A study of life time management of Power Transformers at E. ON's Öresundsverket, Malmö

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Preface

This Master's Thesis was carried out at E.ON Värmekraft, Öresundsverket in Malmö in cooperation with Division of Industrial Engineering and Automation at Faculty of Engineering at Lund University. This work is the final part of my master's degree in electrical engineering.

During this project, I have got quite a lot support and help and first of all would like to thank E.ON Värmekraft for giving the opportunity to carry out this project. I would also like to thank my supervisors, Jonas Stenlund at E.ON Värmekraft and Olof Samuelsson at the Division of Industrial Electrical Engineering and Automation, LTH for their help and support.

I would like to further thanks to Mårten Svensson at Vattenfall, Mark Wilkensson at SMIT transformer, ABB power transformers team and many more who took their precious time to help and guide in this project.

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Abstract

The objective of this master thesis is to review the present and future condition of generator step up power transformers at the combined heat and power plant Öresundsverket, in Malmö.

The objective of this work was to prolong the lifetime of power transformers at Öresundsverket.

The thermal properties of power transformer are been taking into consideration for their life time assessment.

The most suitable thermal model was chosen which can prolong life to these transformers in the future. Electrical, mechanical and chemical properties of power transformers were taking in account for evaluation. The comparisons were made between different calculated models to find the most suitable thermal model for transformers.

Sammanfattning

Målet med detta examensarbete är att granska nuvarande och framtida kontroll av funktionsdugligheten för aggregattransformatorerna i Öresundsverket i Malmö som ägs av E.ON Värmekraft.

Syftet med detta arbete är att förlänga livslängden på transformatorerna på Öresundsverket.

Termiska egenskaper togs med i beräkningarna för att säkerställa vilka parametrar som inverkar på livslängden hos krafttransformatorerna.

För att utvärdera den mest relevant modellen så jämfördes resultaten av olika modeller. Den termiska modellen som gav högst förlängd livstid hos krafttransformatorerna fastställdes som slutgiltig modell. Denna bedömning utgår från att studera hur krafttransformatorers elektriska, mekaniska och kemiska egenskaper ändrar sig vid olika driftförhållande.

Terminology

AC	Alternating Current
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BAT 10	Gas turbine generator step-up transformer
BAT 50	Steam turbine generator step-up transformer
DP	Degree of Polymerization
FAT	Factory Acceptance Test
GSU	Generator Step Up
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MSEK	Million Swedish Kronor
ODAF	Oil Direct Air Flow
OFAF	Oil Forced Air Flow
ONAF	Oil Natural Air Flow
ONAN	Oil Natural Air Natural
PGIM	Power Generation Information Management
TCG	Total Combustible Gases
TDCG	Total Dissolved Combustible Gases
Trafo.	Transformer
ÖVT	Öresundsverket

Contents

1 Introduction

This chapter contains background, objective, approach and outline of this thesis.

1.1 Background

’’The reliable supply of power in form of electricity to industrial, commercial and domestic consumers has come to underpin the economies and standard of living of industrial world. The efficient transmission of bulk electrical power from where it’s produced to where it’s consumed relies critically on ability to reduce transmission losses by reducing the transmitted current. The invention of transformers over 100 years ago brought the ability to achieve this by increasing the transmission voltage and thus decreasing the current.’’ ***[ABB Transformer Manual]***

The power transformers are important and expensive elements of a power system. In case of failure of power transformer would cause long interruptions in power supply with consequent loss of reliability and revenue to the supply utilities. The normal delivery time of a new large power transformer, in case of failure can vary from half a year to one year. Early detection of all possible causes leading to an impending failure in any part of transformer reduces failure risk, thereby enhancing the life and reliability of transformer in power system.

The goal for this project is to study and analyze most appropriate cooling method for the power transformers at E.ON’s Öresundsverket in Malmö. The final goal will be to implement this method for better function and prolong lifetime of power transformers.

1.2 Objective

The main objective of this master thesis is to analyze thermal conditions of power transformers through monitoring of measured data. This data is used to estimate influence of different parameters on transformer’s lifetime.

1.3 Approach

The analysis in this report is based on general information on loading characteristics of representative power transformers in form of ¨Loading Guides of Power Transformers¨ by standardized bodies like IEC, IEEE, ANSI and ASTM (refer to terminology list).

Protocols from Heat Run test from transformer Factory Acceptance Tests (FAT) have also been studied. Heat Run test from Factory Acceptance Tests is a thermal performance running test conducted at the factory to check the integrity of the equipment.

Interpretation of transformers oil condition and dissolved gas analysis results have been studied at different occasions to get a deeper understanding of power transformers present and future conditions of the power generator step up transformers at Öresundsverket.

Futhermore, interviews with power transformer manufactures and experts were carried out.

Study visits to Karlshamnsverket, Karlshamn and Åbyverket, Örebro were also done to study the generator power transformers condition at these places.

1.4 Outline of the thesis

This thesis report has following outline:

- Chapter 2 and 3 covers the general principle of the transformers and the types of power transformers found in power generation plant and electricity distribution networks. The transformer in ideal, practical and major differences between different types of power transformers are explained here.
- Chapter 4 covers the design of power transformers. This chapter explains different parts of transformers and their significance in electrical and mechanical properties of transformers. Different standard terms, explaining the transformer's properties are also mentioned here under ratings.
- Chapter 5 and 6 covers the thermal design and insulation of transformers. These chapters explain the different types of cooling system present and role of insulation in the transformers.
- Chapter 7 explains the thermal degradation in transformer's insulation and influence of various factors on aging of insulation.
- Chapter 8 and 9 illustrates the transformer's oil and gas formation in transformation. Chapter 8 gives detail information about oil's properties and their influence. The following chapter explains the various methods of interpretation and evaluation of gas analysis.
- Chapter 10 gives the detail version of thermal aging of power transformers based on different standardized bodies.
- Chapter 11 is the case study of power transformers at Öresundsverket. The above mentioned analysis and methods have been implemented for reaching to conclusion.
- The report ends with Chapter 12 and 13 which are conclusion of the work and further scope of this thesis.

2 Transformers: General Principles

This chapter contains some general theory of the transformers. The ideal transformer for one phase is studied and then applied to developed theory of three-phase transformers in practical.

2.1 Magnetic Induction in one winding

This section of the chapter is based on Johannesson N.(2010).

Power transformers work on the electromagnetic principle just like any other electric machine. The ideal transformer also works on the following principle:

Magnetic flux (Φ) through area (A) and magnetic flux density (B) is given by:

$$\Phi = B \cdot A \tag{2.1}$$

Magnetic flux in a coil depends on number of turns (N), current (I), length of coil (l) and permeability (μ) which is material dependent:

$$B = \frac{\mu \cdot N \cdot I}{l} \tag{2.2}$$

According to Faraday's induction law rate of change of flux through coil surface induces an electromotive force (EMF):

$$e = -\frac{d\Phi}{dt} \tag{2.3}$$

Negative sign is explained by Lenz law which opposes any change in the magnetic flux producing EMF.

If N is number of winding turns which are series connected the total voltage over the coil will be N times the EMF and is given as follows:

$$u\,(t) = N \cdot e(t) \tag{2.4}$$

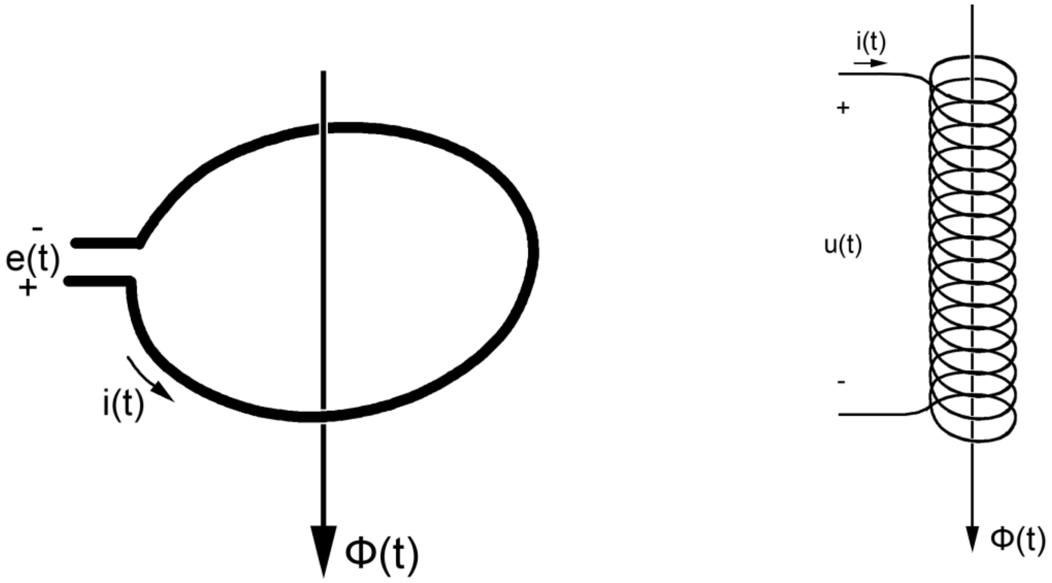


Figure 2.1 Direction of current and induced EMF in a coil with one and N turns in a magnetic flux **[1]**

Magnetic flux (Φ) as a function of voltage (u) is given by integrating the above equation 2.4 gives:

$$\Phi\ (t) = \frac{1}{N}\int u\ (t)\, dt \qquad (2.5)$$

The above two equations 2.4 and 2.5 shows the relation how voltage and magnetic flux are time dependent.

2.2 The ideal transformer with two windings

This section of the chapter is based on Johannesson N. (2010).

The ideal transformer theory is based on magnetic induction as described above, but in two steps from voltage to flux and from flux back to a possibly different voltage. In other words ideal transformer is based on principle of transfer of magnetic energy between two coils in a closed magnetic circuit.

The ideal transformer has the following characteristics:

- The resistances of the windings are negligibly small.
- Permeability of the core is so high that a negligibly small magneto motive force (MMF) produces the required flux and that there is no magnetic flux loss i.e. all flux goes through the core.
- The core loss is negligibly small.
- The capacitances of the windings are negligibly small.

When the voltage is applied to the primary side of the transformer, the magnetic flux induces the voltage on the other side of transformer through core.

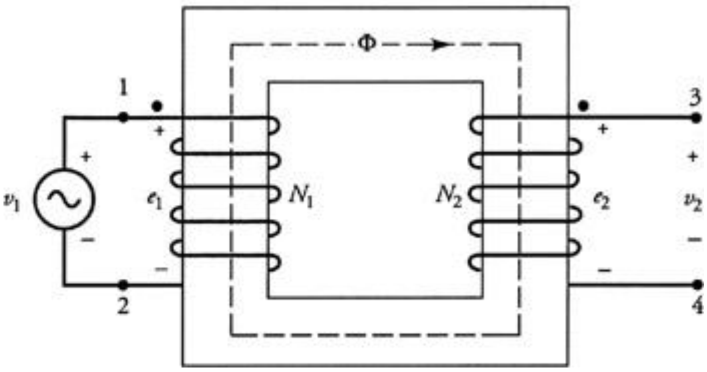


Figure 2.2 The single phase ideal transformer ***[1]***

When the alternating voltage is applied on the primary side with constant frequency, the induced voltage on secondary side will have the same frequency but different amplitude and phases. The phase of the secondary voltage is usually shifted by π/2, which gives following:

$$\Phi = |\Phi| \cdot e^{j\omega t} \tag{2.6}$$

$$\frac{d\Phi}{dt} = |\Phi| \cdot e^{j(\omega t + \frac{\pi}{2})} \tag{2.7}$$

Voltage over primary and secondary side of transformer can be given as in equation 2.4 which leads to:

$$u_1 = N_1 \cdot \frac{d\Phi}{dt} \tag{2.8}$$

$$u_2 = N_2 \cdot \frac{d\Phi}{dt} \tag{2.9}$$

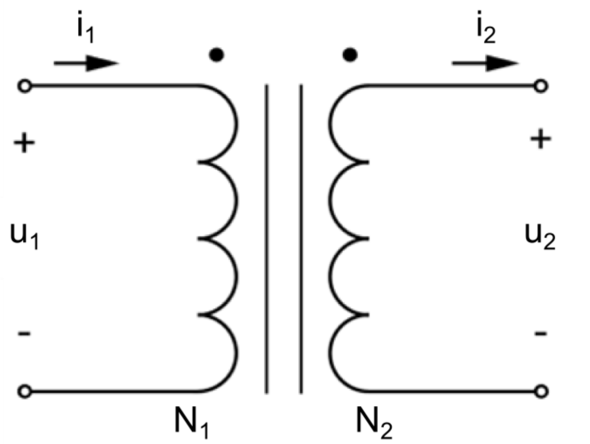


Figure 2.3 The circuit diagram of an ideal transformer ***[1]***

Since the transformer is ideal, all the energy is transferred from primary to secondary with zero losses. Thus the following equations are valid for energy transfer:

$$u_1 iI_1 = u_2 i_2 \tag{2.10}$$

$$\frac{i_2}{i_1} = \frac{u_1}{u_2} = \frac{N_1}{N_2} \tag{2.11}$$

The above equations are derived for ideal transformer but also work quite well with some modifications for a transformer in reality.

2.3 Practical transformers

This section of the chapter is based on Johannesson N. (2010) and E.E. Staff M.I.T. Magnetic Circuits and Transformers (1943).

A practical transformer has the following characteristics:

- The windings have non-zero resistance.
- There is magnetic flux loss i.e. not all the flux passes through the core.
- The presence of capacitance in the windings.

When displacement currents due to the capacitances of the windings are neglected, the fundamental principles from which the theory of transformers is developed are expressed in the following voltage equations:

$$u_1 = R_1 i_1 + N_1 \frac{d\Phi_1}{dt} = R_1 i_1 + e_1 \qquad (2.12)$$

$$u_2 = R_2 i_2 + N_2 \frac{d\Phi_2}{dt} = R_2 i_2 + e_2 \qquad (2.13)$$

where the subscripts 1 and 2 refer to primary and secondary windings of transformer and:

u_1 and u_2 are instantaneous terminal voltages,
i_1 and i_2 are instantaneous currents,
R_1 and R_2 are winding resistances,
Φ_1 and Φ_2 are flux linkages,
e_1 and e_2 are induced voltages by time-varying flux linkages.

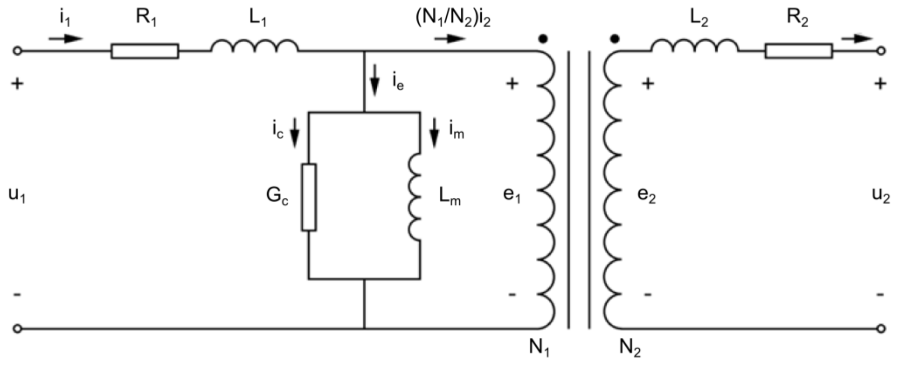


*Figure 2.4: Schematic diagram of a real transformer **[1]***

If the permeability of the core is constant, the flux linkages are proportional to the currents producing them and the flux linkages can be expressed as the sum of the components produced by each current acting alone. That is:

$$\Phi_1 = L_1 i_1 + L_M i_1 \quad (2.14)$$

$$\Phi_2 = L_2 i_2 + L_M i_2 \quad (2.15)$$

where L_1 and L_2 are leak-inductances of the windings and L_M is the mutual inductance.

In these equations the term of Li represent the component of flux linkage produced by the winding's own current and L_Mi is the component of flux linkage produced by the current in the other winding

The inductances L_1, L_2 and L_M are the constants of proportionality relating the component flux linkages and the constants of proportionality relating the component flux linkages and the currents producing them. The voltage equations for transformers windings can be written as:

$$u_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + L_M \frac{di_2}{dt} \quad (2.16)$$

$$u_2 = R_2 i_2 + L_2 \frac{di_2}{dt} + L_M \frac{di_1}{dt} \quad (2.17)$$

Unlike as in the ideal transformer case, there is an energy loss due to resistance presence in the windings. Reactance in the windings also causes a voltage drop on the secondary side of transformer.
Since the permeability of the iron core is not infinite in reality, there are losses in flux transfer to the secondary. In other words all magnetic energy cannot be transferred to the other side. The current I_e in the diagram above shows the losses in the iron core, which can be further, divided into real and imaginary part. This is due to reluctance presence which causes hysteresis and magnetic flux losses in the iron core of the transformer.

3 Power transformers

This chapter is based on ABB Industrial handbook (1998).

The development of high voltage oil filled power transformers has eased the three-phase alternating current electricity transmission and distribution systems. The basic technology remains as it has been for past century that is laminated iron core with paper insulated conductors which are made of copper. This iron core together with copper conductor and paper is immersed in a mineral oil filled steel tank. However there has been quite a lot of development in transformers area in terms of cost, size, electrical losses etc.

