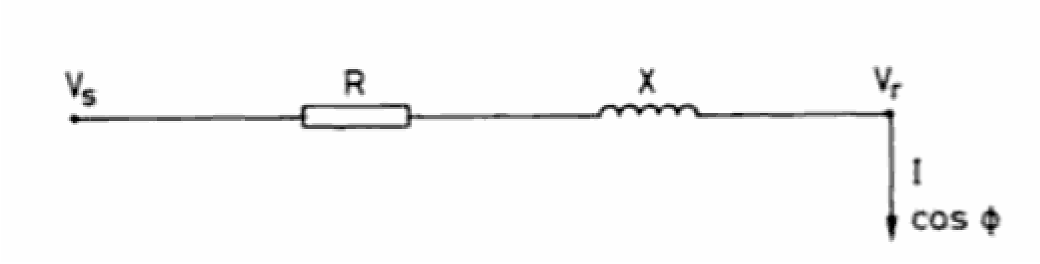


Fig. 4.17. Single-phase equivalent circuit for a section of line. (Lakervi 2008)

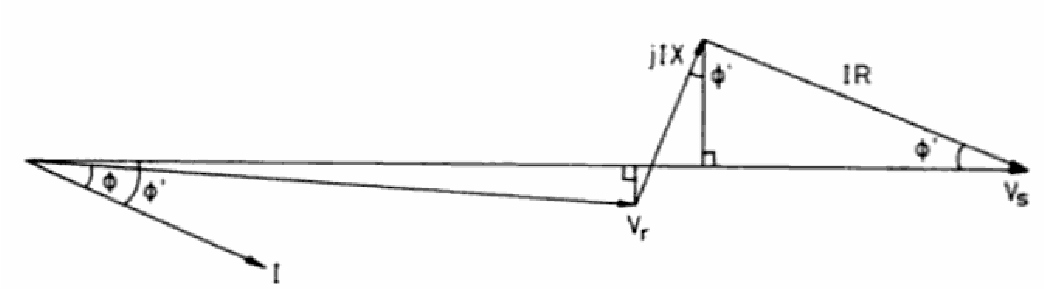


Fig. 4.18. Phasor diagram for the line represented in the figure 4.17. (Lakervi 2008)

The voltage drop U_d in the line is given by:

$$U_\mathrm{d} = |U_\mathrm{s}| - |U_\mathrm{r}| = I \cdot R \cdot \cos\varphi + I \cdot X \cdot \sin\varphi = I_\mathrm{r} \cdot R + I_\mathrm{q} \cdot X \qquad (4.3)$$

In equation. 4.3 I_p and I_q represent the resistive and reactive components of the load current I. In single-phase calculations the resistance and reactance of the return path must be included in R and X. For 3-phasc systems the voltage drop in line-line voltage can be calculated from:

$$U_\mathrm{dLL} = \sqrt{3} \cdot \left(I_\mathrm{r} \cdot R + I_\mathrm{q} \cdot X\right) \qquad (4.4)$$

Voltage flexibility can be calculated by:

$$U_\mathrm{n} = 100 \cdot \sqrt{3} \cdot \left(I_\mathrm{r} \cdot R + I_\mathrm{q} \cdot X\right) / U = 100 \cdot \frac{P}{U} \cdot \left(R + X \cdot \tan\varphi\right) \qquad (4.5)$$

The results of calculation for LVDC distribution system shows figures 4.19 and 4.20 :

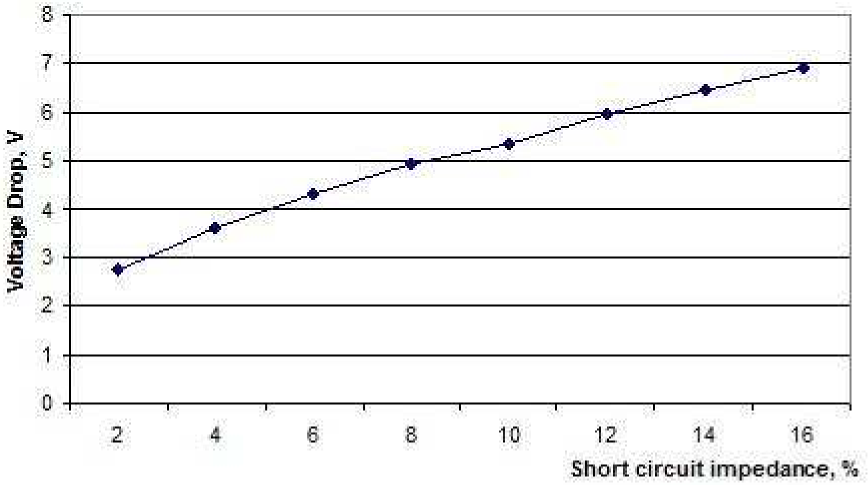


Fig. 4.19. Dependence of Voltage Drop on short circuit impedance at $\cos\varphi = 0,95$.

