

CHAPTER ONE

INTRODUCTION

1.1 Overview

A transformer is a static machine used for transforming power from one circuit to another without changing frequency, consisting of a winding, two or more coupled windings, with or without a magnetic core, for inducing mutual coupling between circuits with Classification:

- Based on the number of phases, single or three phase.
- Based on the shape of the magnetic media, core or shell type.
- Based on the loading condition, power or distribution type.
- Based on transfer ratio, step up or step down type.
- Based on operating frequency:
 - Very low frequency transformer (power and distribution).
 - Intermitted frequency transformer.
 - Very high frequency transformer.
 - high frequency transformer.
- Based on cooling method:
 - Self air cooled (dry type).
 - Air blast cooled(dry type).
 - Oil immersed transformer:
 - ❖ ONAN.
 - ❖ ONAF.
 - ❖ OFAN.
 - ❖ OFAF.

1.1.1 Historical of transformers

Discovered in 1831 the theory of mutual inductance between the two coils separate and a part from each other and present Heart Made of Magnetic and measured the electrical motive force practically on one of the two coils a result of the current change in the other coil. Then for first time it appeared in 1882 transformer made of Primary coil and many of secondary coil in order to obtain different values for the secondary voltages.

Magnetic core transformer in 1884 it was the first use in transforming electrical energy to high voltages and transmitted for far distance by John and Edward Hopkinson where they made simple transformer with isolated steel plates core and two coils one for low voltage and the other for high voltage. Then came Weri who first launch name of transformer on this devices and later advented the idea of connect transformer on parallel, and for three phase transformer it was appear by Russian Dolph Dobrovska in 1889.

The history of transformer was commenced in the year 1880. In the year 1950, 400 KV electrical power transformer was introduced in high voltage electrical power system. In the early 1970, unit rating as large as 1100 MVA was produced and 800 KV and even higher KV class transformers were manufactured in year of 1980. [1]

1.1.2 Working principle of transformer

The working principle of transformer is very simple. It depends upon Faraday's law of electromagnetic induction "Rate of change of flux linkage with respect to time is directly proportional to the induced EMF in a conductor or coil". Actually, mutual induction between two or more winding is responsible for transformation action in an electrical transformer.

Say you have one winding which is supplied by an alternating electrical source. The alternating current through the winding produces a continually

changing flux or alternating flux that surrounds the winding. If any other winding is brought nearer to the previous one, obviously some portion of this flux will link with the second. As this flux is continually changing in its amplitude and direction, there must be a change in flux linkage in the second winding or coil. According to Faraday's law of electromagnetic induction, there must be an EMF induced in the second. If the circuit of the later winding is closed, there must a current flowing through it. This is the simplest form of electrical power transformer and this is the most basic of working principle of transformer.

The winding which takes electrical power from the source, is generally known as primary winding of transformer. Here in our above example it is first winding such as shown in Figure (1.1) below:

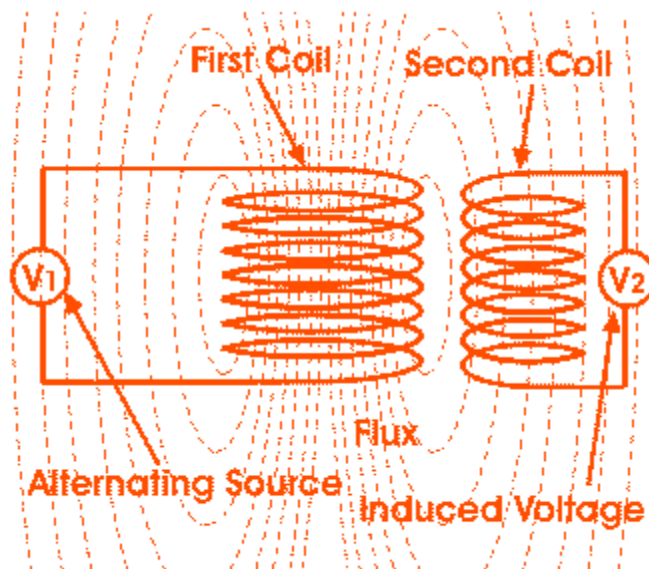


Figure (1.1): Primary winding

The winding which gives the desired output voltage due to mutual induction in the transformer, is commonly known as secondary winding of transformer such as shown in Figure (1.2) below:

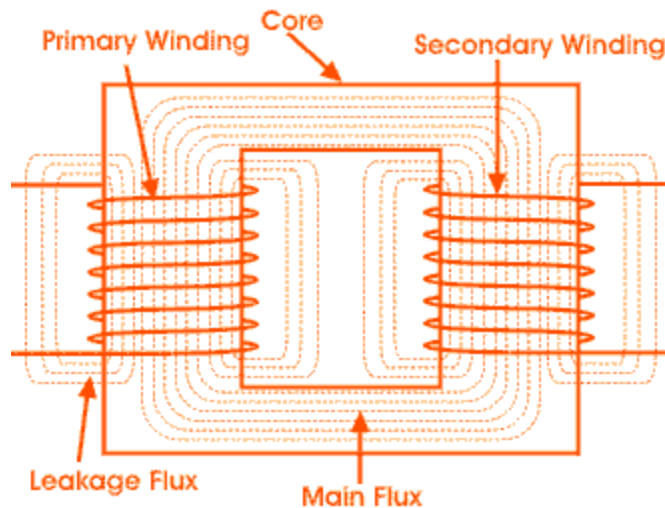


Figure (1.2): Secondary winding

The above mentioned form of transformer is theoretically possible but not practically, because in open air very tiny portion of the flux of the first winding will link with second, so the current that flows through the closed circuit of later, will be so small in amount that it will be difficult to measure.

The rate of change of flux linkage depends upon the amount of linked flux with the second winding. So it is desired to be linked to almost all flux of primary winding to the secondary winding. This is effectively and efficiently done by placing one low reluctance path common to both of the winding. This low reluctance path is core of transformer, through which maximum number of flux produced by the primary is passed through and linked with the secondary winding, all transformer with main constructional as follow:

Primary winding of transformer which produces magnetic flux when it is connected to electrical source.

The magnetic flux produced by the primary winding, that will pass through this low reluctance path linked with secondary winding and create a closed magnetic circuit. Secondary Winding of transformer the flux, produced by primary winding, passes through the core, will link with the secondary winding.

This winding also winds on the same core and gives the desired output of the transformer. [1]

1.1.3 Types of transformer

- I. Step up transformer and step down transformer generally used for stepping up and down the voltage level of power in transmission and distribution power network.
- II. Three phase transformer and single phase transformer is generally used in three phase power system as it is cost effective than later but when size matters, it is preferable to use bank of three single phase transformer as it is easier to transport three single phase unit separately than one single three phase unit.
- III. Electrical power transformer, distribution transformer and instrument transformer it is generally used in transmission network which is normally known as power transformer, distribution transformer is used in distribution network and this is lower rating transformer and current transformer and potential transformer, we use for relay and protection purpose in electrical power system and in different instruments in industries are called instrument transformer.
- IV. Two winding transformer and Auto transformer is generally used where ratio between high voltage and low voltage is greater than two. It is cost effective to use later where the ratio between high voltage and low voltage is less than two.
- V. Outdoor transformer and indoor transformer. Transformers that are designed for installing at outdoor are outdoor transformers and transformers designed for installing at indoor are indoor transformers.

[1]

1.1.4 Definition of distributed transformer

The step down transformers used for electric power distribution purpose are referred as distribution transformer. There are several types of transformer used in the distribution system. Such as single phase transformer, three phase transformer, pole mounted transformer, pad mounted transformer, and underground transformer. Distribution transformers are generally small in size and filled with insulating oil. These transformers are available in the market in various sizes and efficiencies. Selection of distribution transformer depends upon the purpose and budget of the end users. [1]

1.2 Problem Statement

- Poor insulation level.
- High losses.
- High design and operation cost.
- Short lifetime.
- Rapidly maintenance.

1.3 Objectives

The objectives of this research are summarized as follows:

- Improve insulation level.
- Reduce losses.
- Abatement the cost.
- Achieve high efficiency.
- Increasing transformer lifetime.

1.4 Methodology

- Firstly we had overview of distribution transformer manufacturing by having a visit to transformer factory (TRANSUDAN), from this visiting we had learn more about transformer production line stages (i.e. silicon steel cutting stage, core collecting stage, winding wound methods and tank construction), also we found real problem in (1000KVA , 11/.433KV) design such as: high loss, poor insulation level, high designing cost and short life time. As result we desired to improve the design above ratting and solving this problems which had been mention.
- Secondly made the equation design with design factors and having more knowledge about materials quantity and cost.
- Thirdly selecting parameters substituted in transformer design equation and new design were obtained, also to ease the design performance excel sheet designing programming was performed.
- Finally new design result was compared with old one .

1.5 project Lay-out

This project is organized as follows:

Chapter one gives brief introduction of the transformer and the principle of it is working and the type of it, also it summarizes the research's problem statement and objectives. Chapter two discusses and shows the design equation and calculations of the core. Chapter three provides an insight and detailed view of the different Interior elements and components of the winding and equation of its design under its own specific consideration. Chapter four discusses and shows the design equation of the mechanical parts of transformer and also compare the results with Sudanese electricity distribution company and Transudan Factory results. Chapter five consists of the conclusion of this research and the recommendations presented by the students of this research.

CHAPTER TWO

CORE DESIGN

2.1 Introduction

The process of establishing a working design of a 1000 kVA medium rating copper wound 11 kV distribution transformer. Since it is a tailor made job, a complete specification incorporating electrical, mechanical and environmental requirements must be available in advance to the designer.

Selection of number of turns is the first choice. It is calculated from the formula

$$E/T = K \sqrt{KVA} \quad (2.1)$$

where:

$E \equiv$ rated voltage

$T \equiv$ number of turns per phase

$KVA \equiv$ rated kVA of the transformer

$K \equiv$ constant depend on transformer type. It is the choice of the designer to select any value of 'K' between 0.25 to 0.55 to find out the number of turns. The manufacturing cost of the transformer may also get effected due to incorrect estimation of the value of 'K'.

The working flux density and current density are two valuable inputs which are also to be assumed on the basis of targeted No-load and Full-load losses. Flux density and current density help us to estimate the requirement of core area and size of conductor respectively. Internal clearances at various locations are also to be conceived by the designer. This is assumed on the basis of the system voltages and basic insulation level.

2.2 Proposed Specification

We have taken up a task to design a 1000 kVA copper wound distribution transformer having following specification as shown in Table (2.1) below.

Table (2.1): the specification of transformer

Specification	Types and value
Rating KVA	1000
No-load voltage ratio	11/0.433 KV
No. of phases	3
Frequency	50 Hz
Winding material	Electrolytic Copper
Tapping	$\pm 2.5\%$
No. load/load loss	1098.31/12024 watt
Impedance	5.42 %
Flux density	1.7 Tesla
Current density	3 A/mm ²
Connection	Delta/star
Temperature rise	45/55°C

2.3 Basic of Design

Most transformers are built in accordance with the current standard specification and the design of a transformer must be such as to bring it within the bounds set out there in and also to meet guaranteed technical data. Broadly speaking there are three main limiting factors Losses, temperature rise, and cost. But other factors such as reactance or dimension may influence the design.

2.4 Cost

The cost of transformer so far as the designer is concerned can be subdivided into Firstly, material costs and Secondly, labour costs. Overhead charges, except in so far as they are influenced by the material and labour charges, are usually beyond his control.

2.5 Transformer Core Materials

The main problem with transformer core is, its hysteresis loss and eddy current loss in transformer. Hysteresis loss in transformer mainly depends upon its core materials. It is found that, a small quantity of silicon alloyed with low carbon content steel produces material for transformer core, which has low hysteresis loss and high permeability. Because of increasing demand of power, it is required to further reduce the core losses and for that, another technique is employed on steel, which is known as cold rolling. This technique arranges the orientation of grain in ferromagnetic steel in the direction of rolling.

The core steel which has under gone through both the silicon alloying and cold rolling treatments is commonly known as CRGOS or Cold Rolled Grain Oriented Silicon Steel. This material is now universally used for manufacturing transformer core.

Although this material has low specific iron loss but still; it has some disadvantages, like, it is susceptible to increase loss due to flux flow in direction other than grain orientation and it also susceptible to impaired performance due to impact of bending and blanking the cutting CRGOS sheet. Both the surfaces of the sheet are provided with an insulating of oxide coating.