The transformers installed at power stations or substations must operate fault free over a long period of time. Transformers in turn rely on a number of factors to provide desired voltage and current. The primary function of the power transformer is to reduce the transmission cost in electrical power system. It reduces the transmission losses by reducing the required current for transmission. This cost reduction is achieved by increasing the transmission voltage in the system. For long transmission routes, very high voltages up to 750 kV are preferred while for common transmission 550 and 400 kV voltages are preferred. To fulfill this variety of voltages and power, power transformers are required from generation plant to consumer. The voltage variations are done by step up or step down transformers. Step up transformer increases the voltage ration on secondary side while step down decreases the voltage ratio on the secondary winding side of transformer.

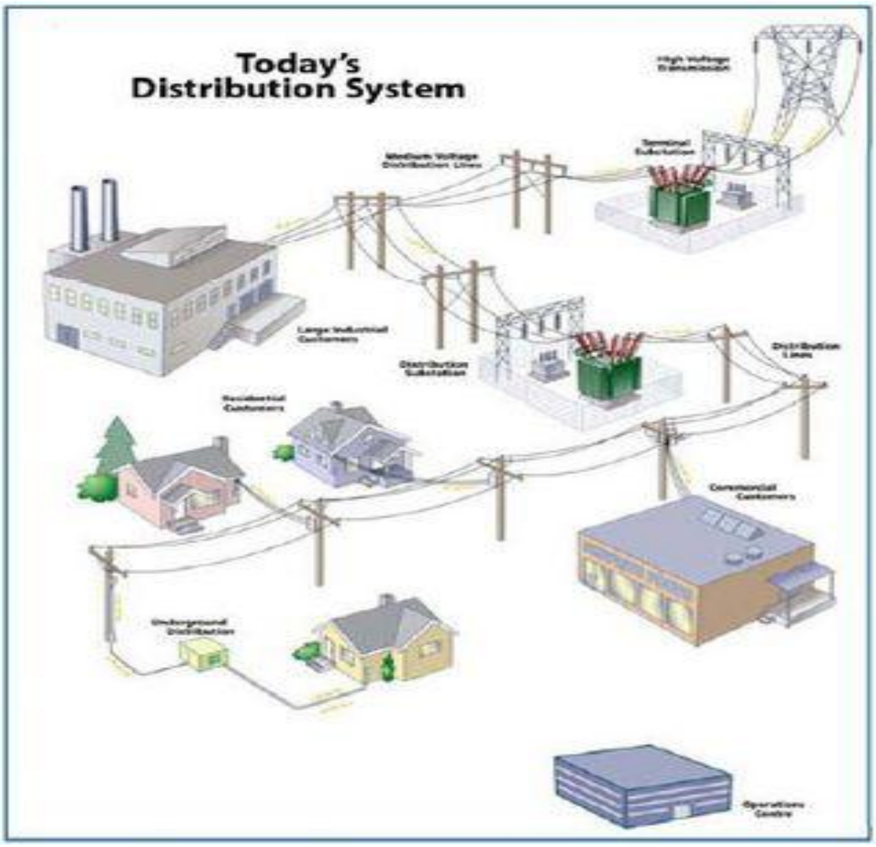


Figure 3.1 Power distribution system

Source: geospatial.blogs.com

3.1 Generator transformers

The operation voltage for generator transformers varies between 1 to 25 kV, depending on the size of the power generating plant. The generator transformer is usually connected with a power stations generator unit. The purpose of such kind of transformers is to step up voltage to network and reduce current by factor of about 20. Voltage and current produced by the generator at the power plant may not be exactly in same phase and this slightly increases the current required to transmit a given reactive power, so the generator transformer normally has a rating in MVA some are 10 to 20% higher than the generator MW ratings. Generator transformers normally run at maximum load at a power station and rarely subjected to overloads. Some of the biggest transformers in terms of size and weight are generator step up transformers, with power up to 1000 MVA and weight exceeding 500 tones.

3.2 Transmission transformers

Transmission transformers often known as inter-bus transformer are used to interconnect two or more voltages at transmission networks. Transmission transformers usually operate at main bulk supply substations to reduce the transmission voltage to the sub-transmission or distribution voltage. In addition to this these transformers can control sub-transmission voltages by means of tap changers, which can change voltage ratio. Transmission transformers also help to limit the current flow in a short circuit fault on lower voltage network. These transformers have ratings of 100 to 300 MVA and secondary voltages of 132 to 33 kV. These transformers are often installed in sets with at least one extra transformer so that load can be shared by another following a failure or during maintenance. As a result transmission transformers are normally loaded below their ratings throughout their operational life but are also capable of sustaining overloads up to 150% in case of emergency.

3.2 Distribution transformers

Distribution transformers can be easily distinguished as small units mounted in the residential areas. Distribution transformers can be up to 100 MVA and 33kV and have at least two stages of transformation. The first is from the sub-transmission voltage to the local distribution voltage and the second from this voltage to the domestic voltage supply voltage. The primary distribution transformers are usually less than 100 MVA and have two secondary windings. The secondary transformers are usually from few kVA to few MVA and can be seen mounted on poles. Tap changers are not present in these types of transformers, for change of voltage ratio the transformer is disconnected from system. Distribution transformers have no backup capability like in transmission transformers and therefore reliability of distribution is quite important to both customers and supplier.

3.3 HVDC transformers

It's economical to use direct current system for high capacity point to point links between the systems. For AC voltage to DC voltage six phase supply is needed. This is supplied from a three phase system by help of three single phase transformers each with two secondary windings. These kinds of transformers are simultaneously subjected to AC and DC stress, during isolation of DC voltages from the AC system. The insulation requirement for HVDC transformers are most complicated and highly stressed insulation due to stress caused in transformation.

3.4 Phase shifting transformers

Phase shifting transformers are used in a power system to change the flow of real power on a particular network. It's also known as quadrature booster. These transformers act to inject voltage in series with each circuit phase derived from the other two remaining phases such that injected and line voltage are in quadrature. Phase shifting transformers are two-three phase transformers with one connected as shunt providing input to the second connected in series with the line injecting the boost voltage.

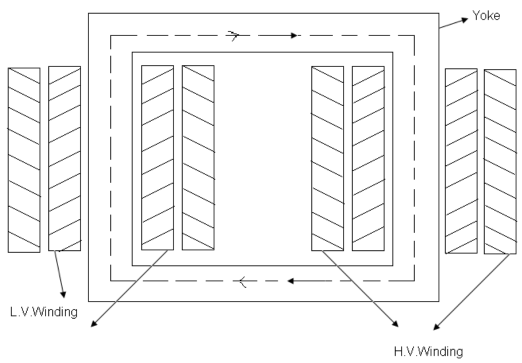
3.5 Other power transformers

There are numerous applications of power transformers other than the above mentioned examples. They can be used for static VAR compensating, railway supply, auxiliary power station supply and in industries for smelting and electrolysis. Most of the power transformers of such types have relatively low voltages and high currents.

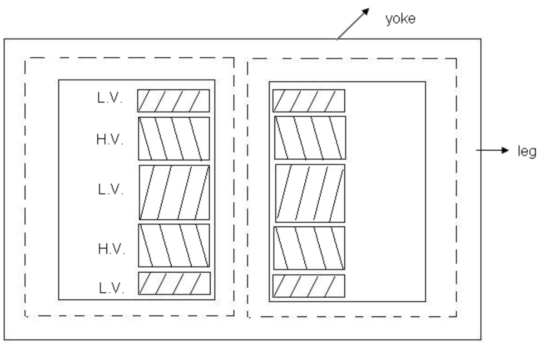
4 Power Transformers Design

This section of the chapter is based on E.E. Staff M.I.T. Magnetic Circuits and Transformers (1943) and Nynas Transformer Oil Handbook (2010).

There are two basic categories of transformer assembly, shell type and core type. These two types have identical function and only difference between the two designs is the customer's request, manufacturing cost and technique and space requirement etc. The figure below shows the two different types of transformer assembly.



(a)



(b)

Figure 4.1 Core type transformer (a) and Shell type transformer (b)
Source: upal.ca/docs/shell-core.html

The cores of power-system transformers are made of suitable annealed steal. This laminated magnetic steel part passes through the windings in the transformer. In addition to types of core which are mentioned above, silicon steel about 4 percent of annealed steel is also used in the core. This cuts down the manufacturing cost, improves permeability at high flux density and decrease the hysteresis and eddy current losses.

In core type transformer, the single core is linked by two groups of windings. In other worlds the limbs of the core are circular cross section with windings that are cylindrical in form of a concentric arrangement around them. The conductor configurations within the windings can vary, most common been disc, layer and foil types. Disc windings have the turns overlapping each other in a radial direction and crossovers between disks in an axial direction. For the cooling and insulation of oil, spacers are used. On the other hand, in layer windings the turns are wound next to each other in axial directions with crossovers and insulation in a radical direction between layers. The primary windings in small distribution transformers consist of a conducting copper or aluminum turns. The ends of core´s limb are connected together by means of yokes (a clip like structure) made of magnetic steel as in core. In a three phase transformer the yokes may simply connect the ends of the limbs in a three limb arrangement; this arrangement reduces the total height of transformer.

This core construction has some serious drawbacks also. First, there are air gaps in this core form. Second, there is hand labor involved in assembling the cores. Third, there are core losses due to flux traveling across the direction of the metal. In spite of these drawbacks, this design is widely used in large size power transformers.

Improvements in the manufacturing technique have resulted in cores in which magnetic flux is almost parallel throughout the direction of the steel, air gaps are significantly reduced and manual labor is also saved. In a shell type design the laminated magnetic steel core is square or rectangular in section with slots for the windings which are arranged as pancakes with primary and secondary windings disposed alternately along the slots length. This construction is achieved by forming each of two cores from a single continuous steel ribbon, spot welded at the ends to hold the ribbon tight. Another important change in terms of improvement is use of Hipersil, silicon steel which has 33 percent more permeability property than common silicon steel. Three- phase transformer has usually shell type design, in which windings disposed length or side by side.

4.1 The Core

This section of the chapter is based on E.E. Staff M.I.T. Magnetic Circuits and Transformers (1943) and Nynas Transformer Oil Handbook (2010).

The main function of the core is to reduce the current drawn by the transformer from the network when not carrying load. The presence of the core forces the turns multiplied by magnetizing current in each winding summed across all the windings to be zero. There is a fundamental limit to the magnetic flux for the steel can carry, this determines the cross section of the core. The flux in the core is proportional to the applied voltage and inversely proportional to the number of turns and the frequency, also known as transformer formula (in Swedish literature) is given as following:

$$U = c \cdot f \cdot N \cdot \varphi \tag{4.1}$$

where U is the voltage,
c is the proportionality constant,
f is the frequency,
N is the number of turns and
φ is the magnetic flux.

Design of transformer, for given voltage and frequency is preferred to have large cross section and high number of windings.

4.2 Windings

This section of the chapter is based on E.E. Staff M.I.T. Magnetic Circuits and Transformers (1943) and Nynas Transformer Oil Handbook (2010).
The windings of the transformer consist of form-wound coils wrapped with insulating tape, which is then vacuum treated and impregnated with insulating varnish and baked. Round wire is used in small low voltage transformers while in large power transformer the conductors are rectangular shape. In order to minimize the losses caused by non-uniform current distribution within the conductor, large conductors are subdivided into strands and are slightly insulated from each other. The presence of strands links the total flux which helps in dividing the total current equally and thus copper loss is reduced significantly.

In the core type transformer, the primary and secondary are each divided into two equal parts which helps to reduce the magnetic leakage between primary and secondary. The windings are usually concentric with low voltages windings next to the core, and are separated from the core and from each other by insulating barrier.

In shell type transformer, the windings are usually concentric, with the high voltage winding sandwiched between two halves of the low voltages winding. This arrangement of the windings gives less magnetic losses than simple concentric arrangement, but has higher manufacturing cost. This kind of arrangement is generally used voltage rating below 5 kV. For large shell type, thin pancake coil are used, which are assembled in a stack interleaving high and low voltages coils. In small shell type of transformer, straight concentric or concentric sandwiched interleaving of windings.

4.3 Windings connection

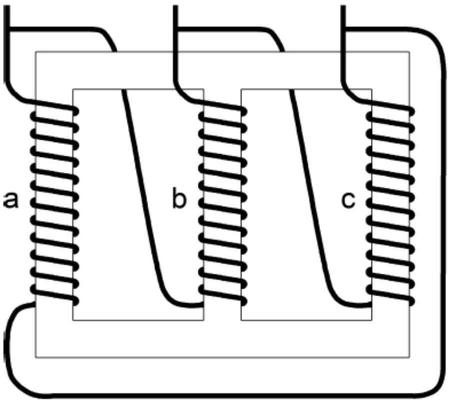
This section of the chapter is based on ABB Industrial Handbook (1998).

The windings of a three-phase transformer can be connected in two different ways. They can be in a delta formation between phases or in a star formation between phase and a neutral. The choice of type of connection is determined by network as the phase angle on parallel connected transformers must be the same, if not the transformer will introduce a phase shift between the primary and secondary sides. The relative phase of the primary and secondary sides is often mentioned in a clock face with 30 degree phase shift being 1 or 11 depending upon which side of the transformer leads or lags.
Short notations of three-phase windings employs a code and numerical, ex. Ynyn0, Dy11 etc. The system is as follows:

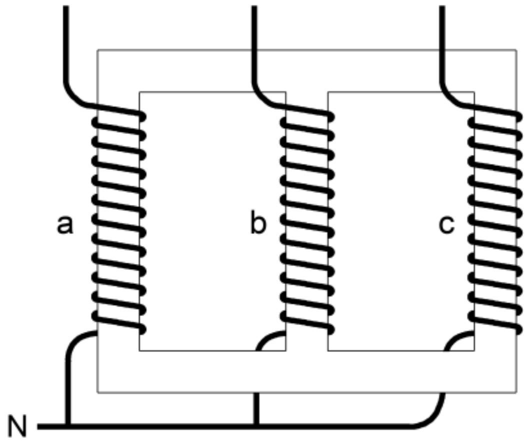
The windings are noted beginning with the high voltage winding, and with following windings in the order of falling rated voltages. The high voltage winding connection is noted with capital letters while others with lower letters.

The connections are Y (or y) for star, D (d) for delta and Z (z) for zigzag. The transformer windings are connected in Y when three terminals of like polarity are joined to form the neutral point of the Y. These neutral points are often grounded. Delta connection on the other hand is a phase to phase connection in which terminals of opposite polarity are connected to form delta formation. It’s effective in blocking the third harmonics which generate in connection with magnetizing in case of generator.

The figure 4.3 on the following page illustrates the three main types of connections found in the transformers.



(a)



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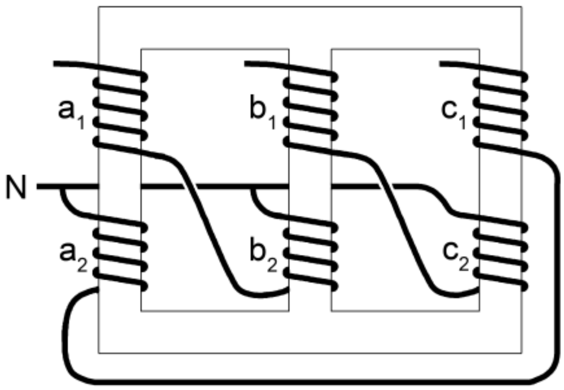


(c)

Figure 4.3 Delta (a), Y (b) and Z (c) connections **[1]**

These connections are generally used in combinations. The simplest combination is Yy and it’s generally used in large system transformers. In separate winding transformers either the primary or the secondary voltage winding, or both, may have their neutral terminal available for earthing purpose, such connections are called YNy, Yyn or YNyn. Distribution transformers on low voltage networks with single phase loading between loading between phase and neutral are specified with mixed connections: Dyn or Yzn.

4.4 Electrical design

This section of the chapter is based on Nynas Transformer Oil Handbook (2010) and ABB Industrial Handbook (1998).

The power transformer is designed to withstand the electrical voltage stresses during its operations throughout the lifetime. The power frequency stress is equally divided between turns of windings and this result in small amount of stress between the turns. The stress is also present between windings and from the windings to the earthed parts such as frames and core. The impulsive stress can also be caused due to short lighting strikes. The power transformers are fitted with surge arresters or gaps to limit impulses at transformers terminal but the impulse voltages can be much larger than the magnitude of peak voltage's frequency. This impulse will have high frequency and due to capacitance in the windings the electric stress is more or less concentrated within first few turns of the windings in the transformers. The electrical design must take into consideration all these factors and techniques such as electrical shield rings or interleaved turns are used to reduce the electrical stress. The thickness of the insulation paper is also carefully chosen to withstand the stress. Increasing the insulation paper provides better electric stress protection but on the other hand adversely effects on thermal proprieties of transformer.

4.5 Mechanical design

This section of the chapter is based on Nynas Transformer Oil Handbook (2010) and ABB Industrial Handbook (1998).

