DESIGN AND MANUFACTURING REQUIREMENT OF SOLAR APPLICATION TRANSFORMER

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING
(Electrical Power Systems)

By

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May 2014

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This is to certify that the Major Project Report entitled **"Design and Manufacturing requirement of solar application transformer "** submitted by **Mr.Parth M. Shah (12MEEE26)** towards the partial fulfillment of the requirements for degree in **Master of Technology (Electrical Engineering)** in the field of **Electrical Power Systems** of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

In the renewable edge of energy sector, solar energy is playing important role. Gujarat itself has a second largest solar park in the world. Transformer is a vital link in the power system, which is connected in the network at different stages right from the generating station to the user's premises. Transformer required in solar park to transfer energy from PV panels to grid is known as solar application transformer. As solar park is at very recent edge of development in India, designing and development of solar application transformer has good space of research.

Transformers are operating on same principle of electromagnetic induction. However, designs are differ as per its application.This project include study of requirement of solar application transformer and appropriate change in design of its active part due to special requirements. In the next phase flow chart development of design procedure and detail design which includes required parameters calculation according to flow chart is done. In the last phase of this project simulation results of created 3D model,based on design of active part of transformer,under different conditions and for different plots are presented which itself validate the design of transformer.

Acknowledgements

Success of any work depends upon the dedication, sincerity and hard work. It also requires some ingredients such as motivation, guidance, encouragement and time. I am very thankful to all those who are behind the successful completion of the dissertation work.

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I specially want to thank my parents for their motivation, moral support and encouragement through out my dissertation work. And above all, I pay my regards to the Almighty for his love and blessing.

- Parth M. Shah
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Abbreviations

SAT .... Solar Application Transformer
CFVV .... Constant Flux Variable Voltage
VFVV .... Variable Flux Variable Voltage
PV .... Photo Voltic
mlt .... Mean Length Turn

Nomenclature

I_{Lv} .... Lv rated current
I_{Hv} .... Hv rated current
A_Lv .... Copper area of Lv
A_Hv .... Copper area of Hv
A_core .... Core area
R_{Lv} .... Resistance of Lv winding
R_{Hv} .... Resistance of Hv winding
$Cl_{Lv-shield}$ .... Clearance between Lv and shield
$CL_{shield-Hv}$ .... Clearance between shield and Hv
ρ .... Resistivity of copper
Ht_{Hv} .... Height of Hv winding
Ht_{Lv} .... Height of Lv winding
D .... Diameter
Wt_core .... Weight of core
Bm .... Flux density
j .... Current density
Vt .... Volt per Turn
f .... Frequency
Th_{insu} .... Thickness of insulation
Th_{foil} .... Thickness of foil
N .... Number of turns
LL .... Load loss
NLL .... No load loss
X .... Reactance
L .... Impedance

Contents

Chapter 1

Introduction

1.1 Background

Transformer form an important element of transmission and distribution network of electrical power system. Transformer is become a very essential device because of its application in various functions like Step-up or step down of voltage, regulation of voltage,for isolation purpose, for converter duty function etc. It is very costly and large device in any power system project or industrial project.

"Transformer is integral parts of a power system and form important links between utility and supply."

Production of any Transformer is a precise job. There are many inputs required for electrical, mechanical, civil design of the transformer

- **Electrical Design**

  Electrical design relates to the MVA rating of system, Hv-Lv rating in Kv, selection of volt per turn, flux density, current density, core area, copper area, load loss, no load loss, percentage impedance,etc .

1.2 Recent scenario of power generation

Limited non renewable resources of power production is a burning problem of today. Renewable energy sources are only alternatives. Solar energy is on higher priority in renewable energy sources because solar irradiation is available to almost everywhere on earth and it is much more stable than wind all over the day. Solar application transformer is very essential product in Solar power plant which is basically built up for converter duty application in solar plant.

1.3 Solar power transformer

It is a very specially design transformer for converter duty application in solar plants to meet the challenges in solar power plants such as imitation of inverter Kva capacity, harmonic production in inverter, tap switch arrangement is crucial as Lv side voltage variation regulated by tap switch on Hv side, over rated tap switch required as voltage fluctuation is sever. -Distinction of SAT from ordinary distribution transformer

- It has two separate Lv windings to connect two inverter simultaneously
- Electrostatic shield between two winding to filter harmonics
- Tap changer is placed at Hv side to regulate voltage fluctuation on Lv side.This type of working of tap switch is based on phenomenon of variable flux voltage variation.In distribution transformer tap changer is connected to Hv side to regulate voltage variation of Hv side and keep Lv voltage constant.This type of working of tap switch is based on phenomenon of constant flux voltage variation

1.4 Objective of Project

In this Project, main objective is to identify various requirement of SAT.Design a active part of SAT for given ratings on basis of actual application.To prove that Lv foil winding is more preferable than traditional spiral winding.The study include transformer specification, design of transformer, requirement of shield, requirement of foil winding.

1.5 Scope of Work

The work fulfills objective in following steps:

- Identify requirements of SAT.
- Study of Designing of transformer.
- Optimized transformer design of SAT by using foil winding as Lv winding.
- Development of 3D model to meet objective

1.6 Problem Identification and Project Planning

1.6.1 Problem Identification

- Most of the solar power plants are directly connected to grid without any capacitor bank connected between PV cell and inverter. Because of weather condition,sag in voltage generation occurs and this sag can recover it self by improvement in weather condition. The another case of voltage variation could be also done by fluctuating demand on grid where Hv is connected.

- The severe fluctuation in PV cell generated DC Voltage can effect the inverter side connected spiral type Lv winding and layer type Hv winding. This may cause failure of Lv or Hv inter layer insulation,hance short circuit condition may occurs transformer kept in hazardous condition.

- Though the inverter technologies become very sophisticated,it generates 3% to 1% of harmonics which will through Lv winding Hv winding and atlast feed to grid. To mitigate this harmonics a grounded Electrostatic shield of Aluminium is placed between two windings.

- To meet this problems suitable changes required in electrical design of SAT.