2.6 Frame Proportions

Owing to the influence of so many technical factors it is hardly possible to give any formula for determining the most economical frame proportions. The

limp section is usually "stepped" in order to fit the circular coil approximately with as high a space factor as possible, the coil diameters and hence the losses being thus kept down to a minimum for the core section used. The yoke section is often stepped as shown in Figure (2.1) in order to facilitate the building-up of the laminations and to allow more freedom for the flow the winding ducts. A sectional area of yoke about 25 per cent greater than that of the limb gives a slight reduction in iron loss and magnetizing current. The limb length is usually 3-4 times of window width, and the window width 1-1.5 times of the limb width. [2]

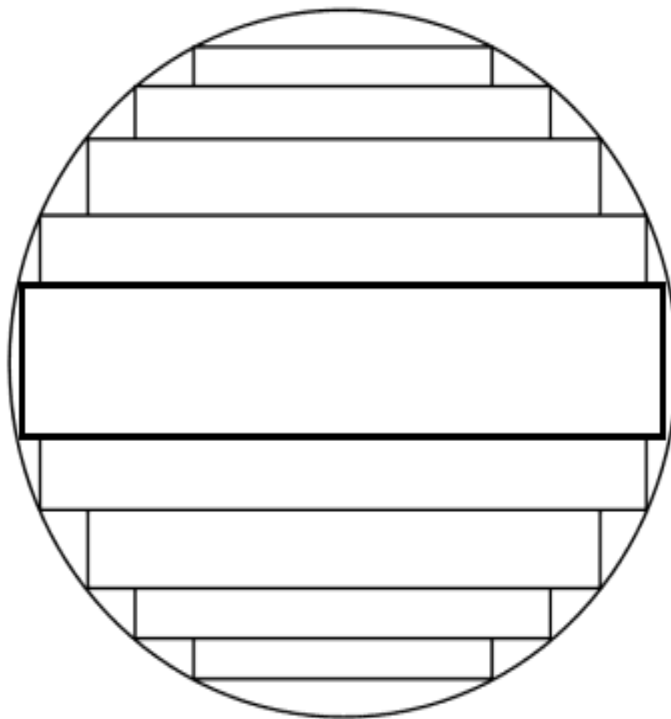


Figure (2.1): Core gradient

2.7 Core Types

The two most common and basic designs of transformer construction are the Closed-core Transformer and the Shell-core Transformer. In the “closed-core” type (core form) transformer, the primary and secondary windings are

wound outside and surround the core ring. In the “shell type” (shell form) transformer, the primary and secondary windings pass inside the steel magnetic circuit (core) which forms a shell around the windings.

The window area and iron area of two types of core configuration, is shown in Figure (2.2) and Figure (2.3) The elimination, shown in Figure (2.2), is known as a shell type, because it looks like the core surrounds the coil. The core, shown in Figure (2.3) is known as a core type, because it looks like the coil surrounds the core.

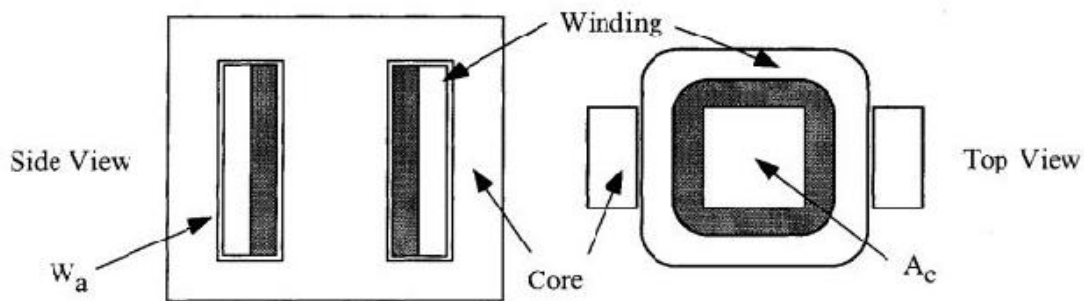


Figure: (2.2): shell type transformer

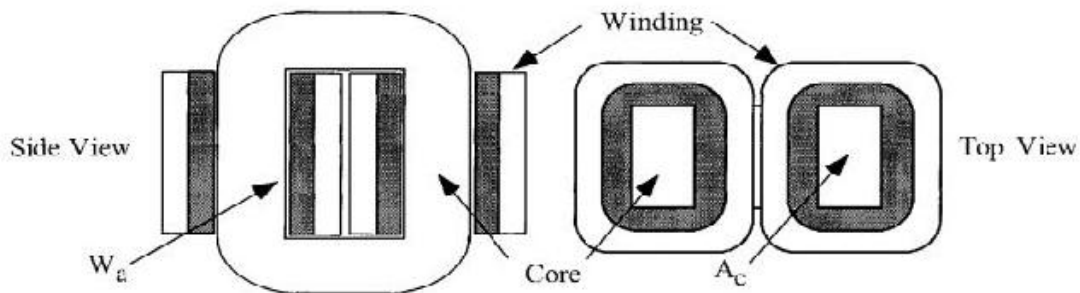


Figure: (2.3): core type transformer

Three-phase transformer are shown in Figure (2.4) These cross-sectional views show the window and iron areas. The three-legged core is designed to take advantage of the fact that, with balanced voltages impressed, the flux in each phase leg, adds up to zero. Therefore, no return leg is needed under normal conditions. When the transformer is subjected to unbalanced loads, or

unbalanced line voltages, it may be best to use three single-phase transformers, because of the high-circulating currents.

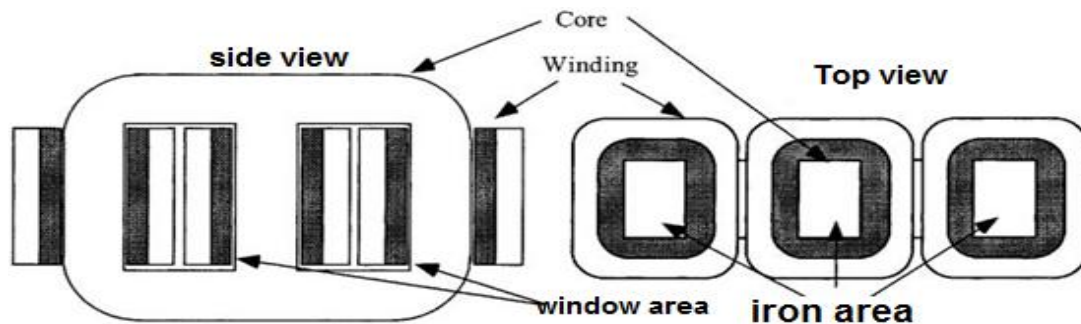


Figure (2.4): three phase transformer.

In both types of transformer core design, the magnetic flux linking the primary and secondary windings travels entirely within the core with no loss of magnetic flux through air. In the core type transformer construction, one half of each winding is wrapped around each leg (or limb) of the transformers magnetic circuit as shown above.

The coils are not arranged with the primary winding on one leg and the secondary on the other but instead half of the primary winding and half of the secondary winding are placed one over the other concentrically on each leg in order to increase magnetic coupling allowing practically all of the magnetic lines of force go through both the primary and secondary windings at the same time. however, with this type of transformer construction, a small percentage of the magnetic lines of force flow outside of the core, and this is called “leakage flux”. shell type transformer cores overcome this leakage flux as both the primary and secondary windings are wound on the same center leg or limb which has twice the cross-sectional area of the two outer limbs. The advantage here is that the magnetic flux has two closed magnetic paths to flow around external to the coils on both left and right hand sides before returning back to the central coils, this means that the magnetic flux circulating around the outer limbs of this type of

transformer construction is equal to $\Phi/2$. As the magnetic flux has a closed path around the coils, this has the advantage of decreasing core losses and increasing overall efficiency. [1]

2.8 Choice of Flux Density

For reasons of economy, the flux density should be as high as is practicable. The higher the flux density, the fewer the turns in the winding and hence the smaller the frame, so that there is a saving in both copper, core and tank. On the other hand, a high flux density is accompanied by several undesirable features. The iron loss increases in spite of the small reduction in frame size, and also the magnetizing current, the temperature increases on account of the increased loss, although this is usually not serious, as the insulating materials in the interior of the core, where it is hottest, can generally withstand a comparatively high temperature, harmonics in the magnetizing current increase considerably and may cause such troubles as telephone interference, switching surge also are more pronounced.

The material of iron used in core is (MT5-30) has specification as shown in Table (2.2) below. and it has characteristics are saturated point of flux density = 1.9 Tesla, maximum flux density = 1.7 Tesla and the actual value used in this design = 1.62 Tesla as shown in appendix (A). [2]

Table (2.2): Silicon steel specification

Knee point	Thickness	St	Over excitation
1.9 Tesla	0.3 mm	0.9567	10 %

2.9 Design Equations And Calculations

$$B_{\max} = \frac{\text{knee point}}{1 + \frac{\% \text{over excitation}}{100}} \quad (2.2)$$

$$E/T = 4.44 \times f \times B_m \times A_g \times St \times 10^{-6} \quad (2.3)$$

$$A_g = \frac{E/T}{4.44 \times f \times B_m \times 10^{-6}} \quad (2.4)$$

$$\text{Therefore } A = \pi \times d^2 / 4 \quad (2.5)$$

Where 'd' is the core diameter.

$$d = \sqrt{\frac{A}{0.58}} \quad (2.6)$$

$$B_{\text{actual}} = \frac{E/T}{4.44 \times f \times A_g \times St \times 10^{-6}} \quad (2.7)$$

From Equation (2.1) $E/T = 0.38 \sqrt{1000} = 12.016$ (chosen 13.888)

$$\text{From equation (2.2) } B_{\max} = \frac{1.9}{1 + \frac{10}{100}} = 1.7272 \text{ Tesla}$$

$$\text{From equation (2.4) } A_g = \frac{12.014}{4.44 \times 50 \times 1.7 \times 1 \times 10^{-6}} = 31833.59 \text{ mm}^2$$

$$\text{From Equation (2.5) } A = 31833.59 \text{ mm}^2.$$

$$\text{From Equation (2.6) } d = \sqrt{\frac{31833.59}{0.58}} = 234.27 \text{ mm (chosen 232 mm)}$$

$$\text{From Equation (2.7) } B_{\text{actual}} = \frac{13.888}{4.44 \times 50 \times 39898.70 \times 0.967 \times 10^{-6}} = 1.62 \text{ Tesla}$$

2.9.2 Width of core step

The core diameter has been chosen as 232 mm and number of steps as 9. The first and 9th steps may be taken as 220 mm and 50 mm respectively. The rest 9 steps may be chosen as 210 mm, 200 mm, 180 mm, 160mm, 140mm, 120 mm, 90 mm.

2.9.3 Core thickness

Core thickness (K) may be calculated as

$$K = \sqrt{d^2 - L^2} \quad (2.6)$$

where

d = core diameter.

L = width of step.

The core diameter, width of step and stack have been represented in Figure (2.4)

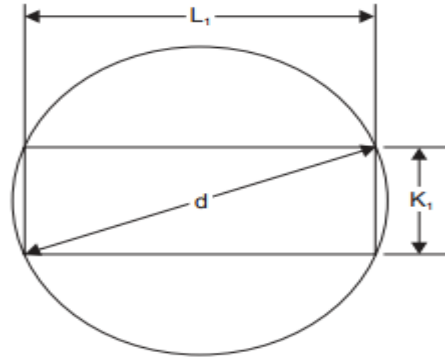


Figure (2.4): thickness of stage

The thickness of first step $K1 = \sqrt{d^2 - L1^2}$

where $L1 = 220$ mm

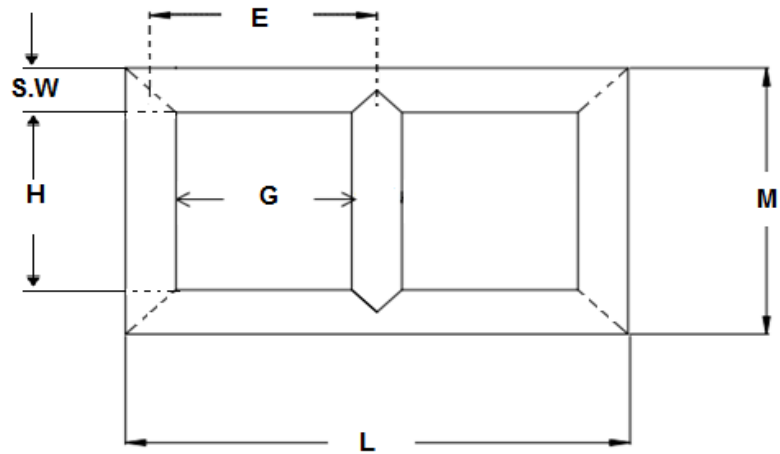


Figure (2.5): core dimensions

The main dimensions of core calculated as :

$$G = E - S.W \quad (2.7)$$

$$L = 2 \times E + S.W \quad (2.8)$$

$$H = 3 \times G \quad (2.9)$$

$$M = H + S.W \quad (2.10)$$

According to above equations core dimensions result shown in Table (2.3) below.