The structural parts of the transformer that support core, tank and windings are included in the mechanical design of power system. The structure of power transformer must be strong enough to withstand the forces generated by current and magnetic field within transformer. Although transformers are equipped with vibration sensors during transport from manufacture to customer site, the structure should provide some support against vibrations. The mechanical design consists of supporting frames on each side of core yokes. These frames are connected at top and bottom by bolts or bands around the yokes. The bolts or bands used for above mentioned purpose must be insulated. The top and bottom frames are on top and bottom of the windings and consists of insulating rings made of laminated wood or pressboard. The axial pressure on the windings from the frame that holds conductors in place in the power transformer. The forces on the conductors are radically outwards on the outer windings and radically inward on the inner windings. These forces compress the windings axially. Sufficient strength to avoid tilt or compress under axial load is provided by tensile strength present in the conductors. The top and bottom frames are connected by separate tension elements to avoid any mechanical stress on the core.

4.6 Transformer ratings

This section of the chapter is based on SMIT Transformers Handbook (2008).

Rated quantities are reference values for guarantees for customer by the transformer manufacturer. These values are derived during the FAT test. According to the standards 'Rated Power' is interpret as incoming power i.e. rated voltage and rated current. The no load loss is referred to rated voltage. The short circuit impedance and the load are referred to rated current. If a primary voltage is equal to rated voltage, the secondary voltage will be equal to secondary rated voltage minus voltage drop. Delivered power excludes power loss and reactive power consumption in the transformer. During the temperature rise test, the total losses are also considered to be rated quantities.

Rated voltage is an important parameter as power transformers with modern core steel operate with flux density close to saturation. Over fluxing a transformer results in abnormal magnetizing current. This may cause overheating of steel parts of the core. For transformers with tapping, the tap changing voltages are specified on the name plate on transformer with other parameters.

If a transformer is connected to a load with a very low power factor, over fluxing problems may develop. The rated voltage drop across the transformer is quite high in such cases. Such cases should be analyzed before ordering and installing a new transformer at a site.

Rated currents limit, if exceeded leads to temperature rise in the tank. The winding loss and eddy currents also depend on rated current. In a modern power transformer there is a significant margin between rated current loading and an overload to prevent any damage to the transformer. Cyclic or temporary overloading above rated current for long time can result in a mechanical failure of transformer. Windings, insulation and structure rigidity can be damaging due to overheating caused by overloading.

Type of cooling is also indicated on name plate. It’s usually indicated by four letter code for oil- immersed and air- immersed transformers, which is described in detail in the next chapter.

The tapping range of the transformer is expressed as rated voltage, plus minus a number of equal tapping steps. The numbers indicate the specified range of variation of voltage on the windings. It can also indicate range of variation of turns available on a winding. Tap changers perform the tapping function and are usually fitted on high voltage side of transformer. When tapping is varied voltage per turn is changed. Tapping range is usually present on transformers name plate, indicating for every numbered tapping voltages on the both the tapped and untapped voltages.

A tap changer present in transformer can be of on-load or off-load type. An on load tap changer is capable of changing the ratio of given transformer without interruption of power supply. An off-load tap changer on the other hand must not be operated unless transformer is disconnected.

5 Thermal Design

This chapter is based on L.F Blume, A. Boyajian, G. Camilli, T.C. Lennox, S. Minneci, V.M Montsinger. Transformer Engineering Second Edition (1951)

The thermal design of the transformer defines the temperature the winding conductor will reach under specific loading condition. The allowed temperature limit for the transformer depends on the type of insulation and oil used in transformer. These limits are relevant to determine the capability of transformer to withstand short and long time overloading conditions. Both insulation and oil in the transformer have different temperature limits. The insulation limit usually lies between 120 ^{o}C and 180 ^{o}C, above this range dielectric failure can occur in insulation due to gas bubbles formation. The limit according to IEC standards for the oil usually lies at 98 ^{o}C, the temperature at which ageing rate of insulation is considered to be normal. This second limit determines the rated load of the transformer, at which the transformer can be accepted to carry normal operation throughout its lifetime.

The parameters that determine the thermal characteristics of any given power transformers are as follows:

- The current density in the winding conductor of the transformer, expressed in amperes per square mm (A/mm^2).
- The thermal resistance of the insulation of the conductor which depends on its thickness.
- The flow of the oil and its flow velocity through the conductor.
- The thermal characteristics of the oil and the coolers.

As discussed earlier in chapter 4.1, the current density depends upon the cross section of the conductor. For large power transformers if a larger cross section is required then the conductor is divided into several small conductors to reduce losses that would otherwise be caused by magnetic flux in the transformer including eddy currents.

There is no critical temperature for describing the deterioration characteristics of insulation, any temperature standards set up for the transformer rating and operation have to be based on transformer's service life experience and to some extent must be within the range of the opinion of the standardizing body. This standardization of the temperature provides help guidelines for transformer operation and a common platform for the comparison of costs and performance characteristics of transformers of different design and manufacture.

These days the limiting hottest-spot temperature is set to be 105 ^{o}C, for continuous operation of the transformer by standardized bodies. It's assumed that average temperature of windings is 10 ^{o}C less than the hot-spot temperature at rated load for the transformers. A maximum limit of 95 ^{o}C was set for the average temperature as determined by the resistance measurement of the transformer's windings.

For example in oil immersed air cooled transformer if the ambient temperature be 40 ^{o}C, the permissible temperature rise of the transformer above ambient becomes limited to 55 ^{o}C. This 55 ^{o}C rise has been accepted as transformers standard rating for its continuous operation. This temperature is also known as transformer's operation point which the unit operates without exceeding this temperature rise.

This temperature rise gives a convenient and uniform basis of rating, and transformers so designed operate successfully at giving ratings for several years. The successful operation of transformer may also depend up on the fact that the ambient temperature for transformer is generally much below the assumed upper limit of 40 ^{o}C. Another fact is that transformers are not generally operated at fully rated load continuously except for generator power transformers. The operation of the transformer with excellent record very much depend on these above mentioned facts and operation conditions cannot be accepted at 40 ^{o}C ambient temperature with continuously full load or at hot-spot temperature of 105 ^{o}C.

If the 40 ^{o}C ambient coincides with continuous rated load, the life of the transformer has been shorter than expected. According to some studies carried out in warmer climates like Africa where the ambient temperature can easily reach to 50 ^{o}C, the average windings temperatures seldom increases above 90 ^{o}C.

5.1 Cooling systems in transformers

In a conventional cooling system the transformer oil is circulated either by means of natural convection or using a pump, up through the transformer windings, leaving the main tank at top and passing down through the coolers.

Classes of transformers with respect to the method of cooling are as follows:

5.1.1 Oil immersed, Self-cooled.

Its simplest means of providing sufficient cooling surface consists in immersing the transformer in oil contained in a closed tank. This method of cooling is usually found in transformers of sizes under 25 kVA. The use of this cooling system above 25 kVA usually becomes expensive as a large surface area is needed for the cooling surface. In other words, the size of tank will be too large. In order to solve this problem of large requirement of surface area sinusoidal corrugation was used in earlier days. This enables to increase the several fold surface area of the tank. The corrugation however doesn't increase the heat dissipated rate in same proportion to the increase in surface area. Today, external metal tubes or channels are welded into the sides of a plain tank. Another method is to attach external radiators to a plain tank.

5.1.2 Oil immersed, Water-cooled.

This technology is mainly practice in American region. It replaces the above method for large unit of transformer when it becomes expensive to provide sufficient cooling area. This type of cooling is achieved by circulating water through spirally wound copper cooling coils assembled inside of a smooth tank. In order to prevent leakage of water into oil, joint less coils are used in water cooled transformers. This method is quite efficient and cost effective for large units but a good maintenance is demanded when compared to self-cooling method.

5.1.3 Oil immersed, Forced-Oil-cooled.

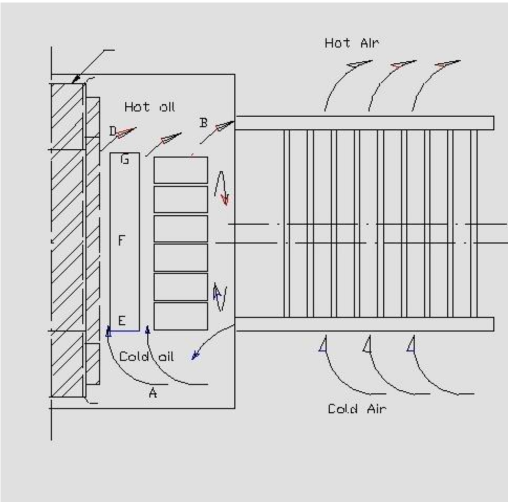
Oil-immersed, forced-oil-cooled transformers can be divided into two categories. First type in which the oil is pumped from the main tank through external oil to water cooler. Second type is that in which the transformer oil is pumped through external oil to air cooler. In both of these cases the oil may be directed or in directed (See figure 5.1 c and d) over the windings in transformer.

When the oil is directed over the surface of the windings by means of enclosures, the cooling is known as directed oil flow. When the oil is not directed over the surface of the windings, the cooling is known as non-directed oil flow. Directed oil flow system has many advantages over non-directed; it increases the cooling efficiency of the windings with high oil velocity and reduces the weight and volume of the transformers. Reduction of size and weight of transformers is very important aspect in reducing investment cost and making it easier to transport from manufacture to customer site.

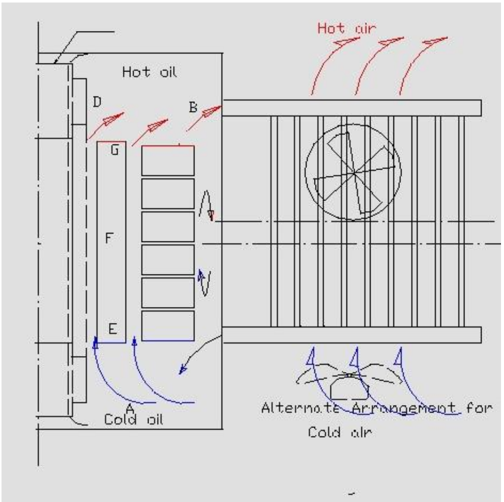
In forced oil cooling there is a limit to the rate at which the oil can be circulated, normally determined by diminishing reduction in temperature achieved as oil velocity increases. For extremely high oil flow velocities it's possible to get static charging of the insulation and can led to electric discharge and insulation failure. Even if the oil is directed into the windings, some oil from the coolers will be allowed to pass directly into the tank to cool other parts like core.

5.1.4 Oil immersed, Forced-Air-cooled.

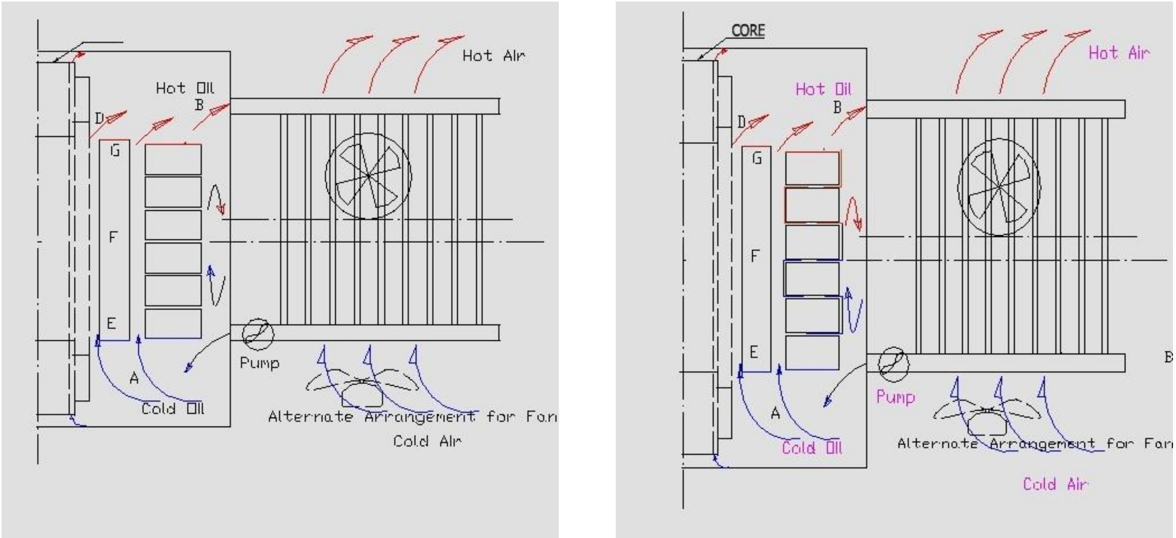
This cooling method involves the use of high velocity fans and pumps for cooling purpose. Forced air cooling increases the rating of transformer up to 1.67 times that of a self-cooling transformer. Transformers with this cooling system can also be classified as having directed or non-directed flow in to the windings. Ratings of these transformers vary according to number of fans in operation. The disadvantage of this type of cooling is that in the event of an auxiliary power failure, the transformer has no cooling capacity.



(a)



(b)



(c) (d)

Figure 5.1 Oil flow diagram in ONAN(a), ONAF(b), OFAF(c) and ODAF(d) types of transformers.
Source: scribd.com/doc/Design-of-Power-transformers

The figure 5.1 above shows four main types of cooling system found in the transformers. The major difference between figure c and d above is the direct flow of cold oil into the windings in figure 5.1 (d) which is denoted by blue color flow direction of cold oil between the windings.

These types of cooling discussed above are usually indicated by a four letter code. The common alternatives for oil immersed and air cooled transformers are:

ONAN:	*(Oil immersed, natural circulation)*	Self-cooled by air - without oil pump or fan.
ONAF:	*(Oil immersed, natural circulation Forced Air Cooled)*	Natural oil circulation- forced air cooling by fans. If fans are stopped transformer becomes ONAN type.
OFAF:	*(Oil immersed, Forced Oil, Forced Air Cooled)*	Oil circulation through coolers forced by pumps – air flow by fans.
ODAF:	*(Oil immersed, Directed Forced Oil, Forced Air Cooled)*	Oil flow by pumps, directed right in to the windings – air flow by fans mainly for large power transformers, above 100 MVA.

Table 5: Types of cooling in power transformers ***[4]***

6 Insulation

Power transformer's insulation is largely consists of cellulose in form of electro-technical paper known as Kraft and pressboard. Various other polymers, wood board and resins are also present in Kraft beside cellulose.

Solid insulation has several functions in power transformers like electrical insulation, mechanical and thermal stability, direction of oil flow etc.

Cellulose is widely used in insulation due to its good electrical and mechanical properties and good adoption with mineral insulating oil. The combination of cellulose and mineral oil gives better electrical properties. This mechanical and electrical behavior of cellulose changes with age which depends mainly up on temperature, water and oxygen. The ageing process is described in detail in chapter 7 of this report.

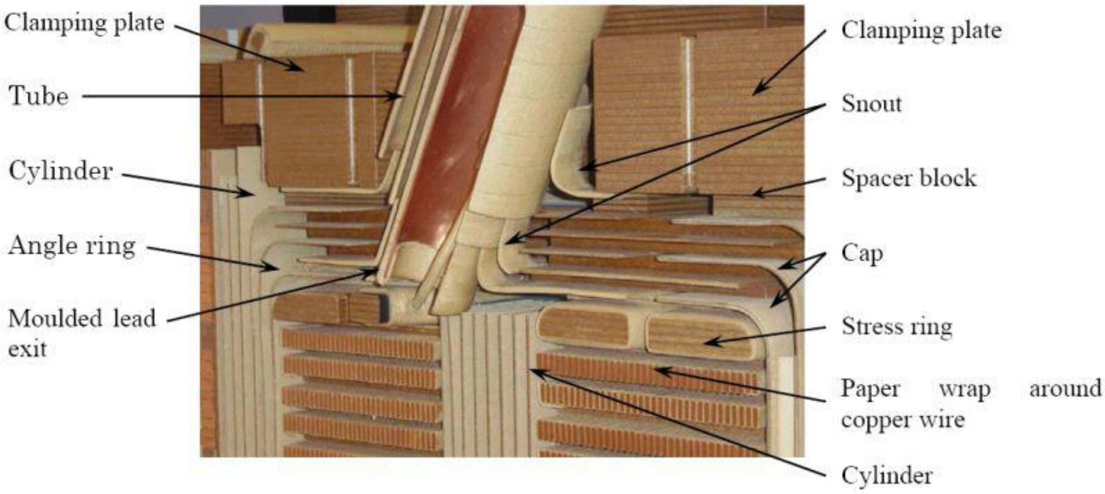


Figure 6.1: Cross-section view of a transformer end insulation [7]

6.1 Kraft Cellulose

This section of the chapter is based on C. Kuen (2010).

In power transformers, cellulose is used in different forms as a solid insulation material. It provides quite good oil impregnation characteristics and improving the performance in electrical fields.

Kraft pulp, unbleached softwood is used for the manufacturing of pressboard and paper for electrical insulation for the transformer. Lignin, resins and mineral substances are completely removed while residual process chemicals and other impurities are removed using an extensive cleaning procedure. This makes cellulose in power transformer very pure and meets the tough purity standards.

Unbleached Kraft pulp after processing usually consist about 80% cellulose, 10% - 20% hemicelluloses and 2% - 6% lignin. Mineral substances under 0.8% in very rare case might also be present.