- In this project,above mentioned problems are analyzed and remedies are found out.This remedies are implemented by making suitable changes in electrical design of SAT such as altering spiral type Lv winding with foil winding,Hv side insulation is designed at flux density and voltage at highest tap position, electrostatic shield between windings.

1.6.2 Project Planning

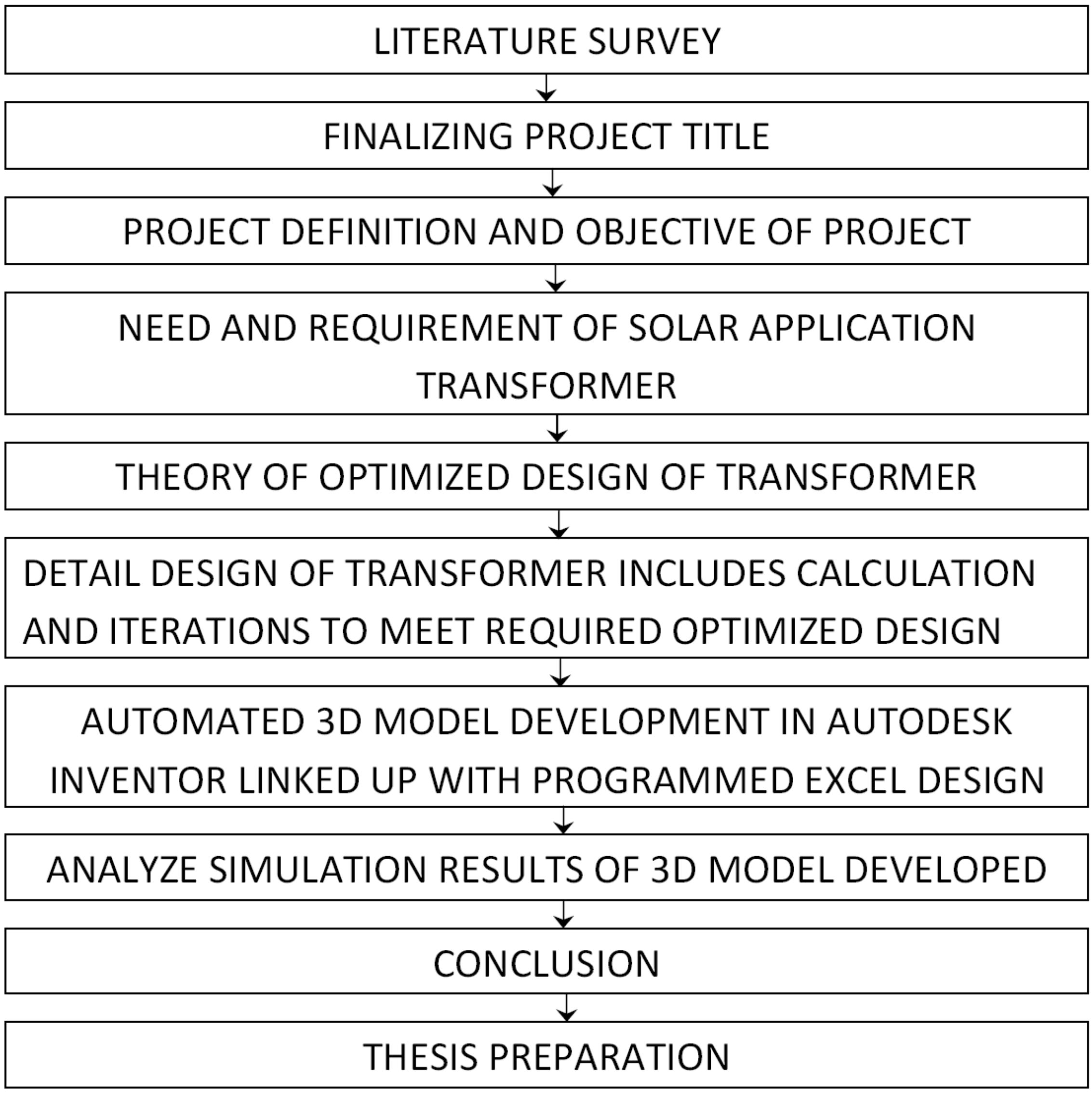

Figure 1.1: Project Planning

1.7 Thesis Organization

Chapter 1 introduces the background of power generation, the recent scenario of solar power generation, Objective of project, scope of work, problem identification and project planning.

Chapter 2 gives literature survey on experiences with design optimization theories,benefits of foil winding and use of electrostatic shield in harmonics reduction.

Chapter 3 explains need of SAT and special requirement of SAT .

Chapter 4 includes Floe chart of design procedure,theory of design and calculation results of required parameters of transformer.

Chapter 5 includes Simulation results of 3D model,prepared according to calculated parameters. This includes the results of simulation under different condition of energization of windings and different parametric plot.

Chapter 6 conclude the project.

Appendix A includes detail transformer design calculation.

Appendix B includes Design data sheets and reference design sheet for core construction.

Chapter 2

Literature Survey

- **Martin J. Heathcote, CEng, FIEE,The J P Transformer Book**
  This edition contains a wealth of new technical information that has been freely made available by transformer manufacturers, the electrical supply industry, learned institutions and industrial associations such as CIGRE. The information contained in this twelfth edition of The J P Transformer Book will update the knowledge of the current generation of engineers
- **S.V.Kulkarni,S.A.Khaparde, Transformer Engineering Design and Practice**
  The book propagates the use of modern computational tools for optimization and quality enhancement of transformers. I know a number of previously published works of the authors in which Finite Element Method (FEM) has been applied for the stray loss control and insulation design of the transformers. The use of FEM has been aptly demonstrated in the book for various calculations along with some tips, which will be helpful to a novice in FEM. The book is therefore a major contribution to the literature. The book will be extremely helpful and handy to the transformer industry and users.
- **Zoheb Akhtar , Hari N Varrier ,K. Bheema prakash, Develop-**

ment of efficient and compact GSP Transformers

This paper reviews importance of distribution transformers, the different components of losses and traditional methods to minimize the same. The paper highlights development of transformers with Global Standard Performance, using foil wound technology and describes the advantages of foil wound transformers in comparison with conventional strip wound transformers. In this extract we will be comparing foil wound transformer with the conventional strip wound transformers and highlighting the advantages of foil wound transformers in terms of quality, compactness and reliability.