Table (2.3): Core dimension

G	L	H	E	M
164	988	420	384	860

$$\text{Core area} = \sum_{i=1}^n S.W_i * S.t_i \quad (2.11)$$

$$\text{Core weight} = \sum_{i=1}^n S.W_i (2 * S.W_i + 3H + 4E) * S.t_i * j \quad (2.12)$$

(n: No. of stages)

Therefore the Table (2.4) below show the result of the stage and core design

Table (2.4): Core design results

Stage No (i)	Slide width S.Wi (mm)	Initial Stage thickness S.thi (mm)	Final stage thickness (S.thi-S.thi-1) (mm)	No of sheets	Core weight Wi (kg)	Core Area Ai (mm ²)
1	220	73.60	73.60	245.50	403.95	16202.50
2	210	98.61	25.00	83.21	129.89	5242.13
3	200	117.57	19.00	63.22	93.40	3793.03
4	180	146.36	28.80	95.98	126.04	5182.90
5	160	168.00	21.60	72.10	83.10	3460.90
6	140	184.99	17.00	56.66	56.41	2379.62
7	120	198.55	13.60	45.19	38.07	1626.90
8	90	213.83	15.30	50.92	31.54	1374.92
9	50	226.54	12.70	42.39	14.19	6355.81
Σ					976.62	39898.70

And this result is also programmed in exile sheet and shown in appendix (D)

Specific magnetic loading (Bav):

$$B_{av} = \frac{E_t}{4.44 * A * f * St} \quad (2.13)$$

From Table (2.1): $St = 0.9567$

Hence

$$B_{av} = \frac{13.888}{4.44 * 39898.7 * 50 * 0.9567 * 10^{-6}} = 1.603 \text{ Tesla}$$

2.10 Transformer Core Losses

The ability of iron or steel to carry magnetic flux is much greater than it is in air, and this ability to allow magnetic flux to flow is called permeability. Most transformer cores are constructed from low carbon steels which can have permeability's in the order of 1500 compared with just 1.0 for air.

This means that a steel laminated core can carry a magnetic flux 1500 times better than that of air. However, when a magnetic flux flows in a transformers steel core, two types of losses occur in the steel. One termed “eddy current losses” and the other termed “hysteresis losses”.

2.10.1 Hysteresis losses

Transformer hysteresis losses are caused because of the friction of the molecules against the flow of the magnetic lines of force required to magnetize the core, which are constantly changing in value and direction first in one direction and then the other due to the influence of the sinusoidal supply voltage. This molecular friction causes heat to be developed which represents an energy loss to the transformer. Excessive heat loss can overtime shorten the life of the insulating materials used in the manufacture of the windings and structures. Therefore, cooling of a transformer is important.

Also, transformers are designed to operate at a particular supply frequency. lowering the frequency of the supply will result in increased

hysteresis and higher temperature in the iron core. So reducing the supply frequency from 60 Hertz to 50 Hertz will raise the amount of hysteresis present, decreased the VA capacity of the transformer.

2.10.2 Eddy current losses

Transformer Eddy Current Losses on the other hand are caused by the flow of circulating currents induced into the steel caused by the flow of the magnetic flux around the core. These circulating currents are generated because to the magnetic flux the core is acting like a single loop of wire. Since the iron core is a good conductor, the eddy currents induced by a solid iron core will be large. Eddy currents do not contribute anything towards the usefulness of the transformer but instead they oppose the flow of the induced current by acting like a negative force generating resistive heating and power loss within the core. Eddy current losses within a transformer core cannot be eliminated completely, but they can be greatly reduced and controlled by reducing the thickness of the steel core. Instead of having one big solid iron core as the magnetic core material of the transformer or coil, the magnetic path is split up into many thin pressed steel shapes called “laminations”.

The laminations used in a transformer construction are very thin strips of insulated metal joined together to produce a solid but laminated core as we saw above. These laminations are insulated from each other by a coat of varnish or paper to increase the effective resistivity of the core thereby increasing the overall resistance to limit the flow of the eddy currents.

The result of all this insulation is that the unwanted induced eddy current power loss in the core is greatly reduced, and it is for this reason why the magnetic iron circuit of every transformer and other electromagnetic machines are all laminated. Using laminations in a transformer construction reduces eddy current losses.

The losses of energy which appears as heat due both to hysteresis and to eddy currents in the magnetic path is known commonly as “transformer core losses”. Since these losses occur in all magnetic materials as a result of alternating magnetic fields. Transformer core losses are always present in a transformer whenever the primary is energized, even if no load is connected to the secondary winding. Also these hysteresis and the eddy current losses are sometimes referred to as “transformer iron losses”, as the magnetic flux causing these losses is constant at all loads. [2]

2.10.3 Connection losses

This losses produced from connection of terminals of yoke and limbs because there is leakage flux at terminals.

2.10.4 No load losses

No-load loss depends largely on the grade of electrical steel being used and its magnetic characteristic at designed flux density. Let us estimate the No-load loss based on widely available grade MT5-30. Specific loss (W/kg) at 1.63 Tesla for MT5-30 grade core steel (Value taken from standard core characteristics Curve available from Nippon Steel Corporation Catalogue) = 1.023 W/kg Handling factor (assumed) = 10%

No load losses = 1.1 × core weight × slide losses

Where : 1.1 is a safety factor

No load losses = 1.1 × 976.017 × slide losses

Slide losses = 1.023 watt/kg see Appendix (B)

Therefore :

No load losses = 1.1 × 976.017 × 1.023 = 1098.31 Watt

CHAPTER THREE

WINDING DESIGN

3.1 Introduction

The winding are invariably of copper owing to its high conductivity and cheapness, while their arrange arrangement is governed mainly by three factors ,Firstly the voltage, Secondly the cooling of the coils, and Thirdly the leakage reactance. Two arrangement are in general use, namely the concentric type and the sandwich type .the former employs two coils, or stacks of coils, of the same axial length but having different diameters so that one (usually the H.V) can be slipped over the other. As shown in Figure (3.1). [2]

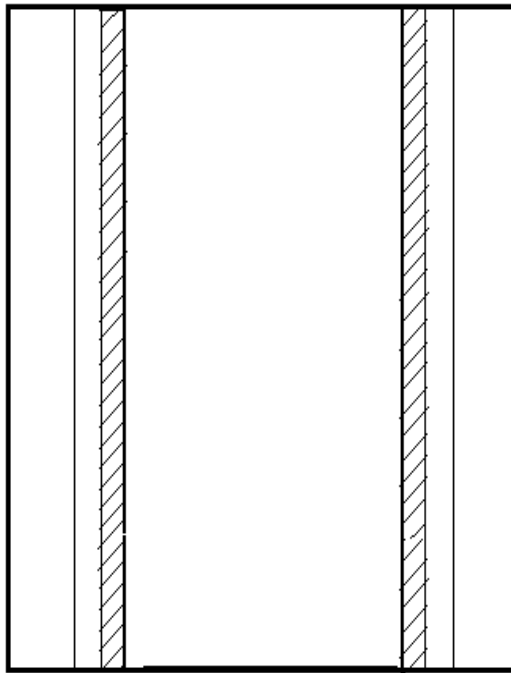


Figure (3.1) : H.V. and L.V. slipped

3.2 Winding Material

The material of winding wire or strip could be copper or aluminum. The choice depends upon the end users. Most of the Indian power utilities prefer transformers up to 250 kVA /11 kV with aluminum windings, because of its wide availability and lower cost. But owing to some limitations in its inherent properties, higher rated transformers are made with copper windings, distribution transformers of 22 kV and 33 kV with smaller ratings are also preferred with copper windings. Because of its low conductivity and high resistivity, aluminum conductor occupies almost double the volume of a copper conductor and hence aluminum-wound transformer looks always bigger than copper-wound transformers of same kVA rating. Aluminum-wound transformer was inducted into service in early seventies after REC has formulated the revised specification for transformers up to and including 100 kVA rating at 11 kV voltage class, even after about 30 years of use, the superiority of copper wound transformers over aluminum wound transformers is yet to be established. In fact, a well designed and good quality aluminum-wound transformer will provide equal, if not better, service to that of a copper-wound transformer. [3]

3.3 Types of Windings

There are two types of windings low voltage winding and high voltage winding.

3.3.1 Low voltage

The coils are usually wound with round wire up to about 20 amp. For higher currents flat copper strip is used, either singly or with several strips in parallel. In the latter case the width of the conductor is chosen so that the turns form a complete layer, and the total thickness is built up to give the required cross-section. For single conductors several layer may be necessary to accommodate the turns.

Larger transformers with L.V. windings for higher voltages such as 6600 or 11000 volts often have a current rating such that a single layer coil may be used, probably with cooling ducts between turns, L.V. windings for higher voltages involve essentially the same type of construction as H.V. windings. [2]

We use foil winding in low voltage side because the current is higher and this current needs a large cross section. In modern distribution transformers, foil winding is frequently used. In this form of construction the winding turn, of copper or aluminum foil, occupies the full width of the layer. The arrangement represents a very cost effective method of manufacturing low voltage windings and also enables a transformer to be built with a high degree of electromagnetic balance and hence good mechanical short circuit strength. With the foil winding, the axial forces during a short circuit is limited to one-tenth of the force which occurs in copper strip winding. Diamond dotted paper is frequently used as interlayer insulation.

I. Design equations

$$(i) V_s/ph = \frac{433}{\sqrt{3}} = 250 \text{ V (being star connected)}$$

$$(ii) I_s/ph = \frac{KVA}{\sqrt{3} \cdot V_1} \frac{1000}{\sqrt{3} \cdot 0.433} = 1333.4 \text{ A (being star connected)}$$

$$(iii) J = 3 \text{ A/mm}^2$$

$$(iv) A_{i_s} = \frac{I_1}{J} = 1333.4/3 = 444.46 \text{ mm}^2$$

No. of secondary turns per phase (N_s), $N_s = V_{ph}/13.88$

Since the secondary voltage is 433 V and is connected in Star, the per phase secondary voltage is $433/\sqrt{3} = 250 \text{ V}$.

Therefore secondary turns/phase

$$N_s/ph = \frac{V_L - L/\sqrt{3}}{V/T} \quad (3.1)$$

$N_s/y_s = 1$ (because we used foil in low voltage winding)

$$y_s = \frac{N_s}{N_s/y_s} \quad (3.2)$$

$$ID_s = d + Dlc \quad (3.3)$$

$$CoTh_s = CoTh_s \times ChTh + iny \times y_s + FoTh \times y_s \quad (3.4)$$

$$OD_s = ID_s + 2 \times CoTh_s \quad (3.5)$$

$$FoA = FoW \times FoTh \quad (3.6)$$

$$J_{actual} = \frac{Is/ph}{FoA} \quad (3.7)$$

$$Cuh_s = FoW \quad (3.8)$$

$$Meh = Cuh_s + 2 \times Hr_s \quad (3.9)$$

$$FoL = \pi \times D_{main} \times N_s \quad (3.10)$$

$$FoV = FoW \times FoTh \times FoL \quad (3.11)$$

$$Cuwi_s = 3 \times Cud \times FoV \quad (3.12)$$

$$Loc = \frac{100}{J_{actual}^2 \times FoTh} \quad (3.13)$$

$$N_p \text{ (at normal tap)} = \frac{Vp/ph}{Vs/ph} \times N_s \quad (3.14)$$

given data used in low tension shown in Table (3.1)

Table (3.1): Given data of low tension

Low tension data	Value
Conductor dimension	Foil 400X0.95 mm ²
High ring	10
Clearance between Low Tension and core	10 according to IEC standard
Insulation thickness between layers	0.15 mm
Cooling canal number	1
Copper density	8890 kg/m ³
L T line voltage	433 volt
L T current	1333.4 A
Current density	3.5 A/mm ²

II. Design calculations

From equation (3.1) $N_s/ph = 250/13.88 = 18$

From equation (3.2) $y_s = \frac{18}{1} = 18$

From equation (3.3) $ID_s = 232 + 5 = 237 \text{ mm}$

From equation (3.4) $CoTh_s = 1 \times 3.1 + 0.15 \times 18 + 0.95 \times 1 = 6.75 \text{ mm}$

From equation (3.5) $OD_s = 237 + 2 \times 6.75 = 250.5 \text{ mm}$

From equation (3.6) $FoA = 400 \times 0.95 = 380 \text{ mm}^2$

From equation (3.7) $J_{\text{actual}} = \frac{1333.37}{380} = 3.5 \text{ A/mm}^2$

From equation (3.8) $Cuh_s = 400 \text{ mm}$

From equation (3.9) $Meh = 400 + 2 \times 5 = 420 \text{ mm}$

From equation (3.10) $FoL = \pi \times \frac{237+250.5}{2} \times 18 = 13783.7 \text{ mm}$

From equation (3.11) $FoV = 400 \times 0.95 \times 13783.7 = 5237820.35 \text{ mm}^3$

From equation (3.12) $Cuwi_s = 3 \times 8890 \times 10^{-9} \times 5237820.35 = 139.74 \text{ kg}$

From equation (3.13) $Loc = \frac{100}{3.5^2 \times 0.95} = 8.5$ so the location between layer 9th and 10th

From equation (3.14) $N_p = \frac{11000}{433/\sqrt{3}} \times 18 = 792$

After calculated the values from above equations we selected another values according to standard values as shown in Table (3.2).