Cellulose is a linear homopolymer and constitutes of (1-4)-β-glucopyranose. It is a polysaccharide and has the following chemical structure:

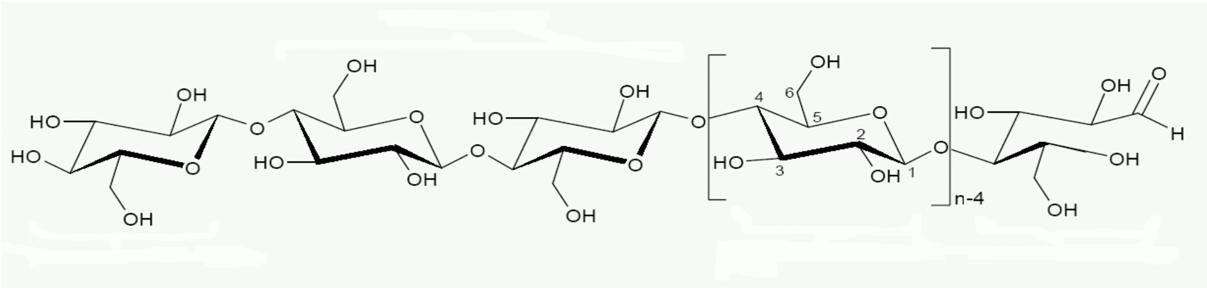


Figure 6.2: Structural formula of cellulose ***[7]***

Cellulose chain consists of number of glucose residues which are linked together in a chain formation. These chain molecules bundles with each other each other in fibrilla[#] form. A large number of fibrilla type chains are required to form a visible cellulose fiber from which the degree of polymerization is determined on the basis of the cellulose structure is the chair-conformation anhydroglucose unit the number. Further chain has a direction since the terminal groups on the chain ends are different. It can be non-reducing end with closed ring structure and reducing end with aliphatic structure and a carbonyl group in equilibrium.

Hemicellulose substances are a non-uniform group of complex polysaccharides that are not cellulose. Their degree of polymerization is substantially lower than that of cellulose and lies in the range of 50-250. Hemicelluloses substances form the actual matrix in which the cellulose fibers are embedded. The hemicelulose substances present in the cellulose fibers also play a vital role in sheet strength. The sheet becomes strengthened due to presence of fiber to fiber bonding as hydrogen bridges to form their hydroxyl groups in a chemical process.

Lignin is a complex, high polymeric natural substance that is difficult to degrade, which together with cellulose forms the main component of wood in transformer. Within the fiber composite, the lignin acts as a binder between the cellulose fibers and thus increases the strength of the wood. The presence of lignin is responsible for brown coloration in the cellulose. Lignin has influence in the diffusion process i.e. water absorption during conditioning or water release during drying.

#Fibrilla is a fine fiber with cable-like strings and is approx. 1mm in diameter.

6.2 Function of insulation in transformers

This section of the chapter is based on Nynas Transformer Oil Handbook (2010) and S. Soares, N. Ricardo, F. Heatly, E. Rodrigues (2001) .

Kraft paper's main function is to provide cover to conductors and separate windings. The use of different types of paper based on different structure and densities depends up on transformer type and application. The paper of higher density provides better insulation properties but drying and oil impregnation properties of paper slows with increasing densities. Cellulose fibers even distribution and free from any kind of impurities is also important factor as it affects electrical and mechanical properties.

Pressboard is used for mineral oil filled transformers and contains a percentage of moisture and small air cavities due to porosity. Pressboard has good electrical strength due to breakdown strength of thin layers of cellulose and oil which also gives dimensional stability to pressboard components as compared with soft paper insulation.

Coils are made of high density board to increase short circuit strength. Spacers which can be radial or axial and strips with rounded edges give protection to wire insulation. The presence of spacers decreases the release of cellulose fiber to oil, hence increasing the dielectric strength.

The reliability of energy transmission strongly depends on the secure operation of transformer's insulation systems. There have been considerable improvements in design criteria and production quality of these insulating components.

There is still a great potential leading to increase its electrical, mechanical and thermal strength. It lies mainly in optimization of its design and thus reducing the overall insulation volume and adding to transformer's performance. The reduction of the insulation requires a good knowledge and understanding of the function of insulation.

Liquid insulation mainly provides the dielectric strength by filling and impregnating the complete electrically stressed volume. The mineral oil in transformer is also a good heat transmission medium.

Solid insulation provides a barrier system to divide the highly stressed oil channels into more narrow gaps. This also increases the dielectric strength of the oil channels. The maximum dielectric strength can be achieved in transformer oil if the barriers are arranged vertically relative to the electrical field lines. In other words geometry and design determine the behavior of insulation system of power transformer.

The dielectric strength of oil impregnated pressboard is approximately three to four times greater than dielectric strength of oil. In pressboard AC voltage stress is reduced by the dielectric constant, which is higher than that of oil.

The most important function of the barriers is the subdivision of oil gaps. Other functions of solid insulation can also be associated with barrier kind of function.

The research work to optimize the volume of transformers and the costs associated to them without comprising the performance or reliability is intensely carried out. Dielectric strength of oil gaps for AC voltages can be optimized by numerical field analysis. The use of high quality barrier with 2 to 3 mm of thickness is also recommended. In modern transformers barrier systems are been replaced by paper-wound conductors that are designed to local electrical stress profile and offer protection against impurities.

7 Thermal degradation and aging of cellulose in transformers

The life time of a power transformer depends upon its cellulose aging rate. The transformer oil can be renewed or regenerated but the cellulose aging process is completely irreversible. Aging models on cellulose mainly refer to dependency of temperature and time factor when it comes to its aging influence. There are other factors besides temperature and time which have influence on aging of Kraft paper like oxygen, moisture and quality.

The current condition of aged cellulose is described by degree of polymerization (DP). For the new Kraft paper DP-value lies between 1000 and 1200, depending upon paper grade. This start value decreases by the operation time of the transformer. This value is also affected by processes like oxidation, hydrolysis and pyrolysis taken place in the transformer. When the value of degree of polymerization reaches around 300 is considered as end of life of insulating paper. At DP value around 300 Kraft paper is quite weak and brittle. The aging of cellulose doesn't affect dielectric strength but a low DP value of insulation significantly lowers tensile strength. Low tensile strength of Kraft paper makes transformer vulnerable to physical damage.

7.1 Degree of polymerization

This section is based on S. Soares, N. Ricardo, F. Heatly, E. Rodrigues (2001).

Kraft pulp paper used in the transformers has standard density 774 kgm^{-3} and contains 8% moisture. Kraft insulation paper consists of 90% cellulose, pentosans, lignins and mainly Na^{+} and Ca^{+2} metal ions. The degree of polymerization (DP) of the cellulose is measured by viscosity of the Kraft paper in a cupriethylene diamine chemical solution. Intrinsic viscosity values are measured according to ASTM method D4243-86 which is mentioned in Annual book of standards, ASTM committee D-9, 1986. The average viscometric degree of polymerization is the ratio of viscometric mean molecular mass to the molecular mass of the monomeric and is related to the intrinsic viscosity(η). This is given by following equation:

$$[\eta] = K * DP^{a} \tag{7.1}$$

where K= $7.5 \cdot 10^{-3}$ and a = 1 for solvent polymer system.

The life of the transformers is mainly determined by the thermal loading conditions during operation while degradation is important in determining the remaining life of insulation system. Degradation of aged insulation is assessed by detection of oil soluble in decomposition products due to inaccessibility to examine insulation paper. Dissolved gas analysis method (discussed in chapter 9) is used to determine the condition of Kraft paper and transformer. The amount of 2-furaldehyde and related compounds are studied to determine the condition of the oil and assessing the condition of the Kraft paper. The result of this latter test gives result of de-polymerization of cellulose chains. The rate of formation of 2-furaldehyde is proportional to the concentration of chain ends in the polymer. DP value is directly proportional to the concentration of furaldehyde in the oil. Kraft paper with DP value 1200 has a tensile strength of 20 Mnm^{-2}. DP value decreases by approx. 40 units paper during 2 years under normal operation condition.

7.2 Influence variables on Kraft paper

This section of the chapter is based on C. Kuen (2010).

The temperature and operational time are the most influencing aging parameters for cellulose insulation which affects the electrical and mechanical properties of a transformer. The presence of water and oxygen in the unit also affects the lifespan of insulation. The quality of Kraft paper also affects the aging process. The presence of all the above mentioned factors speeds up the aging process of the insulation system in the transformer. Cellulose is sensitive to moisture and acid and the presence of acid and moisture directly affects the aging process.

The insulation system's aging parameters temperature, time, water, oxygen and quality and their influence are defined as follows:

7.2.1 Temperature and Time

Figure 7.1 shows the dependency of DP value on aging process at various temperatures during the period. The diagram clearly shows how the start DP value of 1200 degrades during the time and at various temperatures. There is clearly faster aging trend in the insulation paper at higher operational temperature. The new Kraft insulation paper degrades also faster in the start and later degradation process slows with the time. The temperature is the most influential factor on aging trend of Kraft insulation paper of transformer.

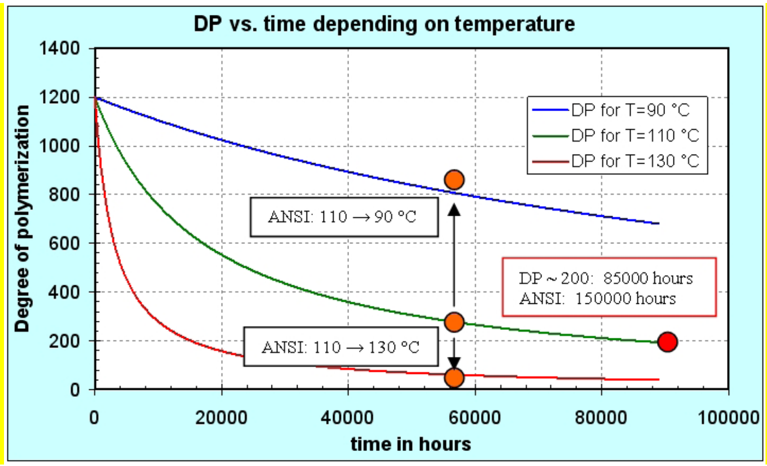


Figure 7.1 : Comparison between different DP values at different temperatures during the time. **[7]**

7.2.2 Water and Oxygen

The aging process also depends upon the water content in cellulose. This process is known as hydrolysis in which long cellulose chains break into smaller sub-chains. Although the cellulose is thoroughly dried in the transformer, moisture can be picked or leak in from surrounding air through the oil due to leakage or poor maintenance of breathers. The aging process of Kraft paper accelerates in presence of water.

The oxygen also shows effects on the aging process of insulation paper in transformers. Presence of oxygen in Kraft paper increases the aging rate of insulation.

7.2.3 Cellulose quality

Kraft paper and thermally upgraded paper are two types of cellulose qualities which are used for insulation purpose. The presence of water and oxygen as mentioned in section 7.2.2 has significant impact on Kraft paper. In a power transformers generally a combination of both Kraft cellulose in pressboard and thermally upgraded paper as solid insulation is used.

7.3 Aging of cellulose insulation

The molecular weight of the Kraft paper and its DP value are constantly reduced during its aging process. This is due to molecular cellulose chains are broken into smaller chains during operating duration of transformer. Aging of cellulose is characterized by the number of chain cleavages; η. Equation 7.2 describes the relation between chain cleavage and degree of polymerization.

$$\eta = \frac{DP_0}{DP_t} - 1 \tag{7.2}$$

The value of chain cleavages, η is also used to describe to describe the aging accelerating factor. For any given value it describes the number of extra small cellulose chains broken from original chain.

The DP value of new cellulose DP_0 is 1200. After aging the value of DP drops down to DP_t after t time duration. The value of DP_t i.e. DP value at a given value can be calculated by Arrhenius equation and is described as follows:

$$DP_t = \frac{1}{\left(A \cdot t \cdot e^{\frac{-E}{R*(T+273)}}\right) + \frac{1}{DP_t}} \tag{7.3}$$

Where:

DP_0 the start DP value

DP_t remaining DP value after time t

A factor representing the chemical environment

R molar gas constant (8.314 J/mole/K)

T absolute temperature in K

E activation energy in kJ/mole (111 kJ/mole)

t time duration in h

At a DP value of 200, the tensile strength of the insulation system has reduced to approximately 25% of its original value. At DP<300 aging rate slows down, which is shown by low inclination in figure 7.2 below. A DP value of 200- 300 is often considered to be end of service life for cellulose in the transformers. This range is also defined as 'end of life' for transformers.

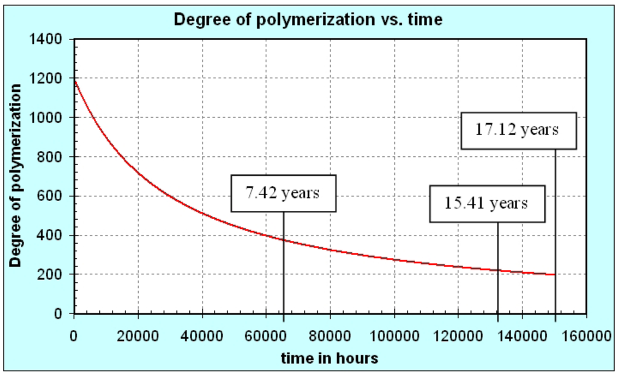


Figure 7.2: Degradation of DP value with time **[7]**

8 Transformer Oil

This chapter lays focus on the composition of the oil and its different properties and behavior during the transformer's operation time.

8.1 Composition of transformer oil

This section of the chapter is based on Nynas Transformer Oil Handbook(2010).

The mineral transformer oil consists mainly of carbon and hydrogen in molecules with different structures. The basic structure of a transformer mineral oil is made of paraffinic, naphthenic and aromatic structure.

Paraffinic structure can be straight or branched group of molecules. Paraffin molecules have low thermal stability and have low solubility for water and oxidation products. The straight paraffin structure hurdles the free flow of oil at low temperatures and thus content of such type of molecules must be reduced.

Naphthenic structure molecules have excellent low temperature properties and better solvency power than paraffin. They are usually having ring structures and also known as cycloalkanes.

Aromatic structure and contains at least one ring of six carbon atoms. They are the most important group present in the mineral oil. Aromatic molecules can be divided into mono- and poly-aromatic molecules based on their structure. Mono-aromatic in transformer oil is quite stable in oxidation, have good electrical properties and are good gas absorbers. Poly-aromatic on the other hand have excellent oxidation inhibiting property i.e. they act as inhibitor which slows oxidation process. Poly-aromatic have better gas absorption properties than mono-aromatic. The electrical properties however have negative effect when poly-aromatic molecules are present.

Transformer mineral oils except for all hydrocarbons which are mentioned above have traces of nitrogen, sulphur and oxygen in it. All these three of molecules are bonded with hydrocarbon's structures.

The content of nitrogen is almost negligible but it contributes quite a lot to oil's behavior. Nitrogen molecules act as charge carriers in an electric field. They also act as initiators or inhibitors of oxidation process depending upon the type of Nitrogen bonding molecules present in oil. The content of sulphur affects the lifespan of transformer. Sulphur can cause corrosion and can also destroy inhibitors in the oxidation process. During aging and oxidation of transformer's oil the more oxygen is associated to hydrocarbon molecules. The product formed as a result from reaction between hydrocarbons and oxygen acts as oxidation inhibitors and prevents oxidation. Some of these molecules are quite polar and orient themselves in electric and magnetic fields to contribute to dielectric losses.

8.2 Properties of transformer oil

This section of the chapter is based on IEC 60296 International Standards (2003) and oral discussions.

The transformer oil has been divided into two main categories: inhibited and uninhibited type. Inhibited oils have excellent oxidation resistance with better electrical properties than uninhibited type of oil. Inhibited oil with synthetic inhibitors uplifts the quality of oil often known as high or super grade oil. For cold climates, inhibited oils with extra low viscosity at all temperatures that can provide good cooling at low temperatures are recommended. This type of oil class is known as arctic grade oil. See appendices 14.1 and14.2 for detailed differences between Uninhibited (Nytro Libra) and Inhibited (Nytro 10XN) oils. The oils mentioned in the appendixes are from Nynas transformer oil manufacture and are very commonly found in transformers in Sweden.

Transformer oil properties like viscosity, flashpoint, density, water content, electrical breakdown, tan delta, interfacial tension, acidity and oxidation stability plays an important role in service life of transformers. Most of the above oil properties are familiar as they are commonly found in transformers. All the properties of transformer oil and their significance have been described below.

8.2.1 Viscosity

The viscosity of oil is important for cooling the transformer. Viscosity index is the measurement of change of viscosity change with temperature. This index should be as low as possible for better cooling of transformer, in other words the lower the viscosity the better the cooling capacity. The use of high viscosity oil in high operational temperatures causes higher thermal losses and faster aging of oil and insulation.

According to IEC 60296 and ASTM D3487 standards, transformers oil should have maximum viscosity 12 mm^2/s at 40 ^oC. The transformer oil requirement in cold countries like Sweden is quite strict. The viscosity is instead measured at -40 ^oC and should meet specific standards set by manufactures. The normal alkanes in standard grade oil at freezing temperatures can crystallize and impede the free oil flow in transformer. That's why artic grade oil containing very few normal-alkanes is recommended for cold climate operations. Appendix 14.3 and 14.4 shows how viscosity changes with temperature in standard oil (Nytro Libra) and in artic grade oil (Nytro 10XN).