Chapter 3

Need and requirement of Solar Application Transformer

3.1 Need of SAT

- Transformers are critical components in solar energy production and distribution. Historically, transformers have ”stepped-up” or ”stepped-down” energy from non-renewable sources. There are different types of solar transformers including distribution, station, sub-station, pad mounted and grounding.
- Solar duty transformer is basically converter duty transformer because It connects with inverter.
- All solar transformers have specialized needs that impact costs.
- For example, solar power applications experience steady state loading during inverter operation. When the sun’s out, there’s a dampened reaction process and more constant loading on the transformer.
- Also, fault ride through has not been defined for photovoltaic systems. This may be because it’s easier to turn solar systems on and off quickly,

or because regulatory requirements have not caught up with the young technology. This may change in the future.

- As for harmonics, the solar inverter's typical harmonic content is below 1%, which has almost no impact on the system. The lower harmonic profile is because there are no generators and switching and protective controls such as those found on wind turbines. Solar transformers do require step-up duty. Yet, the solar inverter converts DC input from the PV array to AC voltage for the transformer in a smooth transition with no overvoltage from unloaded circuit. Because solar transformers operate at a steady voltage, with the rated voltage controlled by inverters, voltage and load fluctuations are considerably lower than in wind turbines. PV systems also operate close to their rated loads.

- This 1% harmonic also impact more on Hv side,thus it need to filter. Electrostatic shield or faraday's shield is the technique by which this filtration is done. This grounded shield of aluminium is put in between two windings.

- Solar-power systems also have special design issues. Because the largest solar inverter size is about 500 kilovoltampere (kVA), designers are building 1,000 kVA solar transformers by placing two inverter connected windings in one box. The transformer must have separate windings to accept completely separate inputs. Design issues also stem from running cables long distances to convert from DC to AC.

- Restrictions on inverter size also limit the size of PV systems. Increasing the size by adding more solar inverters into one transformer box is extremely difficult. With the required box size and running cabling to convert DC to AC, things get complex.

- The key to solar transformers is to understand the variables in every system. Transformers need to customize to work with each particular system. Inverter technology has been slow to advance, and it remains to be seen whether this comparative disadvantage will be a fatal flaw in the advancement of solar technology to the same level as wind farms.

- If two inverters connects to single transformer then land requirement also decreases as separate transformer does not required for separate inverter.

3.2 Typical requirements of SAT

SAT is basically a converter duty transformer but it has to meet some challenges related to solar power station. Some of major challenges of that are described here.

3.2.1 Multi Lv winding

The largest solar inverter size is about 500 kilovoltampere (kVA) and to meet minimum MVA rating of transformer designer should need to connect two inverter output to single transformer. It can be done by two methods.

- The first one is by doing cascade connection of two inverter output and then connect it to transformer input, but in this case the switching of two inverters are never be similar and thus sever distortion in wave form may occurs and additional filters are required to filter the harmonic ride over fundamental wave
- Second one is more technically easy and economical. In this method the Lv winding is separated in two windings. one winding is rated to half MVA rating of transformer. This may reduces the complexity of cascading and two inverters may easily connect to one transformer box