Table (3.2): Low tension winding results

Name	Calculated	Actual	Units
Number of turns	20.81	18	Turn
Number of layers	18	18	Layers
Turns per layer	1	1	Turns per layer
Inner diameter	237	237	mm
Coil thickness	6.76	6.76	mm
Outer diameter	250.5	250.5	mm
Foil cross section	380.96	380	mm ²
Current density	3.5	3.51	A/mm ²
Copper height	400	400	mm
Mechanical height	420	420	mm
Foil length	13783.7	13783.7	mm
Foil volume	5237820.35	5237820.35	mm ³
Weight of copper	139.74	139.74	Kg
Location of cooling canals	8.56	Between layer 9 th and 10 th	-

And this result is also programmed in exile sheet and shown in appendix (D)

Add 5% additional turns for tapping voltage

Total primary turns per phase = $792 + (792 \times 0.05) = 831.6 \cong 832$

In the event the conductor area is more than 7 to 8 mm², we should not go for round conductor . The alternative choice is to select a rectangular strip with the formation of continuous disc coil and one coil per phase.

It has been decided above that the primary coil will be designed in the shape of continuous disc having 832 turns per coil.

The specification has desired a tapping step of 2.5% with a maximum tap voltage of 5%, i.e. the ratio is 2

The turns per tap disc is $40/2 = 20$. With this combination the tap terminals from the winding will come as the last turn of the tapping disc. [3]

III. load losses calculations

Low tension load losses = Low tension copper losses + Low tension eddy losses + Low tension connection losses

$$\text{LT load losses} = \text{LT copper losses} \left(1 + \left(\frac{(F_oTh)^4 * (y)^2}{100000}\right) + \left(\frac{IL}{20000}\right)\right) \quad (3.15)$$

$$\text{LT copper losses at } 75^\circ \text{C} = 3 \times I^2 \times R_{75^\circ \text{C}} \quad (3.16)$$

$$R_{20^\circ \text{C}} = \rho_{20} \times \frac{F_oL}{F_oA} \quad (3.17)$$

$$R_{75^\circ \text{C}} = R_{20^\circ \text{C}} \times \frac{234.5+75}{234.5+20} \quad (3.18)$$

$$\rho_{20} = 0.00000001724 \, \Omega \cdot \text{mm}$$

$$\text{LT eddy losses} = \left(\frac{(F_oTh)^4 * (y_s)^2}{100000}\right) \times \text{LT copper losses} \quad (3.19)$$

$$\text{LT connection losses} = \left(\frac{IL_s}{20000}\right) \times \text{LT copper losses} \quad (3.20)$$

There fore :

$$R_{20^\circ \text{C}} = 0.00000001724 \times \frac{13783.7}{380} \times 1000 = 0.000616 \, \Omega$$

$$R_{75^\circ \text{C}} = 0.000616 \times \frac{234.5+75}{234.5+20} = 0.0007579 \, \Omega$$

$$\text{LT copper losses at } 75^\circ \text{C} = 3 \times 1333.37^2 \times 0.0007579 = 4057.81 \text{ Watt}$$

$$\text{LT eddy losses} = \left(\frac{(0.95)^4 * (18)^2}{100000}\right) \times 4042.85 = 10.709 \text{ watt}$$

$$\text{LT connection losses} = \left(\frac{1333.37}{20000}\right) \times 4057.81 = 269.49 \text{ watt}$$

$$\text{Low tension load losses at } 75^\circ \text{C} = 4057.81 + 10.709 + 270.5 = 4339.1 \text{ watt}$$

3.3.2 H.V. winding

Windings for 11000 volts and over must always be subdivided into a suitable number of coils to give a reasonably low voltage between successive coils and layers, and, in larger sizes, to allow for oil ducts at frequent intervals for cooling purposes some types of design employ specially designed inter-coil and inter-layer insulation which enables the coil voltage to be increased to as high as 5000 or 6000 volts. A small increase in the more efficient vertical cooling surface and a rather different balance of the thermal design compensates for the loss of the few horizontal oil ducts. If the current is not greater than about 20 amp, round wire may be used in "crossover" coils which are wound layer on layer with insulation between layers. For higher currents necessitating strip conductor, an entirely different type of winding is used employing "pancake" or "disc" coils, wound in a flat spiral in much the same way as a roll or watch spring. A three-phase transformer is designed on per phase basis. Phase voltage and current are calculated keeping in mind the connection and vector group. Here primary winding is connected in Delta. The following paragraph will help us to understand the process of calculating the conductor area of primary coil based on the available current density of 3A/mm². [2,3]

I. Design equation

(i) $V_p/ph = 11000 \text{ V}$ (being delta connected)

(ii) $I_p/ph = \frac{KVA}{\sqrt{3} \times V_1} \frac{1000}{3 \times 11} = 30.303 \text{ A}$ (being delta connected)

(iii) $J = 3 \text{ A/mm}^2$

(iv) $A_{i_p} = \frac{I_p}{J} = 30.303 / 3 = 10.101 \text{ mm}^2$

$$N_p = a \times N_{s, \text{actual}} \quad (3.21)$$

$$C_{uh_p} = M_{eh} - 2 \times H_{r_p} \quad (3.22)$$

$$N_p/y_p = \frac{C_{uh_p}}{d_c} - 1 \quad (3.23)$$

$$y_p = \frac{N_p}{N_p/y_p} \quad (3.24)$$

$$ID_p = OD_s + 2 \times DHL \quad (3.25)$$

$$CoTh_p = y_p \times d_c + y_p \times ThIy + cc_p \times ChTh_p \quad (3.26)$$

$$OD_p = ID_p + 2 \times CoTh_p \quad (3.27)$$

$$N_{p \text{ last}} = N_{p \text{ actual}} - (N_p/y_p)_{\text{actual}} \times (y_p - 1) \quad (3.28)$$

$$A_{\text{wire}} = \frac{\pi}{4} \times d^2 \quad (3.29)$$

$$J_{p \text{ actual}} = \frac{I_p / ph}{A_{\text{wire}}} \quad (3.30)$$

Mechanical high = mechanical high of (low tension) = 420 mm

$$CnL = \pi \times D_{s \text{ main},} \times N_p \quad (3.31)$$

$$CnV = A_{\text{wire}} \times CnL \quad (3.32)$$

$$CuWi = 3 \times Cud \times CnV \quad (3.33)$$

$$Loc_p = \frac{100}{J_{p \text{ actual}}^2 \times dc} \quad (3.34)$$

$$Dph = E - OD_p \quad (3.35)$$

$$\text{Gradient} = \frac{4 \times N_p / y_p \times E / N_{s \text{ actual}}}{\sum_{i=1}^3 Si \times Ni + \text{conductor insulation thickness}} \quad (3.36)$$

Si = insulation thickness of level i

Ni = no of insulation paper in level i

The given data used in high tension shown in Table (3.3)

Table (3.3): Given data of high tension

High tension data	Value
Conductor diameter	3 mm
High ring	34.5 mm
Clearance between H.T. and L.T.	18 according to IEC standard
Insulation thickness between layers	0.55 mm
Cooling canal number and thickness	1 with 5.9 thickness
Copper density	8890 kg/m ³

H.T. line voltage	11000 volt
H.T. current /phase	30.3 A
Current density	4.523 A/mm ²
Active conductor diameter	2.92 mm
Over all conductor diameter	3 mm
Outer cylinder	3 mm

II. Design calculation

From equation (3.21) $N_p = 44 \times 18 = 792$

From equation (3.22) $Cuh_p = 420 - 2 \times 34.5 = 351 \text{ mm}$

From equation (3.23) $N_p/y_p = \frac{351}{3} - 1 = 116$

From equation (3.24) $y_p = \frac{832}{116} = 7.17 \approx 8$

From equation (3.25) $ID_p = 250.5 + 2 \times 18 = 286.5 \text{ mm}$

From equation (3.26) $CoTh_p = (8 \times 3) + (8 \times 0.55) + (1 \times 5.9) = 34.3 \text{ mm}$

From equation (3.27) $OD_p = 286.5 + 2 \times 34.3 = 355.1 \text{ mm}$

From equation (3.28) $N_{p \text{ last}} = 832 - (116 \times (8-1)) = 20$

From equation (3.29) $A_{\text{wire}} = \frac{\pi}{4} \times 2.92^2 = 6.696 \text{ mm}^2$

From equation (3.30) $J_{p \text{ actual}} = \frac{30.33}{6.696} = 4.52$

From equation (3.31) $CnL = \pi \times \frac{286.5+355.1}{2} \times 832 = 838508.67 \text{ mm}$

From equation (3.32) $CnV = 6.696 \times 838508.67 = 5592852.84 \text{ mm}^3$

From equation (3.33) $CuWi = 3 \times 8890 \times 10^{-9} \times 5592852.84 = 149.81 \text{ kg}$

From equation (3.34) $Loc_p = \frac{100}{4.52^2 \times 2.92} = 1.67 \text{ location between layer 2}^{nd} \text{ and } 3^{rd}$

From equation (3.35) $Dph = 378 - 355.1 = 22.9 \text{ mm}$

From equation (3.36)

$$\text{Gradient}_1 = \frac{4 \times 116 \times 13.888}{4 \times 0.1 + 1 \times 0.1 + 2 \times 0.1 + (3 - 2.92)} = 8261.9$$

$$\text{Gradient}_2 = \frac{4 \times 116 \times 13.888}{4 \times 0.1 + 1 \times 0.1 + (3 - 2.92)} \times (2/3) = 7407.19$$

$$\text{Gradient}_3 = \frac{4 \times 116 \times 13.888}{4 \times 0.1 + (3 - 2.92)} \times (1/3) = 4475.17$$

After calculated the values from above equations we selected another values according to standard values as shown in Table (3.4).