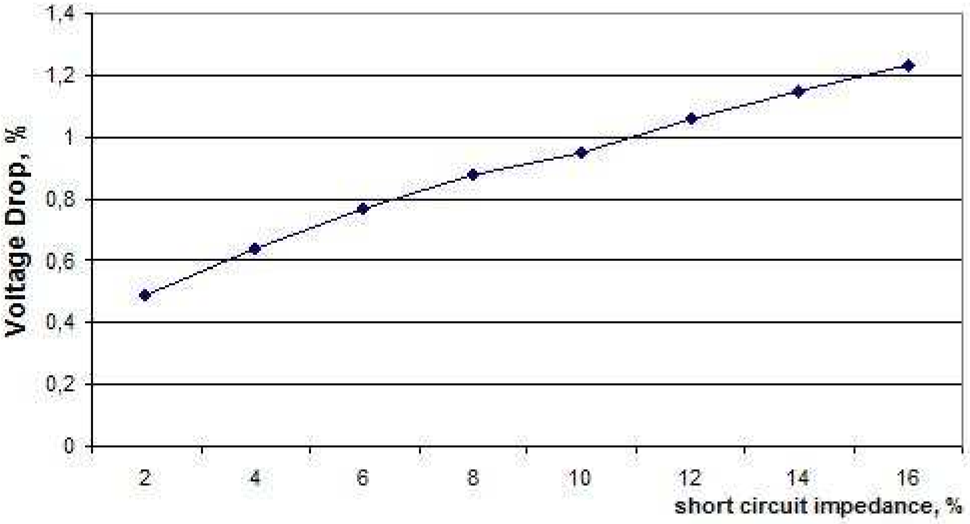


Fig. 4.20. Dependence of Voltage Drop on short circuit impedance at $\cos\varphi = 0,95$.

According to the EN 50160 standard the voltage drop have to be less then 10 % from RMS value of supply voltage. This parameter of distribution system is very important because it shows the difference between of the magnitudes of the sending and receiving voltages. If the level of voltage will be too low or high, some of devices does not work well.

From this point of view possibility of designing of the transformer with the big short circuit impedance for limit short circuit currents is possible.

5 Conclusions

Master thesis was focused on analysis of parameters of transformers from the different viewpoints of its use for LVDC distribution system. From the point of view of limiting of short circuit currents, as a result of work it has been established that one of the ways to solve this problem is to design the transformer with a higher short circuit impedance then standard transformers. It is possible to do so by special arrangements of windings under the relation to each other or to manufacture the core of transformer with an air gap.

Increasing of short circuit impedance leads to a increasing losses in the transformer, therefore level of losses in the transformer will be the main limiting factor at short circuit impedance increase. For exact calculation of losses it is necessary to lower level of THD which is caused by the rectifier to existing standards because influence of harmonics is too high.

The results of simulations show that to use of the transformer as the filter of the higher harmonics irrationally because it reduces THD only for 3 percent. In this connection it is necessary to offer ways of the solving of this problem.

First of all 12-pulse rectifier is recommended to be used instead of 6-pulse rectifier that will decrease the level of THD by 2 times. Another way to solve this problem is by a filter of the higher harmonics which is fixed between the transformer and the rectifier or installation of the smoothing inductance coil in DC section of LVDC distribution system. Designing of the filter and the inductance coil is the important problem which is offered to be solved in the future works.

Optimisation of characteristics of the transformer is very difficult question. But the results of the works shows that transformer with higher short circuit impedance then tradition distribution transformer could be useful in the LVDC distribution system. But selecting optimal transformer characteristics require further studding including economical optimisation within the boundaries defined in this thesis

References

De Keulenaer Hans. 2008. Power Quality and Utilization, EPQU journal Vol. 16 №1

Energy Manager Training, [Available online at http://www.energymanagertraining.com/power_plants/Transformers.htm, May 19, 2009]

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

Gilmour Rick. 2002. Safety Standard for Electrical Installations, Canadian Standards Association, Toronto, Ontario Canada 2002.

Hulshorst W.T.J., Groeman J.F. 2002. Energy Saving In Industrial Distributional Transformers. KEMA 2002.

Lakervi Erkki, Partanen Jarmo. 2008. Electricity Distribution Technology. Lecture book, 2008. LUT

Lassila Jukka, Lappeenranta University of Technology. 2008. Is There Economical Potential For The Low Voltage DC Electricity Distribution. NORDAC 2008.

LVD 2006/95/EC European Commission. Low Voltage Directive, European Union Directive, Brussels 2006.

Markiewicz Henryk, Klajn Antony. 1999. Standard EN 50160 - Voltage Characteristics in Public Distribution System. Wroclaw University of Technology 1999.

National Fire Protection Association, National Electrical Code, 2005 edition Quincy MA, FPN 4 to rule.

Renner Herwig, Sakulin Manfred. 2007. Power Quality. Course material, Helsinki University of Technology 2007.

Sadati S. B., Tahani A, Darvishi, Mazandarn B. Comparison of Distribution Transformer Losses and Capacity under Linear and Harmonic Loads. IEEE International Conference on Power and Energy 2008.

Sener, Jakeluverkon sahkon laadun arviointi (in Finnish). Helsinki 2001. Finnish Electricity Association SENER.

Siemens, Power Engineering Guide, Transmission and Distribution 4th edition. Siemens Aktiengesellschaft, Power and Distribution Group.

Surahammars Bruk, [Available online at http://www.sura.se/Sura/hp_main.nsf/startupFrameset?ReadForm, May 19, 2009]

Vecchio Robert M. Del, Poulin Bertrand, Feghali Pierre T., Shah Dilipcumar M., Ahuja Rajendra. 2002. Transformer Design Principles With Applications to Core-Form Power Transformer. 2002

Wilson Paul. 2005. Users Guide of EMTDC, Research Center of Canada 2005.

Wilson Peter R., Ross J Nail, Brown Andrew D. 2003. Predicting Total Harmonic Distortion (THD) in ADSL Transformers using Behavioral Modeling 2003.

Тихомиров П. М.. 2008. Расчет Трансформаторов. Учеб. пособие для вузов.