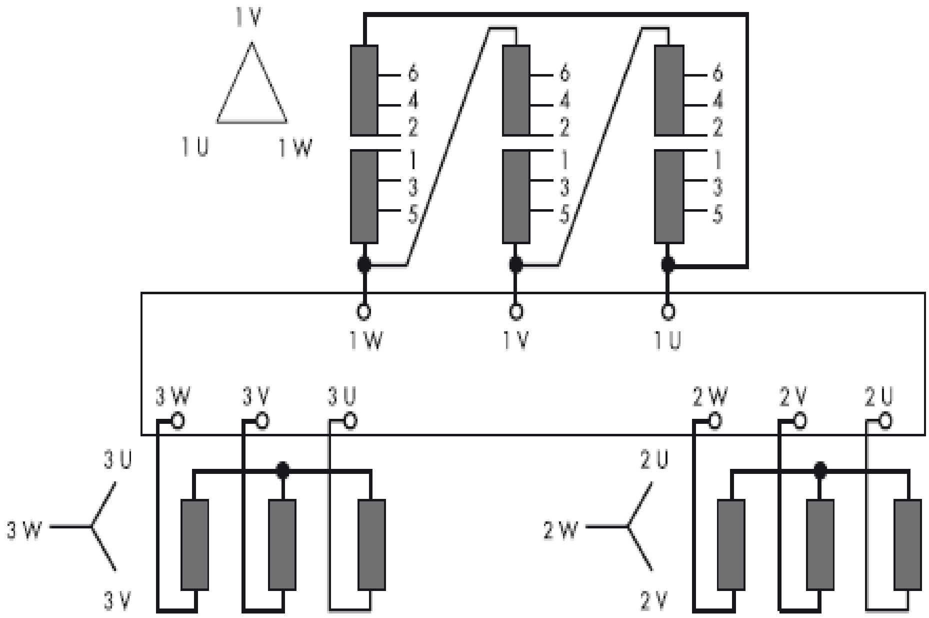

Figure 3.1: circuit diagram of dual LV transformer

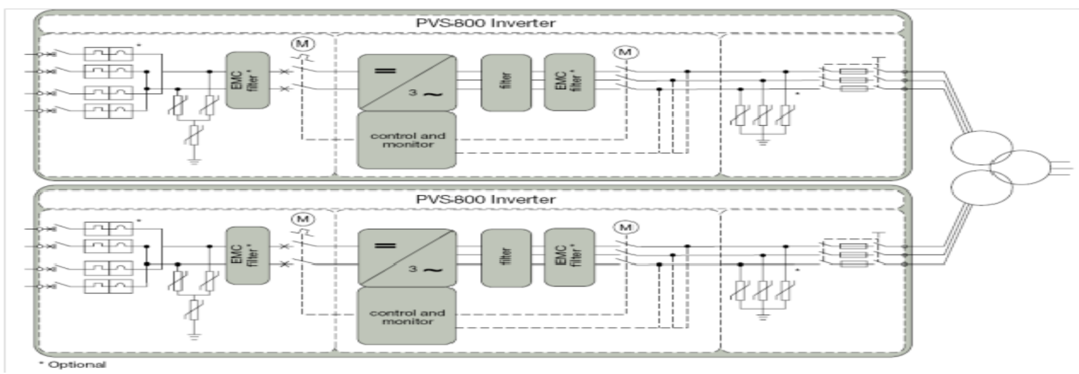

Figure 3.2: schematic diagram of dual LV transformer connection with inverter

3.2.2 Electrostatic shield

Solar power generation has not much fluctuation compared to wind power generation. So that power generation is very much stable and hance harmonics content is only 3% to 1% but still it hazardous when it ride on Hv side as Hv side is connected to power grid. So this need to be filter out. Electrostatic shield is one method by which this could be possible. Electrostatic shield is a single turn of thin aluminium foil which is grounded and is placed in between two windings. By doing this the capacitance coupling between two winding will defer and the wave of higher frequency will grounded. the electrical circuit is presented here.

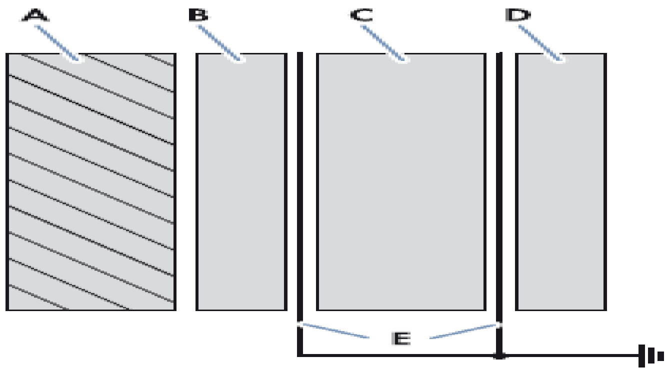

Figure 3.3: Physical arrangement of windings in SAT

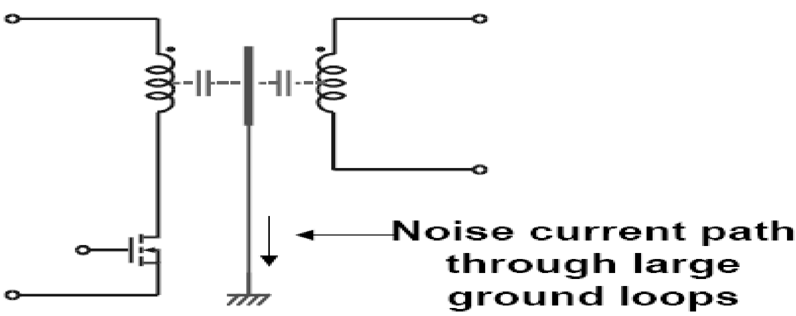

Figure 3.4: Physical arrangement of windings in SAT

3.2.3 Requirement of foil winding

In solar power generation weather play a critical role,it is the only parameter which may interrupt solar irradiation and hance change power generation,following figure may give clear idea about it. This change impact on EMF generation in HV and LV both,and hance increase of losses and forces acting on winding.Also in either case of lightning and impulse condition the winding forces are also increased highly and also voltage stress in winding increases. This may damage winding by acting of high forces or short circuit due to puncture of insulation because of high voltage application. The remedy of this problem is to use Foil winding rather than using traditional spiral winding. some of its advantage are mentioned here.

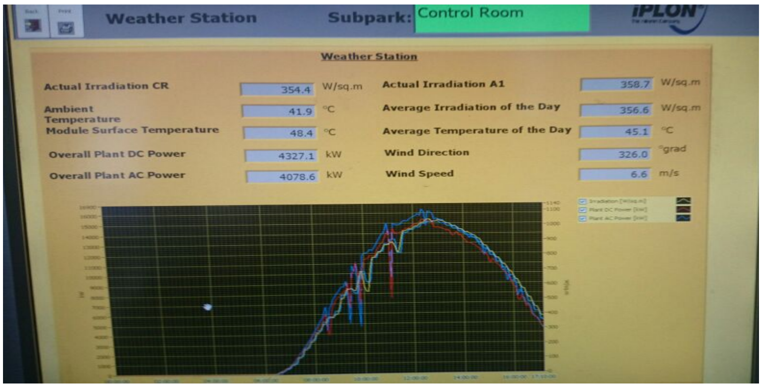

Figure 3.5: All day Power generation of solar power plant at charanka

- **IMPROVED WINDING SPACE FACTOR**:- The most efficient use of winding space is to layer wrap using strip or round wire as shown in Figure 6.1A. Depending upon the size of the wire used, there is a percentage of the winding area which cannot be used for the conductors.

  This lost area is made up of the space between the wires, the insulation with which each wire is covered and the spiral effect. As the voltage stress

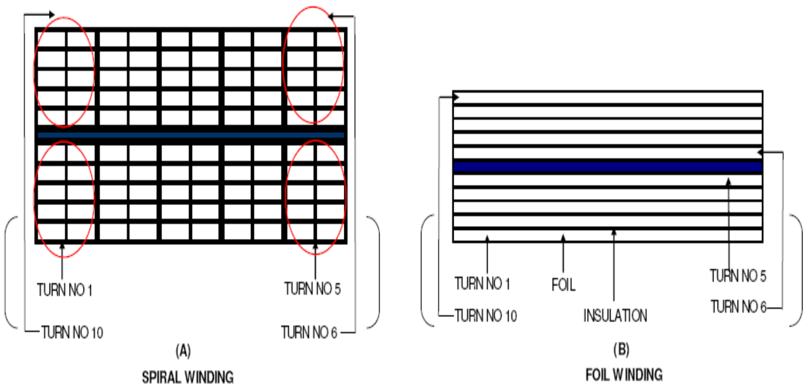

Figure 3.6: space factor

of the winding is increased, it is often necessary to add inter-layer insulation creating more lost space, thus decreasing the available conductor area. The foil-wound coil illustrated in Figure 6.1b can be designed to make optimum use of the available winding area. Each turn of the foil extends edge-to-edge of the coil and is separated from the next turn by one thickness of insulation. There is no lost winding space which means that foil with the same circular mil area as wire will fit into a smaller winding area, or conversely, more circular mils of foil may be wound into the same winding area.