8.2.2 Flashpoint

As the transformer oil is a complex mixture of different molecules, it has a boiling range instead of boiling point. Boiling range is directly proportional to viscosity and increases as boiling range increases. Most of the transformer oils have flashpoint 140 ^oC i.e. boiling curves starts at this particular temperature. The flashpoint increases with poly aromatic compound present in the oil. The higher flashpoint adversely affects impulse breakdown and electric properties of oil.

8.2.3 Density

The density of transformer oil is an important factor to specify to avoid the formation of floating ice in the oil at sub-zero temperatures. The ice formation can occur when there is free water present in standing transformer which can cause problems with startup. It's also known as Cold Startup of transformer. The density of oil decreases with increasing temperature a have standard coefficient 0.00065/ ^{o}C.

8.2.4 Water content

The solubility of transformer oil in water directly depends on temperature and number of aromatic molecules present. It's difficult to maintain low water content especially in generator transformers as they are located in high humidity area near to water source, needed for power-plant cooling. Just super heating the oil doesn't reduce the water content as water solubility increases with temperature. Oils with high temperature foam excessively due to evaporation process.

8.2.5 Electrical breakdown

This property of the oil depends upon the impurities and water content in the transformer oil. It's measured by placing two spherically electrodes at a distance of about 2.5 mm and voltage is increased to 2 kV/s until breakdown occurs. This process is repeated six times and average of these concludes the results. The result of electrical breakdown test gives the information about the electrical insulation capability of the oil. Pure transformer oil can give a breakdown voltage of more than 70 kV to any oil grade. The minimum required specification is set to be 30 kV by transformers manufactures.

8.2.6 Interfacial tension

The interfacial tension is the measurement of strength of interface between oil and water. This property of the oil depends upon the polar groups and impurities in the oil. The value of interfacial tension for normal oil in good service condition usually lies between 45 and 50. The new transformer oil has interfacial tension value of 40.

8.2.7 Interfacial tension

The interfacial tension is the measurement of strength of interface between oil and water. This property of the oil depends upon the polar molecules and impurities in the oil. The value of interfacial tension for normal oil in good service condition usually lies between 45 and 50. The new transformer oil has interfacial tension value of 40.

8.2.8 Tan delta

The tan delta[#] property of the transformer oil depends upon the amount of ionisable and polar molecules present in the oil. New oil usually has low tan delta value. The tan delta value increases if oil is contaminated during its service time. While the transformer oil starts to deteriorate during its service time, tan delta value increases first during oxidation process following a decreased value after some time. The first increase in tan delta value is due to formation of acids and esters during oxidation process and later decrease is caused due to decomposition of oxides into other products with low tan delta value.

New or regenerated transformer oil usually has tan delta value of < 0.001 at 90 ^{o}C.

8.2.9 Acidity

In new or regenerated transformer oil the acidity value usually lies below 0.01 KOH/g oil. The value of acidity is usually the indication of contamination in the transformer oil. The higher the value the greater is the probability that oil is contaminated.

8.2.10 Oxidation stability

This is also an important property of transformer oil. The oil can be of inhibited or uninhibited type. Inhibited oil hindered phenols are added while uninhibited oil have natural inhibitors to slow down the oxidation process. The oxidation of transformer oil is a very complex process which is attributing by peroxides and can result in formation of alcohols, esters, acids, water and carbon dioxide.

The presence of free metal ions mostly copper ions also affects the oxidation process. These ions participate as catalyst in the oxidation process due to their ability in surviving in several oxidation states. This adversely affects dielectric properties and conduction of transformer oil.

#Tan-Delta also known as Dissipation factor is one of the off-line diagnostic tool to monitor the condition of solid insulation of various high voltage equipment.

9 Gassing tendency in transformer

The sections 9.1, 9.2 and 9.3 is based on IEEE Standard C57. 104 (2008).

Formation of gas always occurs even in a new, faultless transformer due to high temperatures, electric field and oil oxidation. Gas formation in an operating transformer has mainly two reasons. The conductor losses during operation produce gases which are caused by thermal decomposition of oil and insulation. Gases are produced from the electrical decomposition of oil and insulation at arc temperatures. Gases are also formed in case of partial discharge or in case of any kind of fault.

9.1 Cellulose decomposition

The thermal decomposition of insulation system which consists of cellulose mainly produces carbon oxides CO, CO_2 and hydrogen H_2 or methane CH_4 gases. The rate at which gases are produced directly depends upon the oil temperature and volume of oil and insulation present in the transformer.

9.2 Oil decomposition

Transformer oil decomposes under thermal and electric fault due to the presence of hydrocarbons molecules in it. During the decomposition carbon-hydrogen and carbon-carbon bonds break resulting in formation of active free hydrogen and hydrocarbon sub molecules. These active free radicals have ability to combine and form molecular hydrogen, methane and ethane. They can further decompose which can lead to formation of ethylene and acetylene gas.

In some cases, the oil is exposed to partial discharges due to poor insulation quality. Design or manufacturing errors can also cause partial discharge. With partial discharge molecules break up to smaller fragments to form hydrogen and methane gas.

All hydrocarbons molecules present in the oil are decomposed finally into same product and remains in equilibrium with each other's like in any chemical process. Formation of methane, ethane and ethylene are dependent upon the temperature. The concentrations of all the gases present can be used to estimate the thermal history of the transformer oil and to predict any fault in the past or future in the transformer.

9.3 Interpretation of gas analysis

All power transformers generate gases even at normal operating temperatures and conditions. Any abnormality in gas generating tendency within an operation transformer can give an analysis of fault and type of fault present. The faults may be thermal or electrical.

Generally weekly gas analysis is recommended after startup of new transformer, followed up by yearly interval of normal operating transformers.

9.3.1 Thermal faults

The thermal decomposition of oil produces ethylene (C_2H_4) and methane (CH_4), together with smaller traces of hydrogen (H_2) and ethane (C_2H_6). When any kind of fault in the transformer occur the overall temperature of oil increases which results in the concentration of hydrogen exceeding methane. Thermal fault associated with higher temperatures, there is increased quantity of hydrogen and ethylene and traces of acetylene. While thermal decomposition produces large quantities of carbon dioxide (CO_2), carbon monoxide (CO) and water vapor due to heating of cellulose. In a cellulose structure fault gas such as methane and ethylene will be formed.

The gas ratio of CO_2/CO is referred as indication for thermal decomposition of cellulose. For normal operating transformer this ratio has to be more than seven.

In short ethylene is the main gas forms during oil decomposition while carbon monoxide is formed during cellulose thermal decomposition.

9.3.2 Electrical faults – Partial discharge

A low intensity electrical discharge produces mainly hydrogen and methane, with small traces of ethane and ethylene. The concentration of acetylene and ethylene rises with the increase in partial discharge.

9.3.3 Electrical faults – Arcing

When electrical discharge reaches temperatures that can vary from 700^{o}C to 1800^{o}C, acetylene gas is formed together with hydrogen. At this stage transformer oil may be carbonized.

9.4 Evaluation of faults using gas analysis

This section of the chapter is based on N.A. Muhamad, B.T. Phung, T.R. Blackburn, K.X. Lai(2007).

There are several gas analysis methods used today for predicting the type of fault occurred in the transformer oil. Gas space and transformer oil equivalents are used to compare results of gas analysis (TCG- Total Combustible Gases) with the results from analysis of gas dissolved in the oil (TDCG- Total Dissolved Combustible Gases). The results are then compared from gas space to dissolved gas in oil. The result is compared to predefined values to predict the condition and to determine the type of fault which has occurred in the transformer.

The most widely used method for evaluations of gases are Doernenburg and Rogers gas ratio method. The gas ratio is used to indicate the type of fault assigning the cause of fault or failure during analysis.

These methods are based on thermal degradation and use a number of ratio criteria of certain combustible gases found in transformer for fault type analysis. These five ratios are as follows:

Ratio1 (R1) = CH_4/H_2

Ratio2 (R2) = C_2H_2/C_2H_4

Ratio3 (R3) = C_2H_2/CH_4

Ratio4 (R4) = C_2H_6/C_2H_2

Ratio5 (R5) = C_2H_4/C_2H_6

Doernenburg's method uses the first four ratios (R1-R4). For the diagnosis to be valid, the gases have to be present in significant levels.

Roger's method uses ratio 1, 2 and 5. This method doesn't depend on specific gas concentrations from the transformer for diagnosis to be valid.

9.4.1 Doernenburg's ratio method

The Doernenburg method is used to predict the three types of faults as mentioned in Section 9.3. This method utilizes gas concentrations from ratio 1, 2, 3 and 4. Table 9.4.1 describes the relation between ratios and type of faults.

Type of fault	**Ratio 1(R1) CH_4/H_2**		**Ratio 2(R2) C_2H_2/C_2H_4**		**Ratio 3(R3) C_2H_2/CH_4**		**Ratio 4(R4) C_2H_6/C_2H_2**	
	Oil dissolved	***Gas space***	***Oil dissolved***	***Gas space***	***Oil dissolved***	***Gas space***	***Oil dissolved***	***Gas space***
Thermal	>1.0	>1.0	<0.75	<1.0	<0.3	<0.1	>0.4	>0.2
Partial discharge	<0.1	<0.01	Not significant		<0.3	<0.1	>0.4	>0.2
Arching	>0.1 to <1.0	>0.01 to <1.0	>0.75	>1.0	>0.3	>0.1	<0.4	<0.2

Table 9.4.1: Comparison between ratios and types of fault. ***[11]***

9.4.2 Roger's ratio method

This ratio method also follows the same principle as Doernenburg's method. Only ratios R1, R2 and R5 are used. Roger's method is divided into more fault categories than Doernenburg's method and gives more detailed version of fault. This method is also valid to both dissolved gases in oil and gases from gas space.

Table 9.4.2 below gives the value of ratio corresponding to suggested fault diagnoses.

Type of fault	**Ratio 1(R1)** CH_4/H_2	**Ratio 2(R2)** C_2H_2/C_2H_4	**Ratio 5(R5)** C_2H_4/ C_2H_6
Normal unit	>0.1 to <1.0	<0.1	<0.1
Partial discharge	<0.1	<0.1	<0.1
Arcing	0.1 to 1.0	0.1 to 3.0	>3.0
Low temperature thermal	>0.1 to <1.0	<0.1	1.0 to 3.0
Thermal < 700 ^{o}C	>0.1	<0.1	1.0 to 3.0
Thermal > 700 ^{o}C	>0.1	<0.1	>3.0

*Table 9.4.2: Comparison between ratios and types of fault.**[11]***

10 Thermal aging of power transformers

This chapter covers the loss of life in the power transformers based on the hot-spot temperatures. For calculation of aging trend in the transformers standard loading guides by IEEE and IEC are used.

10.1 Introduction

This section is based on T. Chiulan, B. Pantelimon (2008).

Power transformers dissipate waste heat as a byproduct in their operation. The heat generated in transformer's operation causes the temperature rise in the internal structures of the transformers. Transformer’s temperature rise is defined as the average temperature rise of the windings above the ambient temperature, caused by loading stated on its name rating plate. Lower temperature rise are noticed in efficient transformers while less efficient transformers tend to have higher temperature rise. A more efficient transformer generates less waste heat, but the temperature rise not only depends upon the amount of heat generated but also heat removed from the unit.

Lower temperature rise in transformer means less loss but also longer life expectancy. Temperature is one of the critical factors which affect the transformer life. Increased temperature above the mentioned rating reduces the transformers lifetime. Failure due to cellulose breakdown as mentioned in previous chapter also depends on operational temperature of the unit. Transformers which have operational temperature above rated temperature over an extended period have significantly reduced life expectancy.

Overload capability of the transformer also increases if the transformer has low temperature rise. Short time overloading at lower ambient temperatures doesn't affect the life time of transformers. Standardized bodies such as IEC and IEEE have developed guidelines about overloading effects on the transformer’s life and its service.

These loading guides have been developed on the basis of following principles:

- The mechanical and dielectric properties contribute to transformer lifetime which is caused by thermal aging.
- Since the temperature distribution is not uniform throughout the transformer, the part operating at highest temperature has also most effect on thermal aging of transformer. This temperature gives the overall aging rate and is called Hot-spot temperature (HST).
- Thermal aging of insulation as given stated in equation 7.3 in chapter 7 also depend upon the absolute temperature of a transformer.
- Thermal aging is linearly cumulative and is known as Accumulated loss of life of the transformer.
- Loss of half of insulation tensile strength represents the end of insulation life in the transformer.

10.2 Loss of life

This section is based on T. Chiulan, B. Pantelimon (2008).

The approach of loss of life assessment was first present in transformers loading guide by IEEE in 1981 in IEEE C 57.92 report to compare the present loss of life to nominal. This was later modified and most recent are IEEE C 57.91 from 1995 and IEC 60076-7 from 2005.

Only thermal life of insulation is been taken into consideration while calculating the loss of life for a transformer. Other deterioration caused by aging such as mechanical and dielectric strength has been limited while assessing the overall loss of life.

The power transformers operating under these standard conditions of loading guides usually have calculated loss of life is not same as actual loss of life. The reason for these can be following:

- Only some power transformers operate continuously at an average ambient temperature at a rated power.
- The transmission and distribution transformers operate at full cyclic loading with loading peaks which causes temperature to reach its limits according to their mentioned ratings.
- The loading guides don't take consideration to load losses and current losses. The current losses also generate energy contributing to the rise in temperature. Loss in windings are also limited in these standards.
- During the overloading the temperature rise is exponential according to thermal constant of transformer while in loading guides it's consider that maximum temperature is reached instantaneously during loading.

10.3 IEEE aging evaluation

This section is based on IEEE Standard C57. 91(1995).

The rate of loss of life is averaged over the complete range of ambient temperature during its operation period. The loss of life was evaluated based on IEEE Standard C 57.91-1995. In this model, the hot spot temperature, Θ_H, is

$$\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\,\Theta_T \tag{10.1}$$

where Θ_H is the hot-spot temperature,

Θ_A is the ambient temperature,

$\Delta\Theta_{TO}$ is the top oil rise and

$\Delta\,\Theta_T$ is the temperature rise in windings.

In the equation 10.1 the temperature rises of the oil and the windings are added to the ambient to get the final hot spot temperature. This relation is only valid for a constant maximum load for a given transformer.

The transformer insulation life can be calculated on a per unit (p.u) base. Per unit life is used to determine power transformer's insulation life. Hot-spot temperature calculated from the above equation is used as the principal variable affecting the thermal life. The degree to which the rate of aging is accelerated beyond normal is the temperature above reference temperature of 110 ^{o}C and aging is reduced for temperature below 110 ^{o}C. The p.u equation is as follows:

$$Per\ unit\ life = 9.8\ \times 10^{-18}\ \cdot\ e^{\frac{1500}{(\Theta_H+273)}} \qquad (10.2)$$

Where Θ_H is the hot-spot temperature of the unit.

The per unit transformer insulation life can be used in calculating aging acceleration factor (F_{AA}) for a given load and temperature or a varying load and temperature.

$$F_{AA} = e^{\left(\frac{1500}{383}\right)-\left(\frac{1500}{\theta+273}\right)} \qquad (10.3)$$

The equivalent life in hours and days at a reference temperature that will be consumed in a given time period for a given temperature cycle is as follows:

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \qquad (10.4)$$

where F_{EQA} is the relative aging factor for the total time period,

Δt_n is time interval,

n is the index of time interval

N is the total number of intervals during the period considered and

$F_{AA,n}$ is aging acceleration factor for temperature which exists in time interval Δt_n.

The time duration for continuous operation at hottest-spot temperature at rated can be calculated by the help of above equations. A normal life time of a transformer is considered to be 180 000 hours (approx. 20 years) operating at constant 110 ^{o}C. A rise of 6 ^{o}C in hottest-spot temperature reduces the insulation system life to half.

10.4 IEC aging evaluation

This section is based on IEC 60076-7 International Standards (2005).

Just like IEEE, IEC 60076-7 report from 2005 gives mathematical model for judging and consequence of different loadings, with different cooling mediums and varying loadings. This model provide for the calculation of operating temperatures in the transformer, especially hot-spot temperature of the windings. This hot-spot temperature is used for evaluation of rate of thermal aging and life time lost during the transformer's operational period.

The hot-spot factor (k) is winding specific and is determined on a case by case basis. Studies show that hot-spot factor vary from 1.0 to 2.1 based on the transformer's size, short circuit impedance and winding design. The factor k is defined either by direct measurements or by calculations based on loss and heat transfer or by direct measurements on prototypes at manufactures. Its accurately assumed k= 1.1 for standard distribution transformers and value of k= 1.3 for medium and large power transformers.

Hot-spot temperature rise according to IEC standard is given:

$$\Delta T_{hsp} = \Delta T_{TOP} + g*k \tag{10.5}$$

where ΔT_{hsp} is the hot-spot temperature rise,

ΔT_{TOP} is the top oil temperature rise,

k is the hot-spot factor and

g is the gradient which is difference between average winding and average oil temperature.