Table (3.4): High tension winding results

Name	Calculated	Actual	Units
Number of primary turns	792	792	Turn
Number of layers	7.16	8	Layer
Number of turns of last layer	19.624	20	Layer
Turns per layer	116	116	Turns per layer
Inner diameter	286.5	286.5	mm
Coil thickness	34.3	34.3	mm
Outer diameter	355.1	361.1with cylinder	mm
Conductor cross section	10.10	6.94	mm ²
Current density	3	4.52	A/mm ²
Copper height	351	351	mm
Mechanical height	420	420	mm
Conductor length	838508.67	838508.67	mm
Conductor volume	5617157.14	5617157.14	mm ³
Weight of copper in three phases	149.81	149.81	Kg
Location of cooling Canals	1.67	Between layer 2nd and 3 rd	-

And this result is also programmed in exile sheet and shown in appendix (D)

iii. Losses calculations

High tension load losses = High tension copper losses + High tension eddy losses + High tension connection losses

$$\text{H.T. load losses} = \text{HT copper losses} \left(1 + \left(\frac{(dc)^4 * (yp)^2}{100000}\right) + \left(\frac{ILp}{20000}\right)\right)$$

$$\text{H.T. copper losses at } 75^\circ \text{C} = 3 \times I^2 \times R_{75^\circ \text{C}} \quad (3.37)$$

$$R_{20^\circ \text{C}} = \rho_{20} \times \frac{CnL}{A_{\text{wire}}} \quad (3.38)$$

$$R_{75^\circ \text{C}} = R_{20^\circ \text{C}} \times \frac{234.5 + 75}{234.5 + 20} \quad (3.39)$$

$$\text{H.T. eddy losses} = \left(\frac{(dc)^4 * (yp)^2}{100000}\right) \times \text{H.T. copper losses} \quad (3.40)$$

$$\text{H.T. connection losses} = \left(\frac{ILp}{20000}\right) \times \text{H.T. copper losses} \quad (3.41)$$

$$\text{Total load losses} = (\text{L.T. load losses} + \text{H.T. load losses}) \times 1.04 \quad (3.42)$$

$$\text{Total losses} = \text{total load losses} + \text{No load losses} \quad (3.43)$$

Therefore:

$$\rho_{20} = 0.00000001724 \, \Omega \cdot \text{mm}$$

$$\text{From equation (3.37) H.T. load losses at } 75^\circ \text{C} = 6884.46 + 320.31 + 18.06 = 7222.84 \text{ watt}$$

$$\text{From equation (3.38) HT copper losses at } 75^\circ \text{C} = 3 \times 30.30^2 \times 2.615 = 6884.46 \text{ Watt}$$

$$\text{From equation (3.39) } R_{20^\circ \text{C}} = 0.00000001724 \times \frac{838508.67}{6.94} \times 1000 = 2.08 \, \Omega$$

$$\text{From equation (3.40) } R_{75^\circ \text{C}} = 2.08 \times \frac{234.5 + 75}{234.5 + 20} = 2.49 \, \Omega$$

$$\text{From equation (3.41) HT eddy losses} = \left(\frac{(2.92)^4 * (8)^2}{100000}\right) \times 6884.46 = 320.31 \text{ watt}$$

$$\text{From equation (3.42) H.T. connection losses} = \left(\frac{52.49}{20000}\right) \times 6884.46 = 18.06 \text{ watt}$$

$$\text{From equation (3.43) Total load losses} = (4339.1 + 7222.84) \times 1.04 = 12024 \text{ KW}$$

$$\text{From equation (3.44) Total losses} = 12024 + 1098.31 = 13122.3 \text{ W} = 13.12 \text{ kw}$$

3.4 Insulation Material

The winding of transformer are, in general, insulated with two materials- papers (with or without synthetic resin varnish) and pressboard. Varnished cloth asbestos, mica, wood and porcelain are used in some cases, but not to any great extent. [2]

Paper

Electrical Grade Insulating Paper (EGIP) is generally used for covering the bare conductor. EGIP has certain properties which makes it a superior material to use as insulation in electrical equipments. These are:

- (a) Flexibility.
- (b) Easy to use.
- (c) Higher insulation with lesser thickness.
- (d) Higher resistance to oil.
- (e) Reasonable heat resistance while in contact with oil.
- (f) Good compatibility with transformer oil.
- (g) Low chloride content. [3]

3.5 Insulation Design

The insulation of transformer may break down in two ways, Firstly by direct puncture through the body of the insulation , Secondly by creepage over the surface of the insulation. Sufficient margin of safety must be provided to meet both cases. In order to increase the strength against direct puncture, the shapes of winding and insulation should be such that there are no sharp corners on which there may be a concentrated electrostatic field, due either to the stress to earth or to that between windings, coils or individual turns.

It is an advantages to have insulating material which has the same permittivity as the oil in which the transformer is immersed so as to avoid

irregular distribution of the electrostatic stress. Pressboard fulfils this condition very well, but does not give such reliable cooling ducts as varnished paper tubes, nor has it the same mechanical strength. Both types are used successfully, but varnished paper tubes predominate. [2]

3.6 Distribution of Voltage in Winding

When steady conditions have been reached, the voltage is distributed evenly throughout a winding, but this is not the case immediately after switching on, or under any other surge conditions. Since the magnetic field takes time to build up, the initial voltage distribution depend on the capacitance values between turns and between coils throughout winding. A surge entering a transformer winding first impresses nearly an its voltage on the end turns, since the capacity between this turn and the adjacent turns is small in comparison with that of the remainder of the winding. Further ,since the winding comprises a system of inductances and capacitances in parallel, it is oscillatory, and the surge is reflected from the earthed end and from such points as tapped coils in the body of the winding.

The conductor insulation must be designed to withstand the most severe distribution of voltage, and hence it is customary to use heavier or "reinforced" conductor insulation on the end turns and sometimes at the tapping points. [2]

3.7 Conductor Insulation

Extensive use has been made in the past of cotton covering for conductors, but this has now been largely superseded by paper. several layers of paper are used, and so staggered that there is always at least one thickness of paper at all points on the conductor.

The value of the surge which may enter a transformer winding is determined by the dry flash-over voltage of the transformer bushings or the line

insulation immediately adjacent, and this determines the strength of reinforced insulation which must be provided. The extent of there reinforcement depends on the size and voltage of the transformer and on the type of winding used, but it usually covers about 3 to 5 per cent at each end, the extreme end turns being designed to withstand one-half to full line voltage instantaneously, and graded down in steps to the normal conductor insulation in the body of the winding. On voltage above about 50 KV. The amount is rather less, and at tapping points in the middle of the winding and at the earthed point (if any) the quantity and thickness are both less than at the line ends.

When small round wires with heavy reinforcement are used, the electrostatic stress on the surface of the conductors under surge conditions becomes strongly concentrated. This is overcome by increased the diameter as the thickness of insulation is increased, so that the diameter of the conductor is not less than the insulation wall thickness.

On very high voltages (above about 50 KV) a brass end ring covering the complete depth of coil is provided and connected to the end turns it must be split to prevent short-circuit currents, and heavily insulated , while immediately under it must be a disc type of coil. This arrangement results in a modified distribution of electrostatic capacity between the end turns and a consequent reduction in the effect of the surge. [2]

3.8 Major Insulation

The major insulation is that which insulates the windings from the frame and from one another ; it can be subdivided into four distinct items. [2]

3.8.1 L.V. winding to core limb

The insulation here must be sufficiently tough and strong to resist damage due to the sharp corners of the core steps. Either a special tough type of

pressboard or a hot-pressed tube of varnished paper is used. The latter gives a more satisfactory oil ducts under the coil.

3.8.2 L.V. winding to core yoke

At each end of the L.V. coil is fixed either a rigid end ring of varnished paper or pressboard, or a series of end blocks with oil spaces between. Ample creepage path is easily provided from coil to yoke, as the end spacing is usually great in order to preserve magnetic balance between windings. End packing of stout pressboard strips built up to shape and size and taped to the end turns for rigidity is often used.

3.8.3 H.V. winding to L.V. winding

In very small low-voltage transformers it is sufficient to wind the H.V. directly on the L.V. with a few layers of paper between, but cooling and voltage usually call for an oil duct. Sometimes layers of paper or stiff pressboard are wrapped round the L.V. and sometimes a varnished paper tube is used, spacing strips being used in either case to give the oil duct. Where the H.V. voltage exceeds 22KV. Tubes are more usual, and for higher voltages still, two or more concentric tubes with oil spaces between. This has the dual effect of giving a better distribution of voltage gradient between the windings, and of preventing the lining up of stray particles in the oil under the action of electrostatic forces.

3.8.4 H.V. winding to core yoke

The H.V. end insulation may belong to one of two general types .the first consists of a series of washers and blocks of pressboard, aligned with the inter-coil spacers for mechanical rigidity, and giving a direct creepage path to earth. The second relies on puncture rather than creepage.

One or more rings of L-shaped section are used on the inside of the coil, with large specially-shaped washers, the overlaps being folded up or down on

the outside. The rings are made either of molded pressboard or hot-pressed varnished paper, while the washers are usually of stout pressboard. The second method gives rather more winding space on the limbs, but interferes slightly with the oil flow at the ends. As the end coils are usually subdivided more than the remainder, and are of heavier conductor and fewer turns for reinforcement purposes, the poorer oil flow in that region is not important. [2]

3.9 Choice of Current Densities

The rated current of a secondary winding is calculated from the volt-ampere output and the no-load terminal voltage; the primary current is then found by dividing the secondary current by the turn ratio.

The most economical density for a winding is that which gives the smallest quantity of copper without excessive heating and without an over-expensive system of oil ducts. The maximum hot spot temperature is fixed by the heat-withstanding properties of the insulation. It may be attained either with a heavy copper section and very little coil cooling surface, or with a small copper section and a large number of ducts. As the copper section is decreased, the saving in copper must be compared with the increase in insulation, winding and assembly costs as more ducts are provided. The optimum section depends on the size and voltage of the transformer and the type of winding used. In addition, the variation in size of the core to accommodate the windings and of the tank to dissipate the losses must be taken into account.

In the case of low copper loss transformer, the copper densities are lower, but fewer cooling ducts are provided, in order to reduce the space occupied by the winding and hence the iron loss and cost.

The current density gives very little clue to the thermal safety of a transformer. A transformer with high current density and a system of carefully

designed oil ducts is often safer than one with low current density and very few, or badly-designed, cooling facilities. [2]

3.10 Mechanical Forces

The magnetic effect of the load currents in the windings gives rise to a force of repulsion between the windings. This force is usually negligible at full load, but, since it varies as the square of the load, it may be serious under short-circuit conditions. Strong bracing of sandwich windings is necessary to prevent distortion of the coils at the ends of the stack, while in the case of magnetically balanced concentric windings, the force is entirely radial and has little effect. A slight unbalance, however, gives rise to an axial component of the force and a consequent danger of displacement of the end coils. It has been indicated that the reactance is increased when the windings are unbalanced. The force is proportional to the gradient of the graph of reactance plotted against amount of magnetic unbalance. [2]

3.11 Tap Changer

It is a normal fact that increase in load lead to decrease in the supply voltage. Hence the voltage supplied by the transformer to the load must be maintained within the prescribed limits. This can be done by changing the transformer turns ratio by changing the number of primary turns as shown in Table (3.5) below.

The taps are leads or connections provided at various points on the winding as shown in Figure (3.3) below. The turns ratio differ from one tap to another and hence different voltages can be obtained at each tap.

Taps are provided at the H.V. windings of the transformer because of the following reasons:

I. The number of turns in the High voltage winding is large and hence a fine voltage variation can be obtained.

II. The current on the low voltage winding of large transformers are high. Therefore interruption of high currents is a difficult task.

II. L.V. winding is placed nearer to the core and H.V. winding is placed outside. Therefore providing taps on the H.V. winding is comparatively easier than that of the L.V. winding. [3]

Table(3.5): voltage and number of turn at each point selector

Tap position	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5
Point selector	1-2	2-3	3-4	4-5	5-6
Tap voltage equation	$V_n + 0.05 \times V_n$	$V_n + 0.025 \times V_n$	V_n	$V_n - 0.025 \times V_n$	$V_n - 0.05 \times V_n$
Tap voltages (volt)	11550	11275	11000	10725	10450
No of primary turns	920	900	880	860	840

Where :

$V_n \equiv$ the nominal voltage

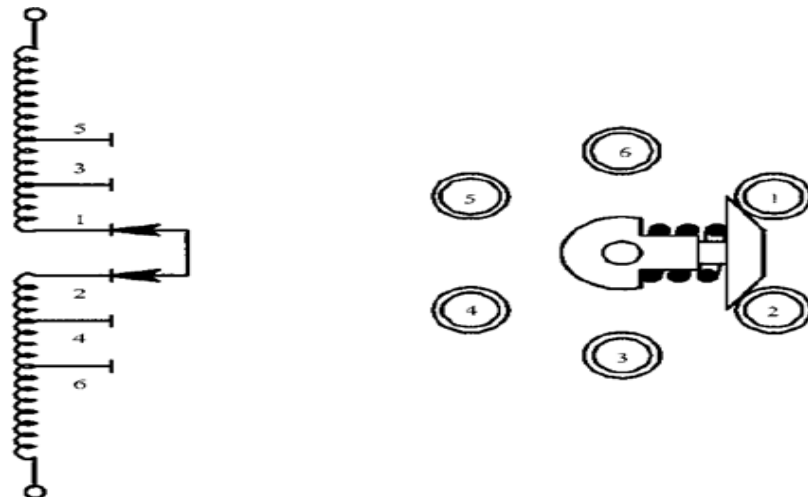


Figure (3.2): The selector and winding tap changer

3.11.1 Ratio error at different tap position

Ratio error is calculated from the voltage ratio and turns ratio for that particular tap. The transformer has nine position taps with having voltage variation from (+) 5% to (–) 5% in steps of 2.5%. Table (3.6) below will indicate the percentage ratio error at different tap position. [3]