– **HIGHER AMBIENT TEMPERATURE OPERATING CAPABILITY**:- Consider the operating temperature of the transformer which affects its rating, efficiency and voltage regulation. The allowable operating temperature is the major factor in determining the size, weight and performance of a transformer. As in any other electrical device, current flowing through the resistance of the coil wire results in heat generation. This generated heat plus the losses associated with the magnetic material will cause an increase in temperature. How high the temperature will rise depends on how much and how fast the heat is generated and also how fast and efficiently this heat is wholly or partially removed. Figure 5 shows to what surface temperature a black body would rise above ambient as a function of watts power square inch of surface area of heat being dissipated or the heat dissipation is proportional to the surface area of the body. Foil has a greater ratio of surface area to cross-sectional area. The assumption is that all internal losses appear at the surface to be dissipated by convection or by radiation to the ambient air. Referring to Figure 6.2, consider the same initial current flowing in each turn of the coil, and each turn starting with the same resistance, and that an equal amount of heat will be initially generated by each turn. Since all of the heat generated must make its way to the outer surface of the coil before it can be dissipated, a temperature gradient starting from the outside turn (the coolest) to the center turn (the hottest) is immediately established.

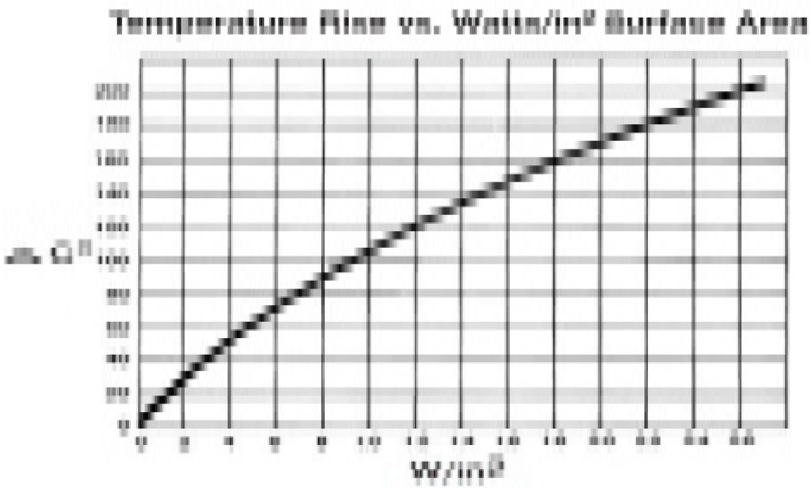

Figure 3.7: Graph-Temp. Vs loss

Further, the temperature of this central inside turn will be very high since the path the heat must travel to get to the coil surface is through many layers of wire insulation which in themselves are very poor thermal conductors. To further complicate the situation, the resistance of each turn of wire will now increase slightly due to its increased temperature. This in turn will increase the heat generated and this cycle will repeat until a temperature stabilization level for each turn is reached. Analysis of Figure 4B shows the unique advantage that a foil-wound unit has relative to the problem of dissipating the generated heat. Each turn extending the full width of the coil has two edges in contact with the surrounding cooling medium. The tremendous advantage of the solid metal conducting path that each turn has for getting the more heat generated per unit increment), is a sharply reduced temperature gradient from the outside to the center of the coil.

– **INCREASED ELECTRICAL STRESS RESISTANCE**:- Third advantage of the foil wound transformer is the voltage stress between adjacent turns. In the wire wound unit, the insulation on the wire must withstand a higher voltage gradient than the foil insulation.

  For instance, assume both coils in Figure 6.1 to be made of 10 turns with 220 volts on the coil. Then, each coil will have a 22-volt drop per turn. In the continuous wound wire coil, turn number 10 is in direct contact with turn number 1 and therefore, the insulation must be capable of withstanding 220 volts. In the foil wound unit (Figure 6.1b), each turn (or layer) is only 10-volt different from its next turn (or layer) and can never be more than 10 volts between any two turns.

– **INCREASED DYNAMIC SHORT CIRCUIT FORCE WITHSTAND CAPACITY**:- Foil winding has greater short circuit withstand strength. During short circuit, the current distribution in the foils spontaneously compensates for asymmetries in the high voltage winding due to tapping. As a consequence, the axial forces are minimized at short circuit operation Fig 6.3

  For the conventional winding during short circuit, the unbalanced forces occur due to the axial unbalances of the windings. These forces tend to

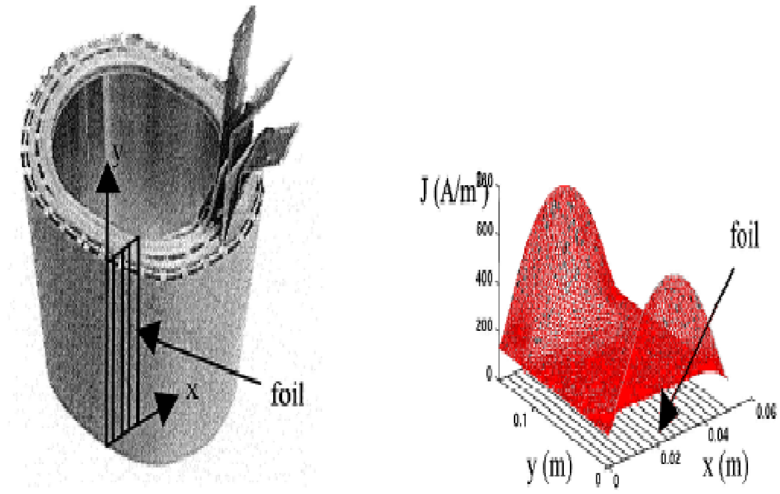

Figure 3.8: foil winding current distribution in foil winding

move the windings axially with respect to each other. The cause of this unbalance is the centers of the windings not remaining aligned with each other at all times during service. This misalignment is due to: Spiral effect of LV winding, Dimensional inaccuracies due to improper drying Clamping and Insulating materials used As is visible from figure 8. that in case of foil wound transformers the magnetic flux lines are more axial than radial. This reduction in radial flux in comparison to conventional transformer results in reduced axial forces in eddy current losses due to radial components. [3]