This hot-spot temperature rise is added to average ambient temperature (T_{amb}) to give the resulting hottest-spot temperature of the unit.

$$T_{hsp} = \Delta T_{hsp} + T_{amb} \tag{10.6}$$

Although aging depends upon temperature, moisture content, oxygen content and acid content, the model presented in IEC 60076 is only based on insulation temperature as the controlling parameter. Since the temperature distribution is not uniform, the part operating at highest temperature is deciding factor and undergoes greatest deterioration. Normal operational temperature for transformer according IEC standards is 98 ^{o}C.

Rate of aging (V) in relation to hottest-spot temperature is defined as:

$$V = e^{\left(\frac{15000}{110+273}\right)-\left(\frac{15000}{\theta+273}\right)} \quad (10.7)$$

Where, Θ is the hottest-spot temperature.

Total loss of life (L) under transformer's operational period is given as follows:

$$\mathrm{L} = \int_{\mathrm{t}_1}^{\mathrm{t}_2} \mathrm{V}\,\mathrm{dt} \quad \text{or} \quad L = \sum_{n=1}^{N} V_n \times t_n \quad (10.8)$$

where V_n is the relative aging rate during time interval n,

t_n is the nth time interval,

n is the number of each time interval and

N is the total number of intervals during the period considered.

10.5 Comparative analysis

This section of the chapter is based on K. Najdenkoski, G. Rafajlovski, V. Dimcev (2007)

Since there are two standardized bodies IEEE and IEC for determining the loss of life of transformers, there are some terminological differences between them. They are as follows:

- Normal transformer life according to IEEE is 180 000 hours while in IEC standards total life of a unit is not defined.
- The difference between hot-spot temperatures and aging rate dependence upon hottest-spot temperature.
- The different hottest-spot temperature for normal aging. For IEEE this temperature is 110 ^{o}C while according to IEC its 98 ^{o}C.

11. Transformers at Öresundsverket

This chapter contains the thermal model calculations done on the transformers at Öresundsverket.

11.1 Introduction

Two power transformers belonging to E.ON Värmekraft, BAT 10 (Gas turbine generator step up) and BAT 50 (Steam turbine generator step up) from year 2007 has been constantly loaded at maximum rated load. These units are placed at Öresundsverket, an combined heat and power plant in Malmö. The power transformers were manufactured by SMIT Transformatoren B.V. in Netherlands. The data which has been analyzed from power generation information management (PGIM) from the power plant shows that the transformers have been at constant maximum load during their operation.

The transformers have the following data:

BAT10	Manufacturer	Smit Transformatoren B.V.
	Type	Gas Turbine Generator Step Up (GSU)
	Batch number	221 32
	Voltage	140/17 kV
	Power	338 MVA
	Oil capacity (weight)	66000 kg
	Manufacturing year	2007
	Cooling type	ODAF
	Cooling system	12 fans and 3 pumps
	Placed	ÖVT

BAT50	Manufacturer	Smit Transformatoren B.V.
	Type	Steam Turbine Generator Step Up (GSU)
	Batch number	221 31
	Voltage	140/15,75 kV
	Power	215 MVA
	Oil capacity (weight)	44100 kg
	Manufacturing year	2007
	Cooling type	ODAF
	Cooling system	9 fans and 3 pumps
	Placed	ÖVT

In order to analyze the most suitable thermal model and its effect on transformers life time and future operational condition, continuous analysis data from gas, oil analysis, operation analysis, heat run protocol and temperature parameters are needed. These analysis results give a clear picture of transformer's condition in different operating conditions. Since the power transformers have been in use since 2009, all the analyses are quite recently carried out.

Thermal data showing maximum temperatures and hot-spot temperature is needed to understand how the insulation system of these transformers has been affected during operational period. Heat run protocol and rated loadings are also taken into consideration for the same purpose.

Operation under high temperatures can cause a potential damage to Kraft paper and pressboard of these power transformers. Deterioration in insulation system is mainly caused due to high temperatures but also due to moisture presence and oil acid content. All these accelerating factors have been taken into consideration for determining the condition of the power transformers in terms of life time and insulation condition.

11.2 Thermal model calculations

The thermal model calculations for each transformer have been described in detail. Both IEEE and IEC model has been taken into consideration while calculating the hot-spot temperatures. Both of the generator power transformers are Oil Directed Air Forced (ODAF) cooled. The calculations are based on the fact that oil temperature reaches up to 60 ^{o}C above the ambient, before the cooling system (fans and pumps) and the cooling system shuts down at 40 ^{o}C above ambient. This is normal operational condition (auto mode) of transformers today, which causes a great amount of stress in oil temperature, Kraft paper and metal. The ideal case would have that the cooling systems consisting of fans and pumps were in constant operation together with the power transformers.

11.2.1 Gas turbine GSU transformer (BAT 10)

IEC method

Benchmark for temperature calculation for gas turbine GSU transformer has been the original guarantee values which were measured at transformer. These measured values are valid for rated 338 MVA loading. The hot-spot temperature rise, ΔT_{hsp} has been calculated by help of gradient, $g = T_W - T_{MO}$.

Hot-spot rise is given as: $\Delta T_{hsp} = \Delta T_{TOP} + g*k$

Where k = 1,3 according to IEC 60076-7, Loading Guide for oil-immersed transformers, for GSU transformers with forced cooling.

The measured temperature values were:

Average oil temperature	(T_{MO})	39.9 ^{o}C
Top oil temperature	(ΔT_{TOP})	41.0 ^{o}C
Average winding temperature	(T_W)	49.5 ^{o}C

This gives the gradient g = 9.6 ^{o}C and hot-spot rise of Δ T_{hsp} = 53.5 ^{o}C.

These values are only valid for the rated power of 338 MVA.

Assuming that the ambient temperature has been 10 ^{o}C throughout the year in Malmö region, gives the hot-spot temperature of **T_{hsp} = 63.5 ^{o}C**.

With ODAF cooling and under the conditions that cooling system i.e. fans and pumps starts at 60 ^{o}C, the hot-spot temperature increases to **T_{hsp} = 85.3 ^{o}C.**

IEEE method

According to IEEE Std. C57.91 hot-spot temperature for a transformer depends upon ambient temperature Θ_A, top oil temperature Θ_{TO} and windings temperature Θ_T.

Hot-spot temperature, in this case is $\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\ \Theta_T$ which gives a hot-spot temperature at **106 ^{o}C**.

With ODAF cooling and under the conditions that cooling system i.e. fans and pumps starts at 60 ^{o}C, the hot-spot temperature increases to **Θ_H = 146 ^{o}C.**

11.2.2 Steam turbine GSU transformer (BAT 50)

IEC method

For BAT 50 steam turbine GSU transformer following temperatures were measured at 215 MVA loading:

Average oil temperature	(T_{MO})	32.7 ^{o}C
Top oil temperature	(ΔT_{TOP})	36.0 ^{o}C
Average winding temperature	(T_W)	37.4 ^{o}C

Gradient according to IEC was measured to 4.77 ^{o}C which gives the hot-spot rise of $\Delta\ T_{hsp}$ = 42.2 ^{o}C. Assuming average ambient temperature to be 10 ^{o}C, gives the hot-spot temperature **T_{hsp} = 52.2 ^{o}C.**

With ODAF cooling and under the conditions that cooling system i.e. fans and pumps starts at 60 ^{o}C, the hot-spot temperature increases to **T_{hsp} = 77.9 ^{o}C.**

IEEE method

According to IEEE standards following temperature rise were measured:

Ambient temperature	(Θ_A)	10 ^{o}C
Top oil temperature	($\Delta\Theta_{TO}$)	36 ^{o}C
Winding temperature	($\Delta\ \Theta_T$)	42 ^{o}C

Hot-spot temperature in this is calculated to be **88 ^{o}C**.

With ODAF cooling and under the conditions that cooling system i.e. fans and pumps starts at 60 ^{o}C, the hot-spot temperature increases to **Θ_H = 141 ^{o}C.**

Summary of calculated hot-spot temperatures

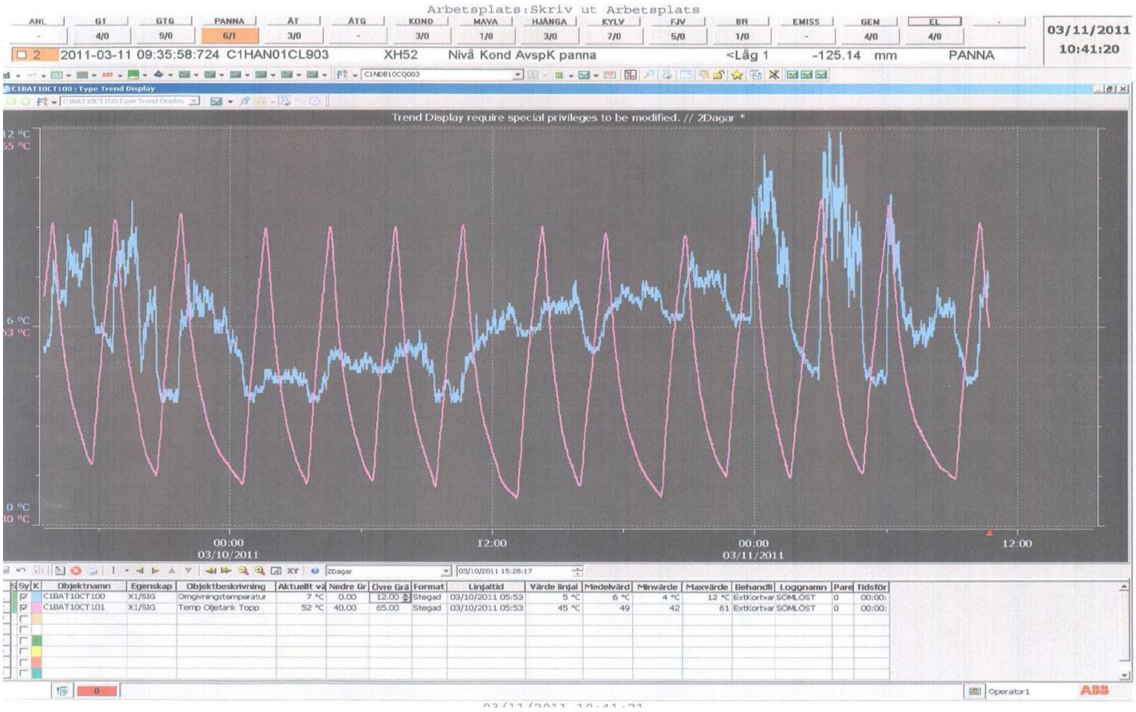
	BAT10		BAT50	
	IEC standard	IEEE standard	IEC standard	IEEE standard
Average oil temperature (^{o}C)	39.92	39.92	32.71	32.71
Top oil temperature (^{o}C)	41	41	36	36
Winding temperature (^{o}C)	49.56	55	37.48	37.48
Load MVA	338	338	215	215
Constant Cooling				
Hot-spot rise (^{o}C)	53.5		42.2	
Ambient temperature (^{o}C)	10	10	10	10
Hot-spot temperature (^{o}C)	**63.5**	**106**	**52.2**	**88**
Cooling starts at oil temp.≥60 ^{o}C				
Hot-spot temperature (^{o}C)	**85.3**	**146**	**77,9**	**141**

Graphs 11.1 and 11.2 on following pages shows how the top and windings oil temperature varies heavily for BAT 10 in auto mode.

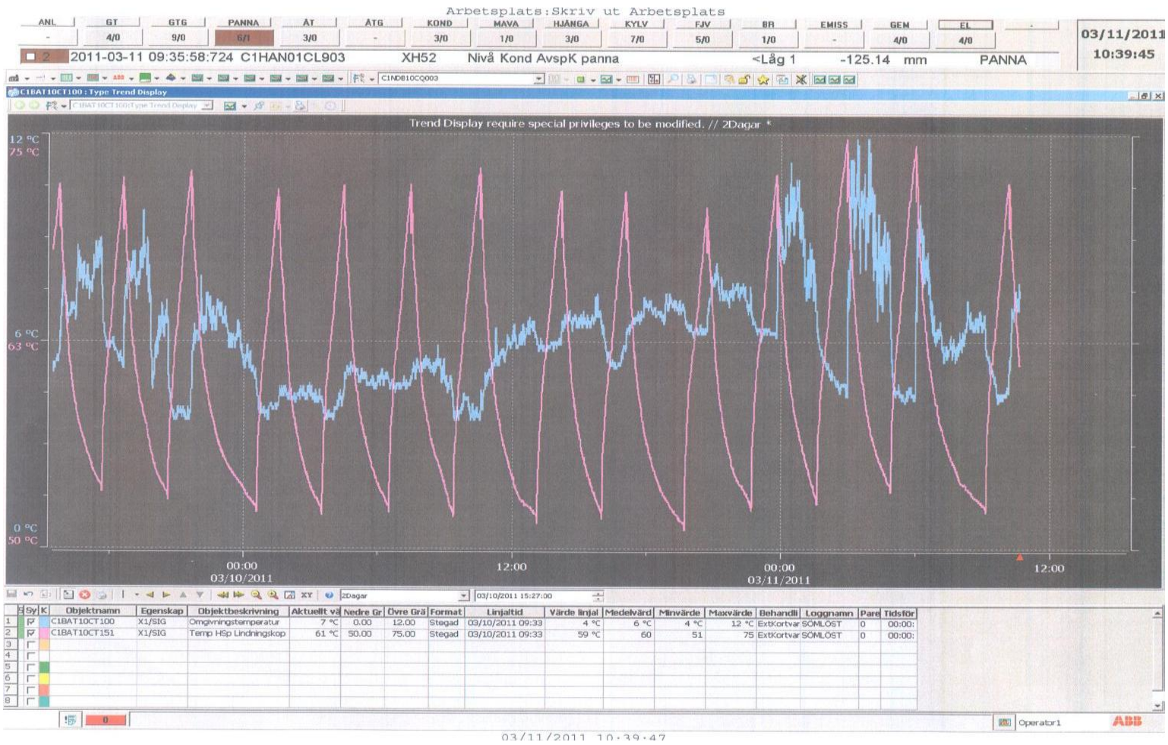
Graphs 11.3 and 11.4 show how the top and windings oil temperature follows the ambient temperature when all the fans and pumps are in constant operation (manual mode) in BAT 10.

The same applies for Steam turbine GSU transformer (BAT 50) in auto and manual mode.

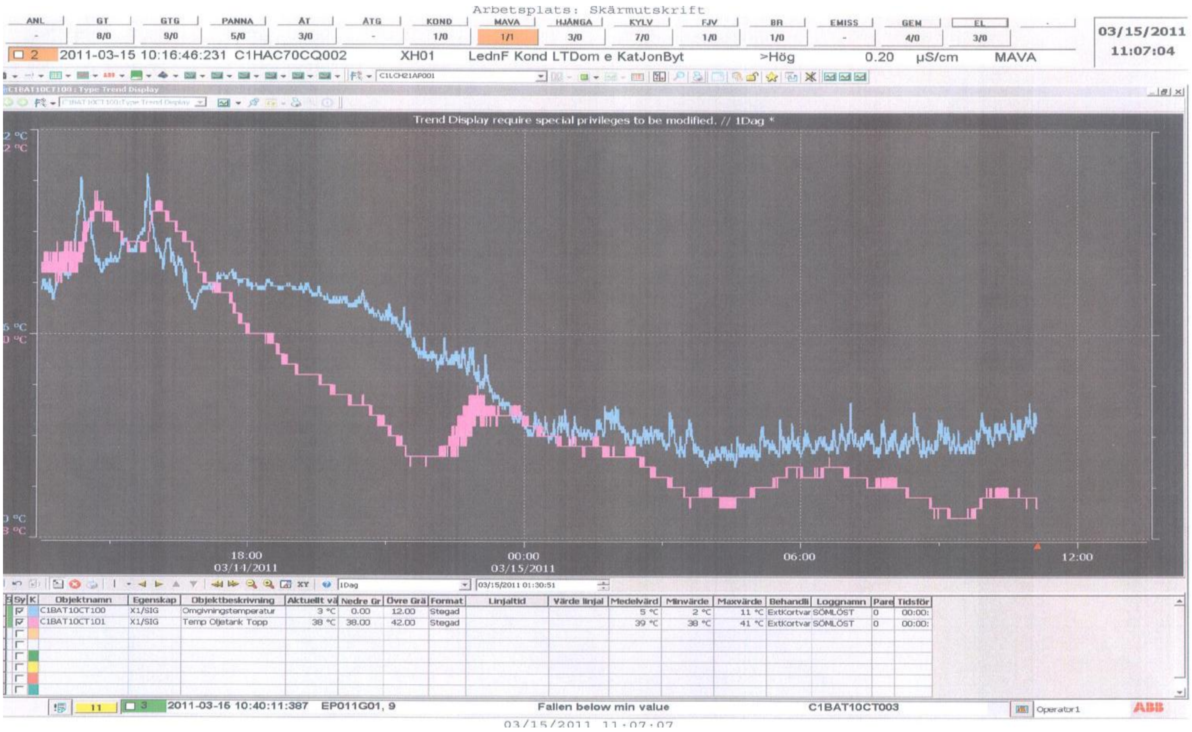
The ambient temperature graph varies when the fans are switched on and off in auto mode. Graph 11.1 and 11.2 above shows how the ambient temperatures are varied when fans start on 60 ^{o}C and shuts off at 40 ^{o}C. This variation is caused due to ambient temperature sensors are situated near to the fans.