Table (3.6): Ratio error at different tap position

tap position	%Tapping	Voltage ratio	Turns ratio	% error
1	+5%	$\frac{11000 \times 1.05}{433/\sqrt{3}}$ = 46.20	$832/18$ =46.22	$\frac{(46.2-46.22)}{46.2} \times 100$ =-0.043%
2	+2.5%	$\frac{11000 \times 1.025}{433/\sqrt{3}}$ = 45.10	$812/18$ =45.11	$\frac{(45.10-45.11)}{45.10} \times 100$ = -0.022%
3	Normal	$\frac{11000 \times 1}{433/\sqrt{3}}$ = 44.001	$792/18 = 44$	$\frac{(44.001-44)}{44.001} \times 100$ =0.002%
4	-2.5%	$\frac{11000 \times 0.975}{433/\sqrt{3}}$ =42.90	$772/18$ =42.88	$\frac{(42.90-42.88)}{42.90} \times 100$ =0.046%
5	-5%	$\frac{11000 \times 0.95}{433/\sqrt{3}}$ = 41.80	$752/18$ = 41.77	$\frac{(41.80-41.77)}{41.80} \times 100$ =0.072%

And this result is also programmed in exile sheet and shown in appendix (D)

3.11.2 All day Efficiency

The ordinary or commercial efficiency of a transformer is given by the ratio $\frac{\text{output in watts}}{\text{input in watts}}$ but there are certain type of transformers whose performance cannot be judged by this efficiency. Transformers used for supplying lighting and general network i.e., distribution Transformers have their primaries energized all the twenty-four hours. The cu losses relatively less important, because they certain time period, usually a day of 24 hours.

$$\eta_{\text{all-day}} = \frac{\text{output in watts}}{\text{input in watts}} \quad (\text{for 24 hours})$$

No-load loss = 1.098 kW; load loss = 12.024 kW.

$$\eta = \frac{\text{KVA} \times U \times \text{pf}}{(\text{KVA} \times U \times \text{pf}) + \text{No-load losses} + U^2 \times \text{load losses}} \times 100 \quad (3.44)$$

$$\eta = \frac{1000 \times U \times \text{pf}}{(1000 \times U \times \text{power factor}) + 1.098 + U^2 \times 12.024} \times 100$$

3.11.3 Maximum efficiency

No-load loss of a transformer is constant and has no effect with the variation of load. However the load loss varies with the change of load and is proportional to the square of the load. The transformer will have maximum efficiency at a load then the no-load loss become equal to load loss and is represented as Load at which maximum efficiency will occur equal K.

$$U = \sqrt{\frac{\text{No-load losses}}{\text{load losses}}} \times 100 \quad (3.45)$$

$$U = \sqrt{\frac{12.024}{1.098}} \times 100 = 3.309$$

$$\eta_{\text{max}} = \frac{\text{KVA} \times U}{(\text{KVA} \times U) + \text{No-load losses} + U^2 \times \text{load losses}} \times 100 \quad (3.46)$$

$$\eta_{\max} = \frac{1000 \times 3.309}{(1000 \times 3.309) + 1.098 + 3.309^2 \times 12.024} \times 100 = 96.14\%$$

3.12 Percentage Impedance

Its calculated from Percentage Reactance and Percentage Resistance.

3.12.1 Percentage Reactance

The formula commonly used for calculating percentage reactance is as follows:

$$x (\%) =$$

$$\frac{2\pi^2 \times \mu_0 \times f \times I_s \times N_s^2 \times V_s}{(V/T)^2 \times AL} \times \frac{\frac{IDp + ODp}{2} \times CoThp}{3} + \frac{\frac{IDs + ODs}{2} \times CoThs}{3} + \frac{\frac{IDp + ODp}{2} + \frac{IDs + ODs}{2}}{2} \times \frac{DHL}{1000} \quad (3.47)$$

$$x (\%) = 5.3130683 \%$$

$$AL = \text{Average length of LV and HV coil} = \frac{400 + 351}{2} = 375.5 \text{ mm}$$

3.12.2 Percentage Resistance

The formula commonly used for calculating percentage resistance is as follows:

$$R(\%) = \frac{\text{Calculated load loss in kW}}{\text{Rated kVA}} \times 100 \quad (3.48)$$

where Calculated load loss = 12.024 kW

Rated kVA = 1000 kVA

$$\text{Therefore } R(\%) = \frac{12.024}{1000} \times 100 = 1.2024\%$$

3.12.3 Percentage Impedance

Percentage impedance is the vector summation of percentage reactance and percentage resistance and is represented as:

$$z(\%) = \sqrt{x(\%)^2 + R(\%)^2} \quad (3.49)$$

$$z(\%) = \sqrt{5.31^2 + 1.2^2} = 5.42$$

Percentage impedance as guaranteed is 5.5% with a tolerance of $\pm 10\%$ as recommended in IS-2026.

3.13 Regulation

The voltage ratio of power and distribution transformer is defined at no-load. During loading, the voltage drop down in accordance with its percentage reactance and percentage resistance. [3]

For any assumed load, other than rated load and at any power factor, the percentage regulation is approximately calculated as:

$$\text{Reg \%} = n \cdot R(\%) \cdot \cos \theta + n \cdot X(\%) \sin \theta + \frac{(n X(\%) \cos \theta - n \cdot R(\%) \sin \theta)^2}{200} \quad (3.50)$$

where :

n = Percentage of loading

$R(\%)$ = Percentage of resistance

$X(\%)$ = Percentage reactance

$\cos \theta$ = Power factor

$\sin \theta$ = Sine component of power factor angle.

Regulation at rated load and at unity power factor

Using the above formula, the regulation can be calculated with the following available parameters.

$$n = 1.0$$

$$R(\%) = 1.2 \%$$

$$X(\%) = 5.3 \%$$

$$\cos \theta = 1.0 \text{ (unity power factor where } \theta = 0 \text{)}$$

$$\sin \theta = 0$$

Therefore, Regulation at rated load and at unity power factor may be rewritten as

$$\text{Reg \%} = R(\%) \cos \theta + \frac{(X(\%) \cos \theta)^2}{200} = 1.34 \%$$

3.14 Vector Group

The transformer shall be connected delta –star in accordance with vector group reference DYn11 of (IEC) 76/IS 2026.

The LV neutral shall be brought out to terminal bushing, which shall be identical to the phase bushing all respect, also in this design we used DYn11 as shown in Figure(3.3) , (a). Figure(3.4),(b) and Figure(3.5), (c) .[3]

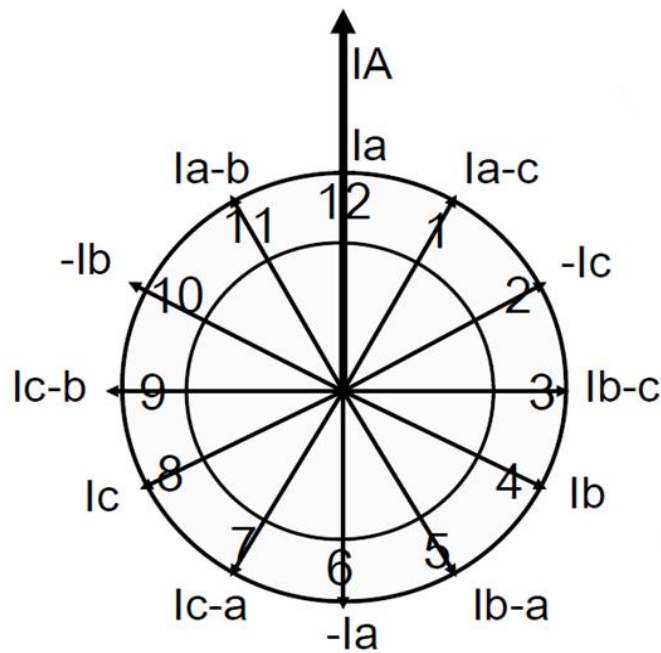


Figure (3.3): vector group (a)

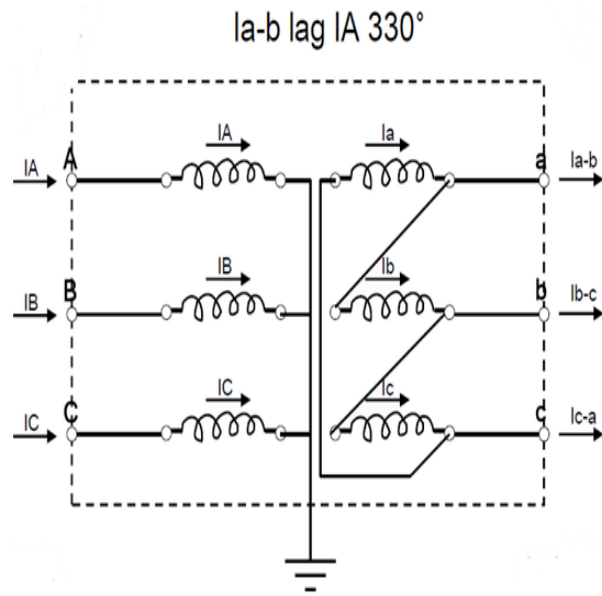


Figure (3.4): vector group (b)

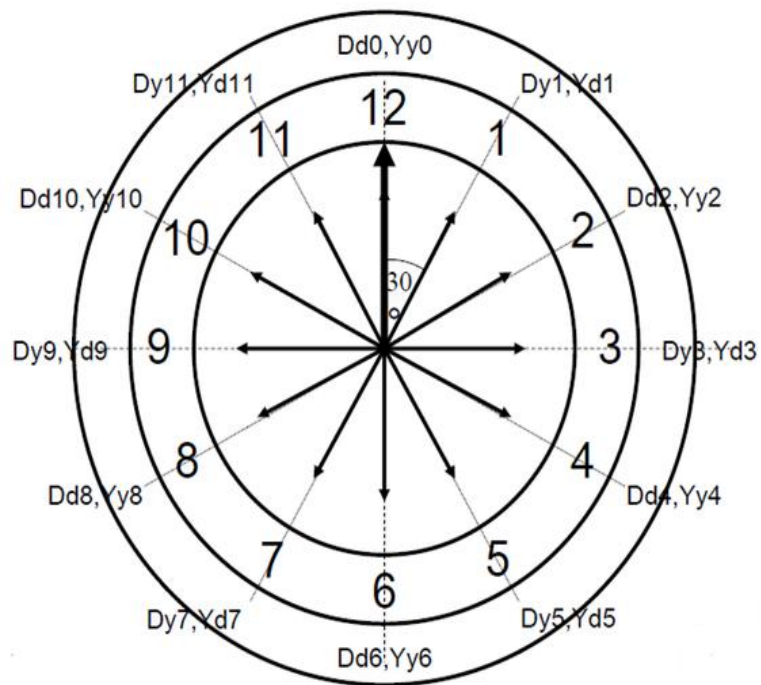


Figure (3.5): vector group (c)

CHAPTER FOUR

MECHANICAL DESIGN AND COMPARISON

RESULT

4.1 Transformer Tank

Tank bodies for most of transformer are made of rolled steel plates which are fabricated to form the container. Small tanks are welded from steel plates while large ones are assembled from boiler plates. The tanks are provided with lifting lugs. Small transformers have cooling tubes let in to the vertical side, but large transformers require separate banks of cooling tubes. Such transformers have plain tanks with provision for pipes and valves to direct and control the oil flow.

The tank should be strong enough to withstand stress produced by jacking and lifting. The size of the tank must be large enough to accommodate cores, windings, internal connections and also must give the requisite clearance between the windings and the walls.[3]

The dimension of core and winding inside the tank is shown in Figure (4.1) below.