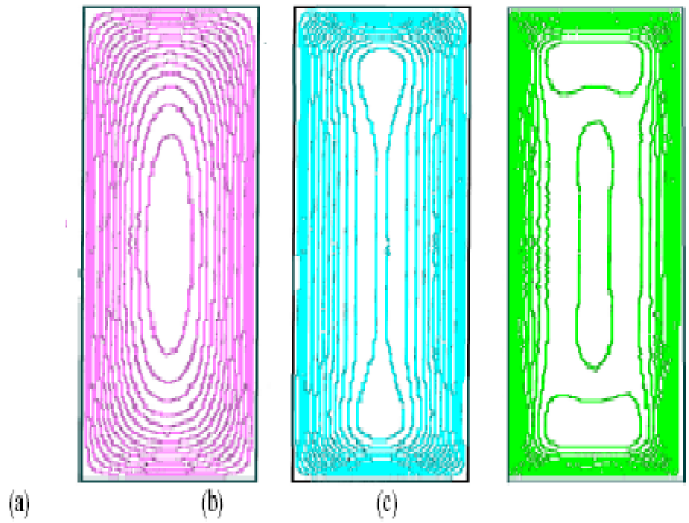

Figure 3.9: magnetic flux lines within (a) a stranded, (b) a foil and (c) a solid conductor.

- **COPPER UTILIZATION FACTOR**:- In conductor winding,conductor is wrapped with insulation paper.so if we take the tolerance of 0.02%, utilized area as active part in winding is

$$Acu(utilized) = totalarea * (1 - tolerance) \tag{3.1}$$

for example,IF we take total copper area is 427 cm^2.$thenAcu(utilized) = 427 * 0.98 = 418.46cm^2$

3.2.4 Special case of working of tap changer

Use of Tap changers Before considering the effects of tappings and tapchangers on transformer construction it is first necessary to examine the purposes of tapchangers and the way in which they are used.

- To compensate for changes in the applied voltage on bulk supply and other system transformers.
- To compensate for regulation within the transformer and maintain the

output voltage constant on the above types.

- On generator and interbus transformers to assist in the control of system VAr flows.
- To allow for compensation for factors not accurately known at the time of planning an electrical system.
- To allow for future changes in system conditions.

The following represent some of the disadvantages of the use of tappings on transformers:

- Their use almost invariably leads to some variation of flux density in operation so that the design flux density must be lower than the optimum, to allow for the condition when it might be increased.
- The transformer impedance will vary with tap position so that system design must allow for this.
- Losses will vary with tap position, hence the cooler provided must be large enough to cater for maximum possible loss.
- There will inevitably be some conditions when parts of windings are not in use, leading to less than ideal electromagnetic balance within the transformer which in turn results in increased unbalanced forces in the event of close-up faults.
- The increased number of leads within the transformer increases complexity and possibility of internal faults.
- The tapchanger itself, particularly if of the on-load type, represents a significant source of unreliability.

Working of tap changer in SAT In distribution transformer tap switch placed at Hv side to make Lv voltage constant. In this case tap changer working on constant flux variable voltage(CFVV) i.e. with the change of tapping the volt per turn remain constant and hance flux is also kept constant. But ,for SAT,as it is a part of generation system ,Lv is connected to inverters and Hv connected to grid. though Lv voltage generation is fluctuating Hv voltage should kept constant. In normal case tap changer is placed at voltage varying side and fortunately it is Hv side in distribution system where it follows principle of CFVV. But in present case Lv voltage is fluctuating and tap changer could not place at Lv side as clearance between two tap leads are not much high because of low Kv rating and hance it may create short circuit. Thus in SAT tap changer is placed at Hv side and working on principle of Variable flux variable voltage(VFVV). i.e. with the change in Lv voltage taps on Hv side changes and it adding or removing turns in Hv winding,hance Volt per turn varies and because of this flux density also varies. Thus insulation co-ordination is also challenge in SAT. Hance distribution transformer of same rating could not be applicable for solar plants.

Chapter 4

Design of Solar application transformer

Designing of any device is a primary step of development of device,execution is a later stage.

Designing a transformer for given specification and requirements is very critical task. Volt per turn,current density and flux density selection is very important. Major of the parameters are depends on selection of Vt,Bm and j.Primary condition of any transformer design is to match Losses and impedance.Here, the selection of primary variables is a trial and error method. It need number of iteration to match parameters with required ones. Many challenges should be fulfil in design of SAT,such as,

- Find Alternative of LV winding type to reinforce forces and voltage stress
- Require a proper tapping design to work in special case of Variable Flux Variable Voltage(VFVV)
- Require a shield between two windings to filter harmonics

The steps that should be follow are mentioned very systematically in Flow char of design. Design of a transformer for given data is explained in this chapter.