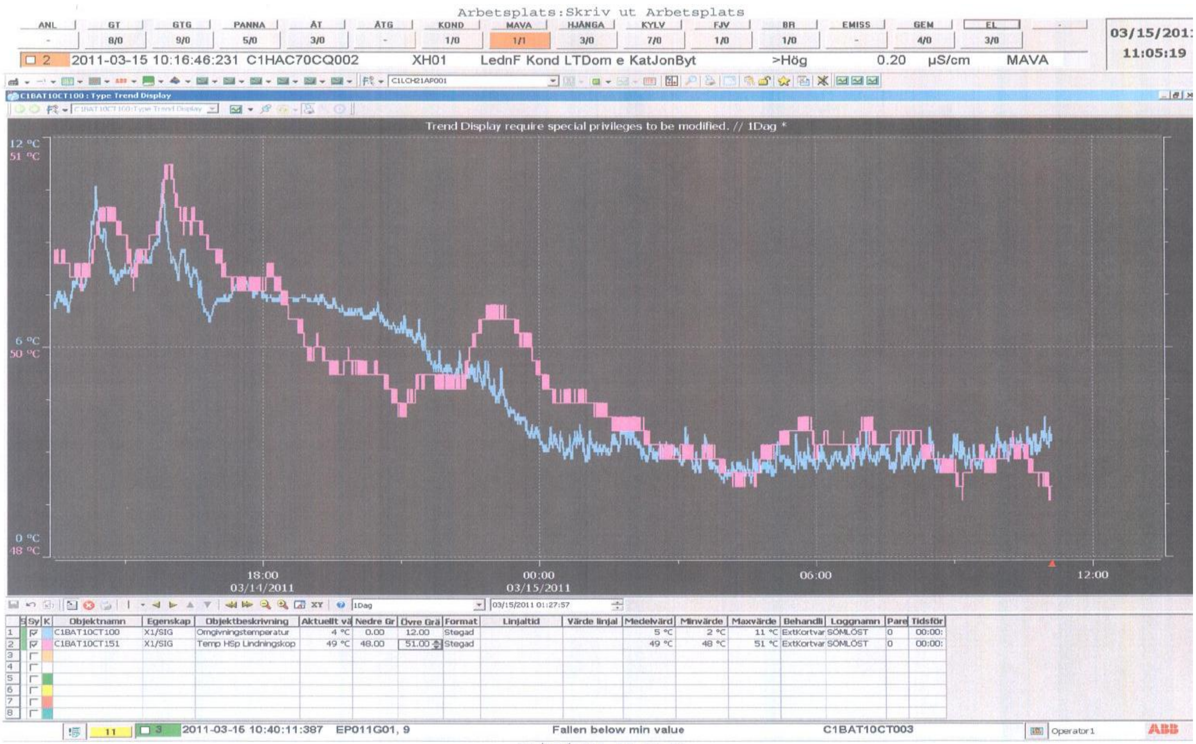
Graph 11.1:Top oil temperature variations in auto mode (pink)of BAT 10 from 49 ^{o}C to 61 ^{o}C Vs. ambient temperature (blue) varying from 4 ^{o}C to 12 ^{o}C in 2 days' time period.



Graph 11.2: Windings oil temperature variations in auto mode (pink)of BAT 10 from 51 ^{o}C to 75 ^{o}C Vs. ambient temperature (blue) varying from 4 ^{o}C to 12 ^{o}C in 2 days' time period.



Graph 11.3:Top oil temperature variations in manual mode (pink)of BAT 10 from 38 °C to 41 °C Vs. ambient temperature (blue) varying from 2 °C to 11 °C in 24 hours' time period.



Graph 11.3:Windings oil temperature variations in manual mode (pink)of BAT 10 from 48 °C to 51 °C Vs. ambient temperature (blue) varying from 2 °C to 11 °C in 24 hours' time period.

11.3 Evaluation of Kraft paper

In order to measure the aging accelerating factor, Arrhenius relation (equation 7.3) has been used. DP-value, known as degree of polymerization is the measure of number of cellulose chains found in the Kraft paper. The number of break up in the chains is represented by parameter η och its value increases with time and temperature as discussed in chapter 7.

The relation is described as follows:

$$\eta = \frac{DPo}{DPt} - 1$$

where DP_O is the orignal DP value of new Kraft paper and DP_t is the DP value of used paper after t years.

Aging accelerating factor is given as:

$$\eta(t) = \eta_o + k(T) \cdot t$$

where k varies with time and temperature and measured to be 0,00075 breakups per 24 hours at 98 ^{o}C according to ASTM D4243-86 standard. This above mentioned value of k is commonly used in the industry. Aging factor is higher in the beginning for the new paper but slows down later with time. The original value of η i.e. η_o is set to be 0.3. This value of η_o can be explained as presence of weaker chains which break up immediately.

11.3.1 Gas turbine GSU transformer (BAT 10)

After adjustment of aging factor according to operating temperature, following calculations were carried out.

Number of cellulose chain break up after 2 years of operation:

$\eta = 0.3 + k(85) \cdot 17500 =$ **2.26**

DP-value after 2 years of operation at 338 MVA is assumed to be **940**.

If the cooling system has been in operation throughout the transformers, the following calculations are valid for transformer:

$\eta = 0.3 + k(63) \cdot 17500 =$ **0.02**

DP-value after 2 years of operation at 338 MVA is assumed to be **1170**.

11.3.1 Steam turbine GSU transformer (BAT 50)

After adjustment of aging factor according to operating temperature, the following calculations were carried out.

Number of cellulose chain break up after 2 years of operation:

$\eta = 0.3 + k(78) \cdot 17500 = \mathbf{0.13}$

DP-value after 2 years of operation at 215 MVA is assumed to be **1060**.

If the fans have been in operation throughout these 2 years, the following measurements are valid:

$\eta = 0.3 + k(52) \cdot 17500 = \mathbf{0.008}$

DP-value after 2 years of operation at 215 MVA is assumed to be **1060**.

Summary of DP values and Kraft paper condition

	BAT10	BAT50
η	**0.02 / 2.26**	**0.008 / 0.13**
DP	**1170 / 940**	**1190 / 1060**
Operation hours	**17500**	**17500**
T_{hsp}	**63 / 85**	**52 / 78**
Evaluation	**Good paper condition according to ANSI- standard.**	

Calculated DP value clearly shows how the aging accelerating factor decreases when the cooling system i.e. all the fans and pumps are in constant operation together with the transformer.

11.4 Thermal aging

There are no direct 'end of life' criteria for assessing the remaining life of transformers. But such terms are useful for transformer users to judge the life time reduction and transformer's condition.

11.4.1 Gas turbine GSU transformer (BAT 10)

IEC Standard

Insulation's aging occurs at all temperature levels and is directly dependent on temperature, moisture, acid and oxygen. According to IEC 60076 standard aging is mainly based on temperature parameter. Since the temperature rise is uneven in the transformer, the hot-spot temperature is an important parameter in calculating the aging acceleration factor.

For BAT10 hotspot temperature is calculated (Section 11.2.1) to be 63.5 ^{o}C with all fans and pumps in constant operation.

Ageing rate (V) of IEC is described by the following relation:

$$V = e^{\left(\frac{15000}{110+273}\right)-\left(\frac{15000}{\theta+273}\right)}$$

The aging rate in this case is estimated to be **4.46 • 10^{-3}**.

Lifetime loss after 2 years of operation is **78 hours** or about **3 days**.

With ODAF-cooling, provided that the cooling system started only when the oil temperature reaches to 60 ^{o}C, aging rate becomes **0.19** and lost life time of transformer is of about **140 days**.

IEEE Standard

The aging rate (F_{AA}) of the transformer according to IEEE Std. C57.91 also depends on the hot-spot temperature and is described as follows:

$$F_{AA} = e^{\left(\frac{1500}{383}\right)-\left(\frac{1500}{\theta+273}\right)}$$

Calculation as above gives an aging rate of **0.96**.

Percentage of total life that is lost during a 2 year period of operation has been estimated at **9.3%**.

When the same ODAF cooling reasoning is applied here, aging rate is calculated to **1.4** percent of total lost life time to be approximately **13.6 %.**

11.4.2 Steam turbine GSU transformer (BAT 50)

IEC Standard

The aging rate according to IEC standard with all fans and pumps running has been estimated at **$9.48 \cdot 10^{-4}$**.

Lifetime Loss after two years of operation is estimated to **17 hours**.

With ODAF-cooling, and provided that the cooling system starts only when the oil temperature reaches 60 ^{o}C, aging rate is calculated to be **0.02** and lifetime loss to be about **20 days**.

IEEE Standard

The aging rate according to IEEE standard with all fans and pumps running has been calculated to be **0.78**.

Percent of total life lost during 2 years operation period is estimated at **7.65%**.

When the same ODAF cooling reasoning is applied here, aging rate is calculated to **1.3** percent of total lost life time to be approximately **13 %.**

Summary of calculated thermal aging

	BAT10		**BAT50**	
	IEC-standard	*IEEE- standard*	*IEC- standard*	*IEEE- standard*
Aging Rate	**$4.46 \cdot 10^{-3}$**	**0.96**	**$9.48 \cdot 10^{-4}$**	**0.78**
Lost life time	**3 days**	**9.3%**	**17 hours**	**7.65%**
Cooling starts at oil temp.≥60 ^{o}C				
Aging Rate	**0.19**	**1.4**	**0.02**	**1.3**
Lost life time	**140 days**	**13,6%**	**20 days**	**13%**

11.5 Gas analysis

In summary, gas-analysis for each transformer is considered with a focus on how viable the transformer is at that particular analysis moment and trends that points to ongoing changes. For detailed results refer to annexes 14.5 and 14.6, where the comprehensive analysis reports are available.

11.5.1 Gas Turbine GSU transformer (BAT 10)

Gas analysis is carried out year 2010 and 2011 have been provided. The condition of the BAT 10 transformer is considered to be good. A stable trend is showing a decrease in combustible gases and total gas content in the latest test. This decreasing trend depends upon the cooling system (fans and pumps) which were in constant operation three weeks before oil samples were collected.

The only thing which can be noticed is the development of hydrogen which is slightly higher than what is usually the case with this new transformer. It can be in absolute worst scenario an indication of beginning of PD (partial discharge) but may develop as a result of high moisture content or presence of inappropriate particles (impurity) inside the transformer.

There is no evidence found from analysis reports to indicate abnormal aging of the insulation material. The insulation's function is completely normal.

11.5.2 Steam Turbine GSU transformer (BAT 50)

Gas analyses carried out year 2010 and 2011 have also been provided. The condition of the BAT 10 transformer is considered to be good. A stable trend is showing a development of combustible gases and total gas content in the last two years test results.

Concentration of carbon dioxide has increased over the past year, which can indicate the low thermal degradation of insulation material.

11.6 Oil analysis

The oil analysis available is summarized in the table below. A summary assessment of the oil condition is specified for each one of transformers during past two years.

For each unit, separate reports are also available as *annexes 14.5 and 14.6* to this report.

Measured data:

	BAT 10		**BAT 50**	
	2010	**2011**	**2010**	**2011**
Parameters				
Testing date	2010-07-09	2011-03-28	2010-07-09	2011-03-28
Acidity	<0,01	<0,01	<0,01	<0,01
Interfacial tension	45		45	
Inhibitor content	0,28	0,29	0,27	0,29
Tan delta	1		1	
Moisture content	2	1	3	2
Oil temperature	55	42	50	52
Electrical breakdown	82	93	86	71
Color	<0,5	<0,5	<0,5	<0,5
Manufacturing year	2008		2008	
Results	Good condition		Good condition	
Measures	None		None	

12 Conclusion

Graphs 11.1 -11.4 shows how top oil and windings temperature varies frequently when fans and pumps are in auto mode. This variation causes a stress in insulation system, Kraft paper and pressboard. Such prolong operation conditions, is not considered for well-being of the transformer's insulation system.

According to IEC, loss of life time is calculated to be one day at 98 ^{o}C transformer's operational temperature. The same operational temperature is calculated to be 110 ^{o}C according to IEEE standards. For every 6 ^{o}C rise in temperature above these temperatures, life time of transformer is reduced to half. Operational temperature below these ranges increases the life of transformer.

By having all the fans and pumps in constant operation with transformers, hot-spot temperature is reduced thus increasing the life of the transformers.

Gas analysis from last year's shows a stable trend in combustible and total gas content. The Doernenburg and Roger ratio mentioned in Chapter 9.4 are found to be normal except for low temperature thermal fault which is consider to be normal in case of such large GSU transformers. The analysis from 2011 in BAT 10 shows a decline in total gas content and improvement in CH_4 / H_2 ratio due to constant cooling. But it will be recommended to closely follow the trend of hydrogen gas formation in gas turbine GSU transformer.

The thermal model shall be seen as indication of insulation's behavior during different operating conditions. Since the presence of certain percent of uninhibited oil from the heat run test from the manufacturer, there is a low risk that the windings can be covered by sludge. In worst case scenario the Kraft paper around the conductor can degrade and mix with oil at high temperatures causing DP value reducing to 400.

Power transformers are sensitive to frequent operating changes which can be caused by temperature variations, vibrations, fast tapping or short circuit. The presence of uninhibited oil from FAT test will accelerate the aging process in the new present oil.

There is also risk of increase in viscosity of the transformer's oil if the cooling system (fans and pumps) are in operation when power plant is still or running in self supply mode. In other words the viscosity of oil will increase in case of low or no load state of transformer when the cooling system of transformer is in operation. This rise of viscosity is also due to presence of uninhibited oil which is estimated to be 10 % of total oil present and is not arctic grade classed. The high viscosity causes slow flow of the oil which gives stagnant cooling. This condition is usually termed as 'Cold start up' of the power transformers.

Overall judgment of transformer's condition is assumed to be good. But non operation of fans and pumps are evaluated to be unacceptable. Under such transformer's operating condition there is a risk that insulation system can strongly accelerate the aging process and reach DP value of 400. At this DP value it's consider end of life for transformer.

Recommendation is to have fans and pumps constantly running together with the power transformers. If the fans and pumps are in constant operation, more frequent revision on them will be required as that of today. Monitoring of these units should occur by studying gas analysis reports which should be carried out yearly. A regular oil analysis is also recommended to follow the any development in these units. The important oil parameters to monitor are color, acidity, moisture content, interfacial tension and electrical breakdown.

In future it is also recommended to perform an actual DP test and short circuit test with modern equipment of the given power transformers.

13 Further development

As discussed in the chapter 12, it's recommended to have all fans and pumps constantly running together with transformer. However, there is scope of further work to study the effects of the following implements on the cooling and lifetime of power transformers at Öresundsverket.

- An external speed control on the fans can be implemented to cut down the running cost. As E.ON requested to investigate only auto and manual mode, running all the 12 fans in BAT 10 and 9 fans in BAT 50 constantly will increase the operating cost of these transformers. These 21 fans are rated at 1 kW each and if considering the normal lifetime of these power GSU transformers is 20 years, the running cost of fans amount to 3.8 MSEK. This cost of 3.8 MSEK has been made on assumption that E.ON's internal electricity prices remain constant at 1 SEK/kWh over next coming 20 years.

- The position of sensors measuring the ambient temperatures in both BAT 10 and BAT 50 are quite near to the fans. The ambient temperature graph varies when the fans are switched on and off in auto mode. Graph 11.1 and 11.2 above shows how the ambient temperatures are varied when fans start on 60 ^{o}C and shuts off at 40 ^{o}C. These ambient temperature sensors can be shifted to an appropriate place or ambient readings can be taking from another sensor located at the power plant.

14 References

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16. Oral discussions with:

- Mårten Svennson (Vattenfall, Malmö)
- Mark Wilkensson (SMIT Transformers, Netherlands)
- Mats O Dahlund, Tomas Olsson, Lars Åker-Lundin, Lars Pettersson (ABB Power-transformers, Ludvika)
- Rickard Tjäder (One Nordic, Malmö)
- Ulf Lager (E.ON Elnät, Malmö)
- Charlotte E Svensson (Nynas Oil, Stockholm)
- Conny Lindsjö (Grontmij, Malmö)

17. Study visits:

- Karlshamnsverket, Karlshamn.
- Åbyverket, Örebro.