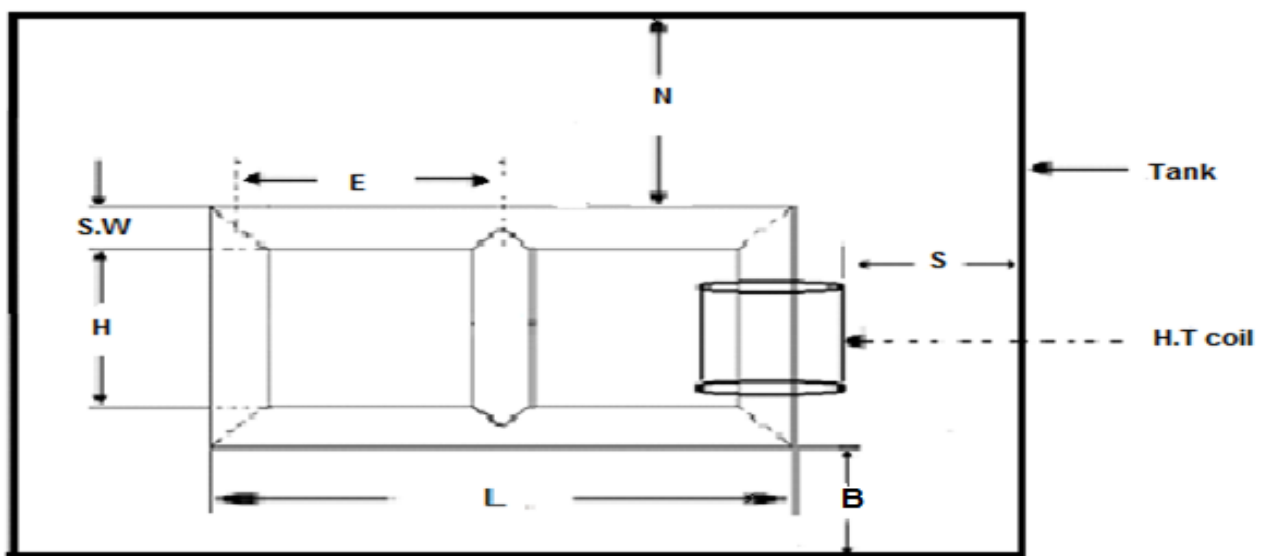


Figure (4.1): dimension of core and winding inside the tank

Design of the tank depend on the clearance tank according to (IEC) Standers Table (4.1) and the dimension of the core which calculated from chapter Three Table(4.2) .

Table (4.1) : clearance tank according to IEC Standers

Clearance tank according to IEC Standers		
Clearance between high tension and tank(S)	35	mm
Core to cover tank (N)	250	mm
Core to bottom tank (B)	36	mm

Table (4.2) : core data of transformer

Core Data		
Clearance between central and lateral leg (E)	378	mm
Coil outer diameter of high tension (OD _p)	361.1	mm
Window height (H)	435	mm
Large slide width (L.S.W)	220	mm
Core height (M)	875	mm

4.2 Equation and Calculation Design

$$TL = 2 \times E + OD_p + 2 \times S \quad (4.1)$$

$$TW = OD_p + 2 \times S \quad (4.2)$$

$$TH = H + 2 \times L.S.W + N + B \quad (4.3)$$

Where :

S $\equiv$ Clearance between tank and high tension

N $\equiv$ core to cover

B $\equiv$ core to bottom

$H \equiv$ Height of window

$L.S.W \equiv$ Largest slide width

from Equation (4.1) $TL = 2 \times 378 + 361.1 + 2 \times 35 = 1187.1 \text{ mm}$.

from Equation (4.2) $TW1 = 361.1 + 2 \times 35 = 431.1 \text{ mm}$.

from Equation (4.3) $TH = 875 + 250 + 36 = 1161 \text{ mm}$. [3]

And this result is also programmed in exile sheet and shown in appendix (E)

4.3 Transformer Oil

The oil which transformer core and winding immersed in is an important factor which determine life and satisfactory operation of transformer.

The transformer oil has two prime function :

- I. to create an acceptable level of insulation in conjunction with insulated conductor and coils.
- II. to provide a cooling medium capable of extracting quantities of heat without deterioration as an insulating medium.

Transformer oil is a mineral oil (clean hydrocarbon oil) obtained by refining crude petroleum. Vegetables and animals oils are not used in transformer as they from fatty acids that attack the fibrous insulating materials used. [2]

4.4 Transformer Oil Characteristic

Some of the important characteristic necessary or desirable in transformer oil are describe below

4.4.1 Electric strength

The transformer oil should have a high dielectric strength in order to minimize clearance between coils and from winding to tank .minimum electric strength of new oils should be 3KV/mm (rms).The resistivity of new transformer oils is more than $13 \times 10^{10} \Omega \text{ m}$. however, if dust and small fibers are present in oil, they tend to align themselves along electric lines of force thereby forming paths of low resistivity which may cause electric failure.[2]

4.4.2 Resistance to emulsion

The oil should have a high resistance to emulsion in order to prevent holding water in suspension in it. This is because even a small tract of moisture severely reduced the electric strength of oil. The oil should not be allowed to come in contact with moisture. [2]

4.4.3 Viscosity

The Viscosity of the transformer should be small to permit rapid circulation of oil.[2]

4.4.4 Purity

The oil must not contain any acid, alkali and sulphur compounds as these cause corrosion of metal parts and insulation and if sulphur compounds, is presented, it accelerate the production of sludge.[2]

4.4.5 Flash point

The flash point is the temperature at which oil vapor ignites spontaneously. The flash point of oil characterizes its tendency to evaporate. The lower flash point the greater is the vaporization of oil. The flash point of the transformer should be higher than 104C°. [2]

4.5 Cooling of Transformers

Cooling of transformer is the process of dissipation of heat developed in the transformer to the surroundings. The losses occurring in the transformer are converted into heat which increases the temperature of the windings and the core. In order to dissipate the heat generated cooling should be done.

There are two ways of cooling the transformer:

Firstly, the coolant circulating inside the transformer transfers the heat from the windings and the core entirely to the tank walls and then it is dissipated to the surrounding medium

Secondly, along with the first technique the heat can also be transferred by coolants inside the transformer.

The choice of method used depends upon the size, type of applications and the working conditions. [2]

4.6 Cooling Ducts

The economically designed transformer has just sufficient oil ducts in the winding to carry away the heat at such a rate that the hot spot temperature is just safely below the maximum permissible limit. Any increase in the number of oil ducts necessitates more space for the winding and an unnecessary increase in the amount of material used and in the labor cost providing the additional spacing. Furthermore, the ducts should be so arranged in the winding as to give the maximum amount of cooling.

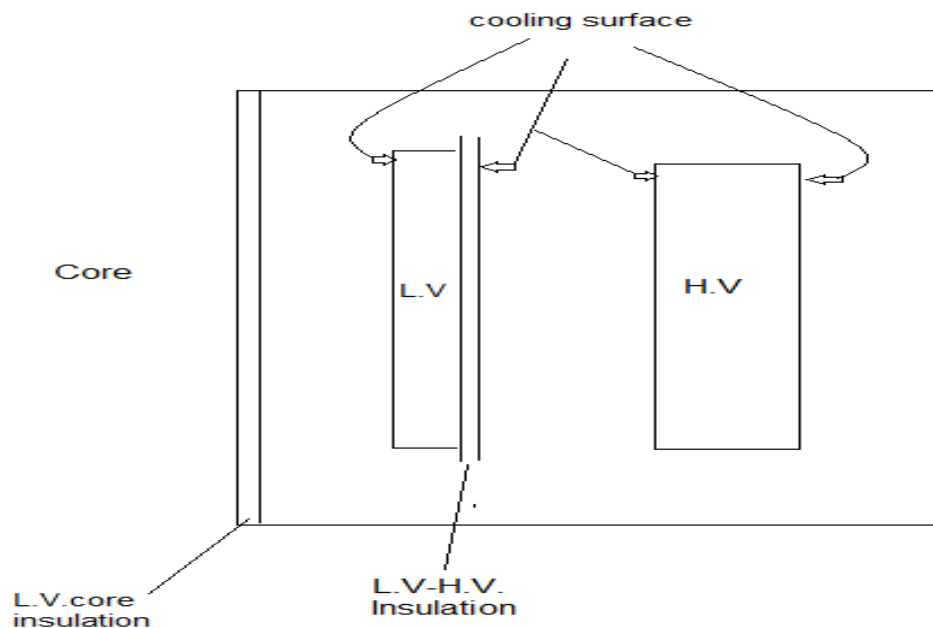


Figure (4.2): Cooling surface

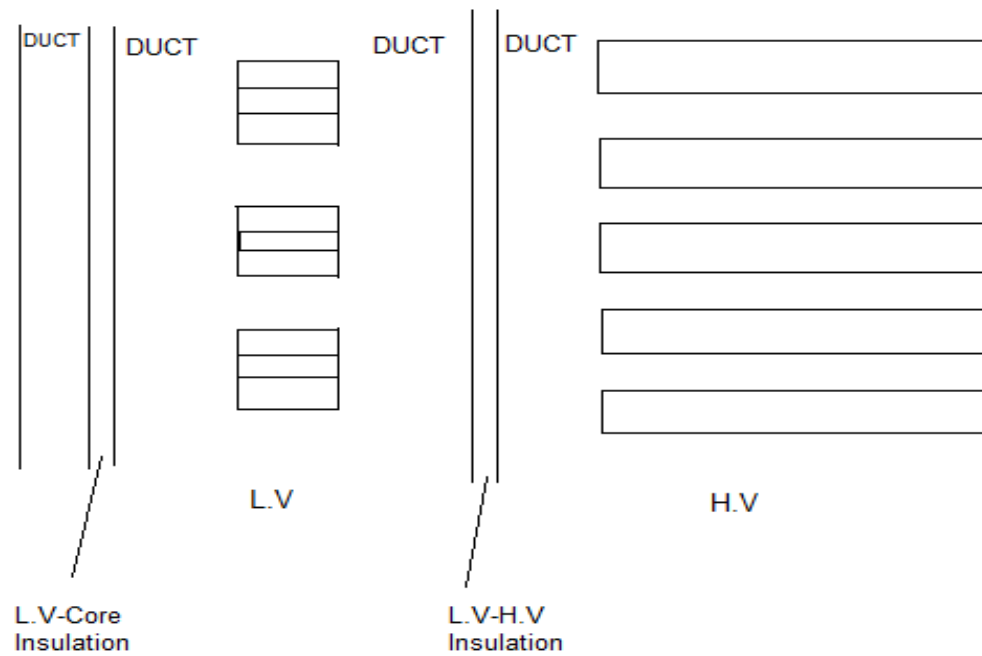


Figure (4.3): ducts between turns of a single layer winding

Horizontal ducts give slower oil circulating and hence poorer than vertical ducts, while in both cases care must be taken to ensure that all ducts are clear and present an unimpeded path for the flow of oil.

Cooling surface is usually provided between core and L.V. winding, between L.V. and H.V. windings and on the outside of the H.V. winding as shown in Figure (4.2) above. Additional vertical ducts may be provided in the middle of the L.V. winding, or even in the H.V winding if the voltage permits. The usual method of the providing further cooling is by the addition of horizontal ducts in the H.V. winding, which is divided into 6, 8 or more coils according to the ducts required and the voltage. In large transformer, every turn of the winding is in constant with cooling surface. In a similar way L.V. winding are provided with ducts between turns of a single layer winding as shown in Figure (4.3) above. [2]

4.7 Methods of Cooling of Transformer

Based on the coolant used the cooling methods can be classified into:

- 4.7.1 Air cooling.
- 4.7.2 Oil and Air cooling.
- 4.7.3 Oil and Water cooling.

4.7.1 Air cooling

It is also known as dry type transformers, in this method the heat generated is conducted across the core and windings and is dissipated from the outer surface of the core and windings to the surrounding air. Also this method classification into two types.

I. Air natural

This method uses the ambient air as the cooling medium. The natural circulation of the air is used for dissipation of heat generated by natural convection. The core and the windings are protected from mechanical damage by providing a metal enclosure. This method is suitable for transformers of rating up to 1.5MVA. This method is adopted in the places where fire is a great hazard.

II. Air blast

In this method, the transformer is cooled by circulating continuous blast of cool air through the core and the windings. For this external fans are used. The air supply must be filtered to prevent accumulation of dust particles in the ventilating ducts.

4.7.2 Oil cooling

In this method, heat is transferred to the oil surrounding the core and windings and it is conducted to the walls of the transformer tank. Finally the heat is transferred to the surround air by radiation and convection. It classification into Four types:

- I. Oil Natural Air Natural (ONAN).
- II. Oil Natural Air Forced (ONAF).
- III. Oil Forced Air Natural (OFAN).
- IV. Oil Forced Air Forced (OFAF).