4.1 Flow chart of design

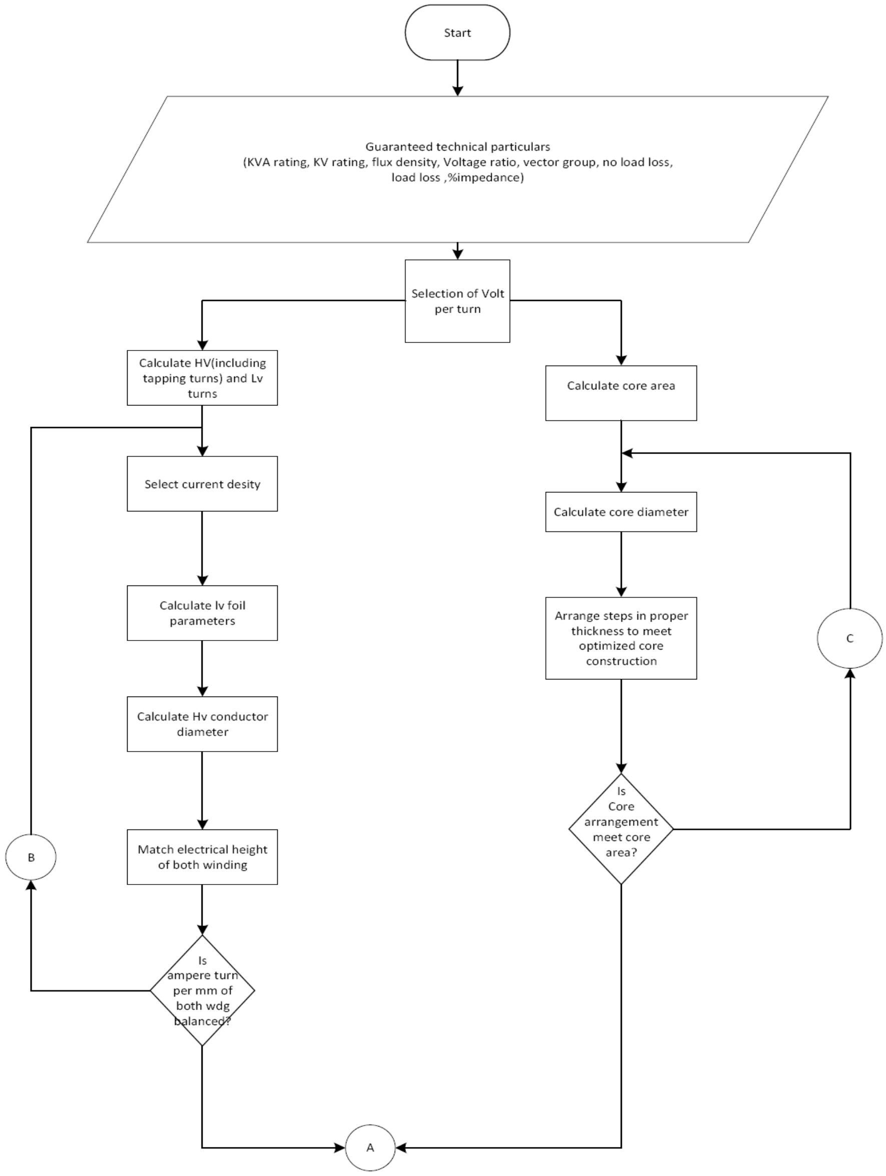

Figure 4.1: Flow chart of transformer design (part-1)

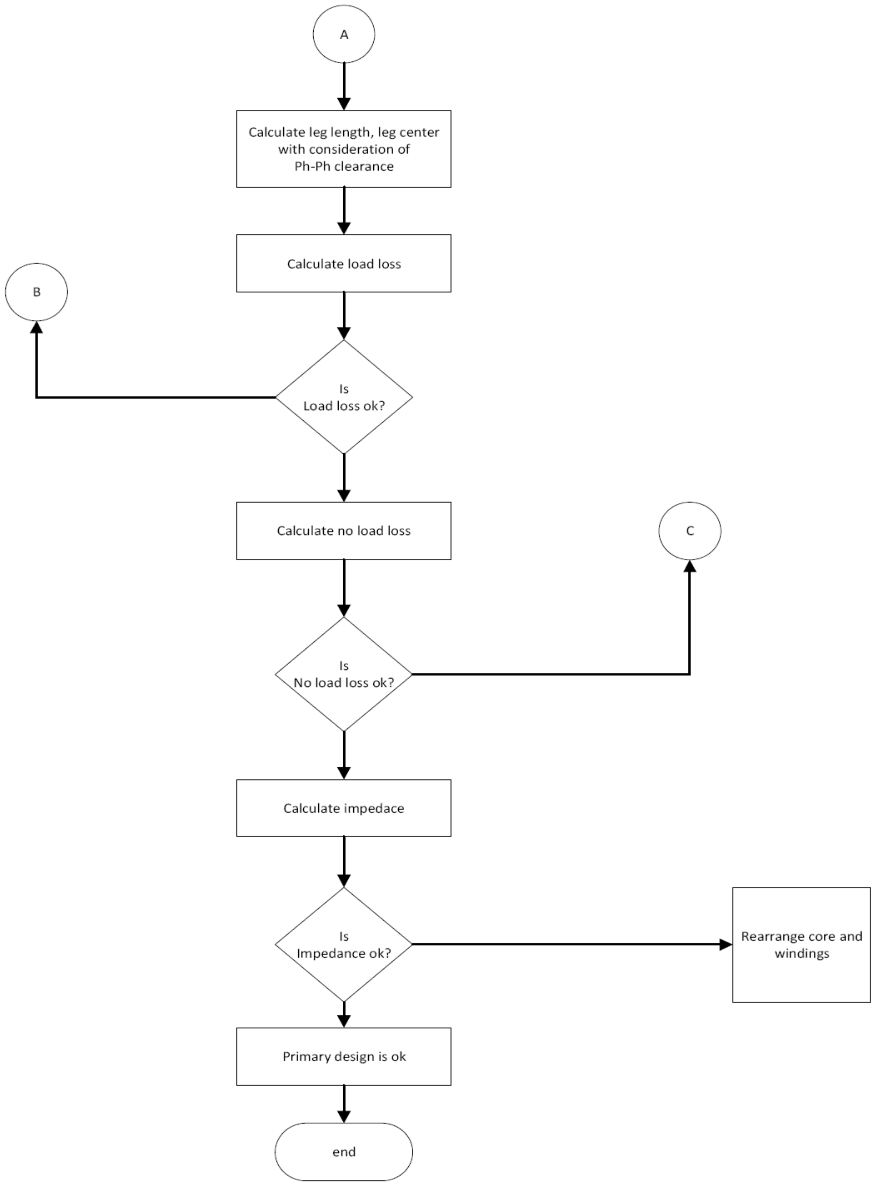

Figure 4.2: Flow chart of transformer design (part-2)

4.2 Theory of design

Theory of design Here in this chapter explanation about selection of every parameter based on requirement are given. Optimization is also very key factor in design. How and What should optimize is also explained at necessary places. Basic steps of design like selection of Volt per turn,selection of flux density,selection of current density, calculation of HV and LV current, calculation of copper area and core area, calculation of number of turns, optimization of core construction to achieve maximum utilization factor, explanation on selection of foil winding rather than conductor, selection of conductor for winding, core weight calculation,core loss calculation, copper loss calculation, impedance calculation are explored here.