15 Appendixes

15.1 Uninhibited Oil (Nytro Libra) properties.

Nytro Libra

PROPERTY	UNIT	TEST METHOD IEC	GUARANTEED DATA MIN	GUARANTEED DATA MAX	TYPICAL DATA
Physical					
Appearance		IEC 60296	Clear, free from sediment		complies
Density, 20°C	kg/dm^3	ISO 12185		0,895	0,879
Viscosity, 40°C	mm^2/s	ISO 3104		12,0	9,4
Viscosity, -30°C	mm^2/s	ISO 3104		1800	1100
Pour point	°C	ISO 3016		-40	-53
Chemical					
Acidity	mg KOH/g	IEC 62021		0,01	<0,01
Corrosive sulphur		DIN 51353	non-corrosive		non-corrosive
Corrosive sulphur		ASTM D 1275 B	non-corrosive		non-corrosive
Corrosive sulphur		IEC 62535	non-corrosive		non-corrosive
Aromatic content	%	IEC 60590			10
Antioxidant, phenols	Wt %	IEC 60666	not detectable		not detectable
Water content	mg/kg	IEC 60814		30	<20
Furfural content	mg/kg	IEC 61198		0,1	<0,1
Electrical					
Dielectric dissipation factor (DDF) at 90°C		IEC 60247		0,005	<0,001
Interfacial tension	mN/m	ISO 6295	40		48
Breakdown voltage					
- Before treatment	kV	IEC 60156	30		40-60
- After treatment	kV		70		>70
Oxidation stability					
At 120°C, 164 h		IEC 61125 C			
Total acidity	mg KOH/g			1,2	0,50
Sludge	Wt %			0,8	0,15
DDF/90°C				0,500	0,080
Health, safety and environment					
Flash point, PM	°C	ISO 2719	135		148
DMSO extractable compounds	Wt %	IP 346		3	<3
PCB		IEC 61619	not detectable		not detectable

Nytro Libra is an uninhibited insulating oil, meeting IEC 60296 (03) General specifications.

Severely Hydrotreated Insulating Oil
Issuing date: 2010-03-24

NYNAS

15.2 Inhibited Oil (Nytro 10XN) properties.

PRODUCT DATA SHEET

Nytro 10XN

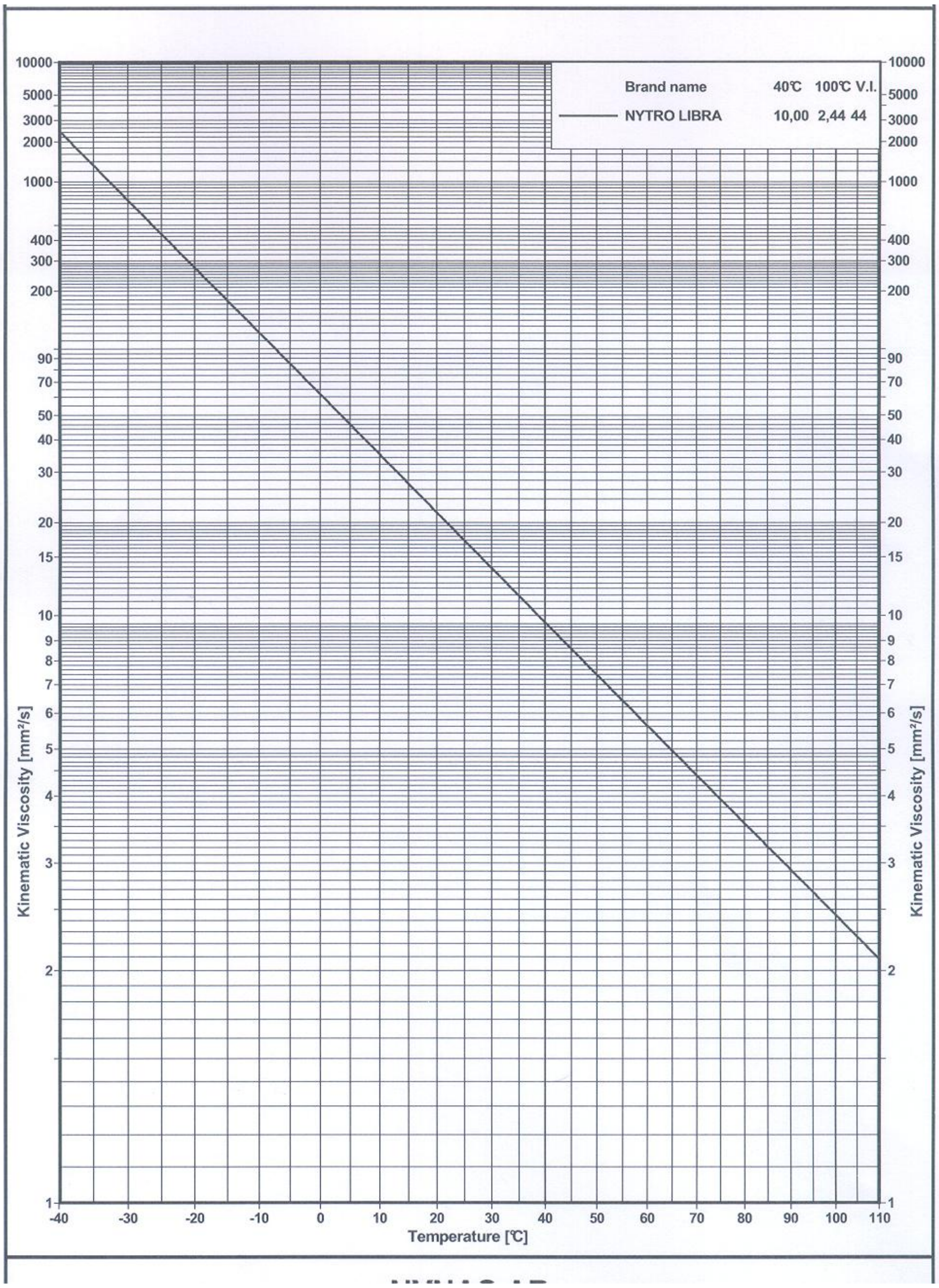
PROPERTY	UNIT	TEST METHOD IEC	GUARANTEED DATA MIN	GUARANTEED DATA MAX	TYPICAL DATA
Physical					
Appearance		IEC 60296	Clear, free from sediment		complies
Density, 20°C	kg/dm³	ISO 12185		0,895	0,877
Viscosity, 40°C	mm²/s	ISO 3104		8,0	7,6
Viscosity, -30°C	mm²/s	ISO 3104		800	730
Pour point	°C	ISO 3016		-45	-63
Chemical					
Acidity	mg KOH/g	IEC 62021		0,01	<0,01
Corrosive sulphur		DIN 51353	non-corrosive		non-corrosive
Corrosive sulphur		ASTM D 1275 B	non-corrosive		non-corrosive
Corrosive sulphur		IEC 62535	non-corrosive		non-corrosive
Sulphur content	%	ISO 14596		0,15	<0,01
Aromatic content	%	IEC 60590			7
Antioxidant, phenols	Wt %	IEC 60666		0,4	0,3
Water content	mg/kg	IEC 60814		30	<20
Furfural content	mg/kg	IEC 61198		0,1	<0,1
Electrical					
Dielectric dissipation factor (DDF) at 90°C		IEC 60247		0,005	<0,001
Interfacial tension	mN/m	ISO 6295	40		49
Breakdown voltage					
- Before treatment	kV	IEC 60156	30		40-60
- After treatment	kV		70		>70
Oxidation stability					
At 120°C, 500 h		IEC 61125 C			
Total acidity	mg KOH/g			0,30	0,04
Sludge	Wt %			0,05	<0,02
DDF/90°C				0,050	0,03
Health, safety and environment					
Flash point, PM	°C	ISO 2719	140		144
DMSO extractable compounds	Wt %	IP 346		3	<3
PCB		IEC 61619	not detectable		not detectable

Nytro 10XN is an inhibited insulating oil with extremely good electrical and low temperature properties and excellent ageing properties. This product meets IEC 60296 (03), special applications and ASTM D3487 type II (excluding gassing tendency).

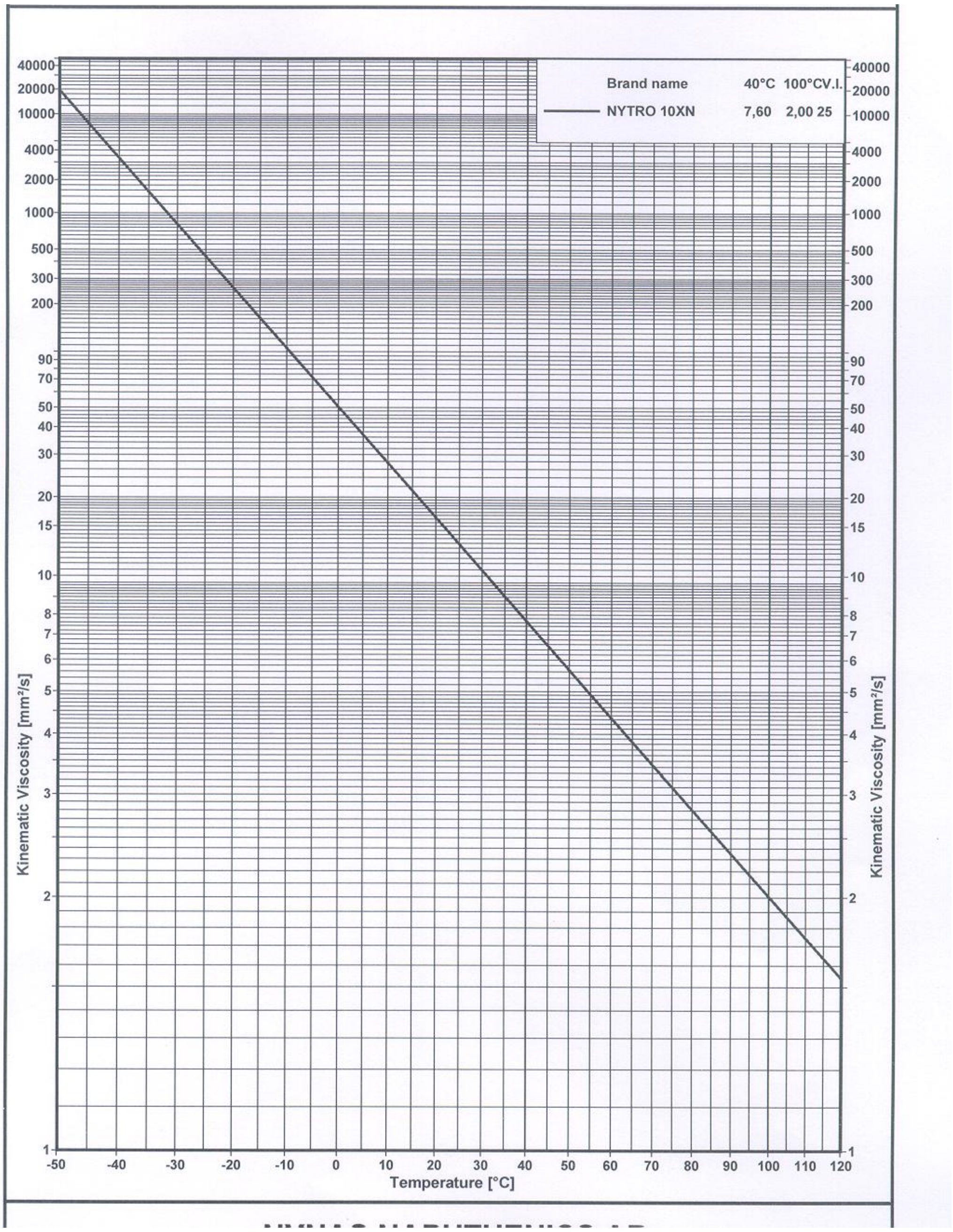
Severely Hydrotreated Insulating Oil
Issuing date: 2008-03-28

NYNAS

15.3 Uninhibited Oil (Nytro Libra) viscosity vs. temperature curve.



15.4 Inhibited Oil (Nytro 10XN) viscosity vs. temperature curve.



15.5 BAT 10 Oil & Gas analysis report.

Kund	Kontaktperson	
E.ON Värmekraft Sverige AB	Roger Österback	**Utskriftsdatum:** 2011-04-13
CHP-kontoret	**Kundreferens**	**ABB ordernr:** W68001667
205 09 Malmö	84700303	

Provobjekt:	Transformator	**Oljevikt:**	65900 kg
Tillverkare:	SMIT Transformers	**Oljetyp:**	Nynäs Nytro 10 XN
Typ:	-	**Typ av kopplare:**	Lindningskopplare
Tillverkningsnr:	221232	**Exp. lk/tank:**	Separat
Spänning:	140/17 kV	**Ägare:**	E.ON Värmekraft Sverige
Effekt:	338 MVA	**Uppställningsplats:**	Öresundsverket
Tillverkningsår:	2009	**Lokal identitet:**	C1 BAT 10
Övriga uppgifter:	-		

Analysresultat

Provdatum			110328	100622
Provnr.			11-1357	10-2421
Provställe			AA403	Mitten
Analys	**Norm**	**Enhet**		
Oljetemperatur		°C	42	55
Fukthalt	IEC 60814	mg/kg	1	2
Isolationsfukthalt		%(w/w)	ca 0.5	ca.1
Syratal	IEC 62021-1	mg KOH/g	<0.01	<0.01
Genomslag, medelv.	IEC 60156/9	kV/2.5 mm	93	82
Standardavvikelse			9	4
Färg	ASTM D1500		<0.5	<0.5
Tan. Delta	IEC 60247	x10-3		1
Gränsytspänning	ASTM D971-9	mN/m		45
Inhibitor (GC-MS)		% (w/w)	0.29	0.28
Väte (H2)	IEC 60567	µl/l	31	45
Syre (O2)	IEC 60567	µl/l	6900	8700
Kväve (N2)	IEC 60567	µl/l	37000	42000
Metan (CH4)	IEC 60567	µl/l	7	7
Koloxid (CO)	IEC 60567	µl/l	364	328
Koldioxid (CO2)	IEC 60567	µl/l	1150	1240
Eten (C2H4)	IEC 60567	µl/l	1	1
Etan (C2H6)	IEC 60567	µl/l	2	1
Acetylen (C2H2)	IEC 60567	µl/l	<1	<1
Propen (C3H6)	IEC 60567	µl/l	2	3
Propan (C3H8)	IEC 60567	µl/l	<1	2
TCG	IEC 60567	µl/l	407	387
Totalgashalt		% (v/v)	4.74	5.45

Bedömning

OLJEKONDITION
Resultatet visar att oljan är i bra kondition.
Isolationsfukthalten har uppskattats under antagandet att jämvikt råder mellan oljan och cellulosan, dvs att drifttemperaturen under en längre tid (minst 1 vecka) varit stabil. Det finns en viss osäkerhet i denna uppskattning. Den uppskattade isolationsfukthalten är dock att betrakta som normal.
GASANALYS
Resultatet tyder inte på något onormalt sedan föregående analys.

15.6 BAT 50 Oil & Gas analysis report.

Kund
E.ON Värmekraft Sverige AB
CHP-kontoret
205 09 Malmö

Kontaktperson
Roger Österback
Kundreferens
84700303

Utskriftsdatum: 2011-04-13
ABB ordernr: W68001667

Provobjekt:	Transformator	**Oljevikt:**	44100 kg
Tillverkare:	SMIT Transformers	**Oljetyp:**	Nynäs Nytro 10 XN
Typ:	-	**Typ av kopplare:**	Lindningskopplare
Tillverkningsnr:	221231	**Exp. lk/tank:**	Separat
Spänning:	140/15,75 kV	**Ägare:**	E.ON Värmekraft Sverige
Effekt:	215 MVA	**Uppställningsplats:**	Öresundsverket
Tillverkningsår:	2008	**Lokal identitet:**	C1 BAT 50
Övriga uppgifter:	-		

Analysresultat

Provdatum			110328	100622
Provnr.			11-1356	10-2423
Provställe			AA 403	Mitten
Analys	**Norm**	**Enhet**		
Oljetemperatur		°C	52	50
Fukthalt	IEC 60814	mg/kg	2	3
Isolationsfukthalt		%(w/w)	ca 0.5	ca.1
Syratal	IEC 62021-1	mg KOH/g	<0.01	<0.01
Genomslag, medelv.	IEC 60156/9	kV/2.5 mm	71	86
Standardavvikelse			6	10
Färg	ASTM D1500		<0.5	<0.5
Tan. Delta	IEC 60247	$x10^{-3}$		1
Gränsytspänning	ASTM D971-9	mN/m		45
Inhibitor (GC-MS)		% (w/w)	0.29	0.27
Väte (H2)	IEC 60567	µl/l	17	20
Syre (O2)	IEC 60567	µl/l	<1000	1600
Kväve (N2)	IEC 60567	µl/l	11000	11000
Metan (CH4)	IEC 60567	µl/l	6	6
Koloxid (CO)	IEC 60567	µl/l	303	247
Koldioxid (CO2)	IEC 60567	µl/l	1320	1300
Eten (C2H4)	IEC 60567	µl/l	4	4
Etan (C2H6)	IEC 60567	µl/l	3	3
Acetylen (C2H2)	IEC 60567	µl/l	<1	<1
Propen (C3H6)	IEC 60567	µl/l	3	6
Propan (C3H8)	IEC 60567	µl/l	<1	3
TCG	IEC 60567	µl/l	336	289
Totalgashalt		% (v/v)	1.42	1.48

Bedömning

OLJEKONDITION
Resultatet visar att oljan är i bra kondition.
Isolationsfukthalten har uppskattats under antagandet att jämvikt råder mellan oljan och cellulosan, dvs att drifttemperaturen under en längre tid (minst 1 vecka) varit stabil. Det finns en viss osäkerhet i denna uppskattning. Den uppskattade isolationsfukthalten är dock att betrakta som normal.
GASANALYS
Resultatet tyder inte på något onormalt sedan föregående analys.