Oil Natural Air Natural ONAN

The transformer is immersed in oil and the heat generated in the cores and the windings is passed on to oil by conduction. Oil in contact with the surface of windings and core gets heated up and moves towards the top and is replaced by the cool oil from the bottom. The heated oil transfers its heat to the transformer tank through convection and which in turn transfers the heat to the surrounding air by convection and radiation.

This method can be used for the transformers having the ratings up to 30MVA. The rate of heat dissipation can be increased by providing fins, tubes and radiator tanks as shown in Figure (4.4) below. Here the oil takes the heat from inside the transformer and the surrounding air takes away the heat from the tank. Hence it can also be called as Oil Natural Air natural (ONAN) method. [2]

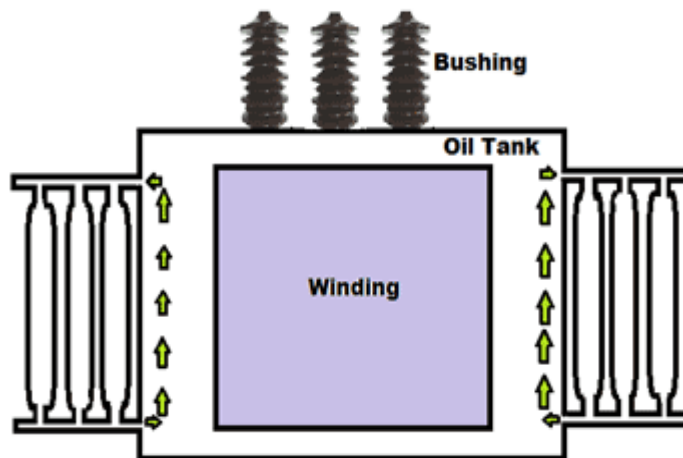


Figure (4.4): Oil Natural Air Natural (ONAN).

4.7.3 Oil and water cooling

It is used for capacity more than 30MVA In this method along with oil cooling, water is circulated through copper tubes which enhance the cooling of transformer. This method is normally adopted in transformers with capacities in the order of several MVA. There are two type of this method :

- I. Oil Natural Water Forced (ONWF).
- II. Oil Forced Water Forced (OFWF). [2]

4.8 Bushing

Bushings are used for terminating windings on the tank body. It is made out of porcelain and generally brown glazed in color. A transformer designed for outdoor use has its core and coils completely enclosed by a steel enclosure. In order to connect the windings to the electrical system, the leads are brought out of the tank through bushings. Since the leads are energized at line voltages, the bushings must insulate and isolate the leads from each other and from the tank. The Leakage distance of bushings shall not be less than 25mm/kV, based on operating phase to phase voltage. Also The high voltage bushing shall be fitted with adjustable double-gap arcing horns set at 2 x 25mm gaps for 11kV and 2 x 55mm gaps for 33kV. The arcing horns shall be in stainless steel. Selection of the Minimum external air clearances according to IEC 60137 as shown in Table (4.3) below.[5]

Table (4.3): The minimum external air clearances according to IEC 60137

Nominal System Voltage between Phases		LV	11KV	33KV
Minimum clearance phase-to-earth and phase-to-neutral	mm	80	300	485
Minimum clearance phase-to-phase between phases of the same winding	mm	100	250	435
Minimum clearance between a line terminal of the high voltage winding and a line terminal of a lower voltage winding	mm	80	300	485
Minimum Creepage distance	mm	60	300	900

4.9 Comparison Results

Table (4.6) below show the comparison between the old design which it produced by Sudanese electricity distribution company as shown in Table (4.4) below and the actual new design as shown in Table (4.5) below.

Table (4.4): actual value from old design

Type	11/0.433KV	Serial number	02909.001/036	Phase	3
Capacity	1000kVA	Frequency	50 Hz	Oil temperature rise ≤50℃	
Voltage: 11±2×2.5% /0.433kV		Current : 52.5 / 1333.4 A			
No-load loss (W)		Load loss75℃(W)		Impedance voltage (%)	
1400		14500		5	
Connection symbol: D yn11					
actual values					
No-load loss (W)		Load loss75℃ (W)		Impedance voltage (%)	
1357.5		14543.98		4.8	

Table (4.5): actual value from new design

Type	11/0.433KV	—	—	Phase	3
Capacity	1000kVA	Frequency	50 Hz	Oil temperature rise ≤50℃	
Voltage 11±2×2.5% /0.433kV		Current : 52.5 / 1333.4 A			
No-load loss (W)		Load loss75℃ (W)		Impedance voltage (%)	
1400		14500		5	
Connection symbol: D yn11					
actual values					
No-load loss (W)		Load loss75℃ (W)		Impedance voltage (%)	
1098		12024		5.42	

Table (4.6):Comparison between old design and new design

quantity	Specification	Old design	New design
No-load losses	1400	1357.5	1098.3
Load losses	14500	14543.98	12024
Percentage impedance	5	4.8	5.42

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project represent designing of 1000 KVA distribution transformer. In this design efficiency improved by reducing total losses which achieved by reducing the quantity of silicon steel and copper also by using optimum conductor dimensions in both low voltage and high voltage sides.

The obtained design out puts (i. e: losses, percentage impedance) were wit in the limit of Sudanese Electricity Distribution Company (SEDC) specification. This proto type reveal better design performance when compared with exist one.

5.2 Recommendation

The following suggested for future studied in this field:

Apply this project practically.

In mechanical part heat radiator must be deigned according to heat transfer equation.

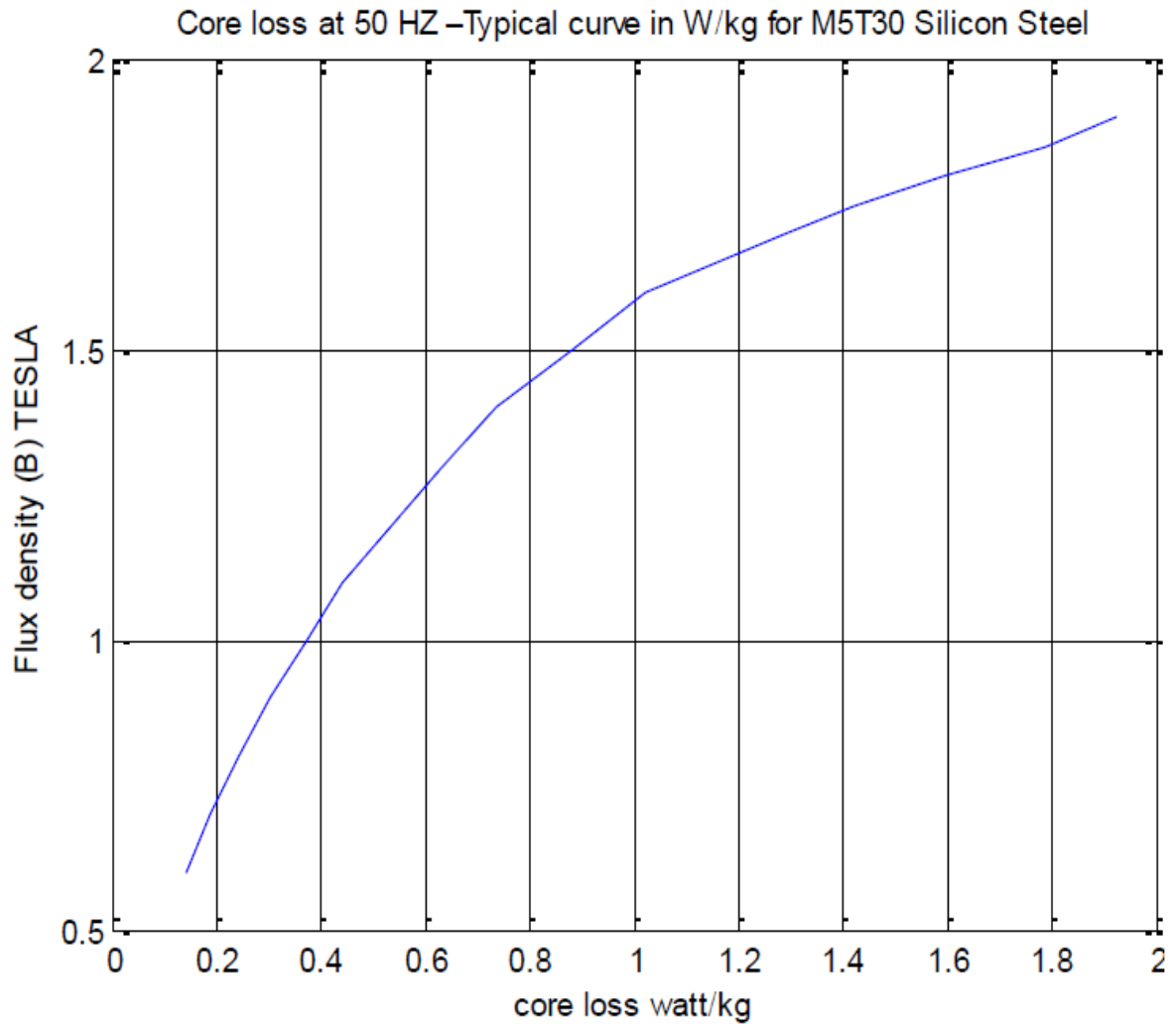
Economical and cost calculation must be added in design software.

REFERENCES

- [1] “Three Phase Transformer Design”, Marcel Dekker, 2004.
- [2] E.E.Wild, “Transformer”, 4th edition.
- [3] Indrajit Dasgupta, “Power Transformers Quality Assurance”, New Age International (P) Ltd, New Delhi, 2009.
- [4] M.G.Say, “The Performance and Design Of Alternating Current Machines”, 3th edition.
- [5] John J. Winders, Jr “Transformers Principles and Applications”, Marcel Dekker, Allentown, 2002 .

Appendix

Appendix (A): Silicon Sheet Specifications



Appendix (B): Core loss at 50 HZ –Typical values in W/kg

Induction TESLA	M5T30
0.6	0.14
0.7	0.185
0.8	0.242
0.9	0.3
1	0.37
1.1	0.44
1.2	0.535
1.3	0.635
1.4	0.735
1.5	0.88
1.6	1.023
1.7	1.29
1.75	1.42
1.8	1.595
1.85	1.785
1.9	1.925

Appendix (C): Specification of (11/0.433 KV) distribution transformers

Rating	Specification of (11/0.433 KV) distribution transformers		
	Percentage impedance (Z %)	No –Load losses (Watt)	Full Load losses (Watt)
100 KVA	4	260	1551
200KVA	4	425	2750
300KVA	4	630	3250
500KVA	4	720	5500
1000 KVA	5	1400	10500

Appendix (D)

1	KVA	100	V(l)t	433	F-	50	V(h)t	11550	11275	11000	10725	10450
2							t.ratio)	46.2013553	45.1	44.0013	42.90126	41.8012
3									DELTA			
4							C(l)t)line	133.3	C(l)t)phar	133.33724		
5										5.249	C(h)t)ph	3.030303
6												
7												
8												
9	N(l)t)arr-	65.8	E(N)arr-	3.799				1.72727273		A)arr-	10066.72	
10	N(l)t)actual-	18	E(N)actu	13.89				1.7		C.D)arr-	131.7437	
11										O.D)actual	232	
12										S.L (ur/k	1	
13	fraction of full	0.327										
14	efficiency	99.29										
15												
16												
17	arr(l)t-	49.73										
18												
19	c.d)l)t)arr	3	wire cr)l)t)arr	44.45						wire cr)h)t)arr	1.0101	
20	c.d)l)t)act	0.351	re cr)l)t)fail)	380	400	0.95				wire cr)h)t)act	6.69931	R-
21												R)uul 3
22	high ring	10										
23	N(l)t)actual-	18										
24	coil height	400	400									
25	mech height)l)t	420										
26	turn/layer	1										
27	na,layerz)l)t-	18										
28												
29	insulation bet.l	0.15	1	0.15	418							
30												
31												
32	distance bet.l)t	5										
33	ID)l)t	237										
34												
35	cooling canals	1	3.1									
36	thick) l)t	6.75										
37												
38	OD)l)t	250.5										
39												

Appendix (E)

Tank Data		
Minimum total length of tank (T _L)	1187.1	mm
Minimum total width of tank (T _w)	447.1	mm
Minimum total height of tank (T _H)	1161	mm

Core Data		
E	378	mm
Coil outer dia	361.1	mm
Clearance	35	mm
H	435	mm
Core to cover	250	mm
Core to bottom	36	mm
L.S.W	220	mm
Core height	875	mm
Total losses	1215.854	W