4.2.1 Volts per turn and flux density

for a given supply frequency the relationship between volts per turn and total flux within the core remains constant. And since for a given core the cross-sectional area of the limb is a constant, this means that the relationship between volts per turn and flux density also remains constant at a given supply frequency. The number of turns in a particular winding will also remain constant. (Except where that winding is provided with tapping, a case which will be considered shortly.) The nominal voltage and frequency of the system to which the transformer is connected and the number of turns in the winding connected to that system thus determines the nominal flux density at which the transformer operates. The designer of the transformer will wish to ensure that the flux density is as high as possible consistent with avoiding saturation within the core. System frequency is normally controlled within close limits so that if the voltage of the system to which the transformer is connected also stays within close limits of the nominal voltage then the designer can allow the nominal flux density to approach much closer to saturation than if the applied voltage is expected to vary widely.

- Selection of flux density Value of flux density is kept near to knee point of magnetization curve,however adequate margin should kept to take care of system condition like over fluxing,frequency and voltage variation. As this is one type of converter duty transformer,some harmonics are introduced and so that flux density is kept to **1.5T** rather than 1.7T, to prevent transformer from overfluxing and saturation.
- Influence of varying flux density Keeping other parameter same,increase in the value of flux density in the core results in higher volts per turn.Hence number of turns in various winding are reduced.Effect of increase of flux density on reactance is similar to that of increase in core diameter.In order to meet the requirement of specific reactance ,coil depth is reduced and lateral dimensions of coil are increased .Inspite of small increase in core leg centers,reduced core height results in lower core steel weight. Increase flux density,with corresponding reduced core steel weight results in higher no-load loss of transformer .Also reduced number of turns in windings results in lower copper weight and load losses. Similarly,reduction in the value of flux density causes increased core steel weight , lower no load loss and increased copper weight and load loss.
- SELECTION OF VOLTS PER TURN

$$E = 4.44 * f * N * Bm * Acore. \tag{4.1}$$

where Acore is area of core

In above equation Flux density(Bm) and frequancy(f) is constant. Volts per turn value select mainly on bases of core area,frequency,flux density,core weight,core loss.

4.2.2 Calculation of HV and LV currents

Current calculation is done in vary simple by below mentioned formula because all ratings are given and only one should put values in equation. formula:

$$Current(I) = \frac{KVArating}{(\sqrt(3) * KVrating)} \tag{4.2}$$

4.2.3 Calculation of copper area

Current density and current rating are the two factor that necessary to find copper area. In most of cases current density is given and if not given than choose value based on given load losses. formula:

$$Acu = \frac{Irated}{j} \tag{4.3}$$

4.2.4 Calculation of core area

Necessary parameters required to calculate core area is volts per turn,frequency and flux density. Optimization of core design is very crucial part of design which is much difficult than to calculate core area. formula:

$$A(core) = \frac{Vt}{4.44 * f * Bm}10000 \tag{4.4}$$

4.2.5 Calculation of number of turns

By having values of volts per turn,flux density, Kv rating,core area ,it is easy to find no of turns.Formula required is as below. formula:

$$N = \frac{V(line)}{4.44 * f * Bm * Acore} \tag{4.5}$$

4.2.6 Core diameter

It is just a simple geometrical formula that we use to find a diameter of circle from the area of circle. formula:

$$D(core) = \sqrt{\frac{4 * Acore}{\pi}} 10^2 mm (4.6)$$

The ideal shape for the section of the cores is circle,since this would waste no space beyond that taken up by the insulation between laminations.A perfectly circular core section,however,involves making a variation in dimensions for each successive lamination,which is possible but uneconamical.As a compromise solution,the core section is made by laminations of varying widths and packets heights in such a way that the overall section approximates a circle.Such a typical core cross section is shown in fig. The net section area is calculated

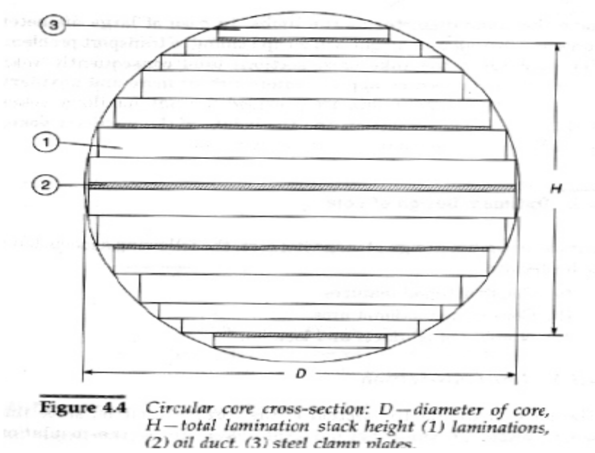

Figure 4.3: core cross section

from the dimensions of various packets and allowance is made for the space lost between lamination(known as stacking factor)which for sheet steel of 0.28mm thickness with carlite insulation coatings is approximately 0.96. By increasing number of core steps utilizing factor improves.This,however,increases manufacturing cost.Typical cost effective values for the number steps lie in the range of 6 to 15.For any particular core diameter based on other design considerations,this gives out not only the optimum area and thereby reduction in flux density and consequently iron loss,but also helps the designer to revert to lesser value of core diameter,whatever the computational margins allow this latitude.Seen from another angle,improvement in the core utilization factor increases core and hence the value of volts per turn for any particular core diameter and specific flux density.This,in turn,results in the reduction in winding turns and thus reduction in copper.Therefore,core area optimization results in better economy of transformer.

4.2.7 Optimization of core

For any particular core diameter,the first and foremost point to be decided is the maximum allowable height of the lamination packets. For a circle of diameter D,the length of cord at distance Y from the center is given by

$$F(Y) = 2\sqrt{\frac{D}{2}^2 - Y^2} \tag{4.7}$$

If H is the maximum allowable packet height,the minimum allowable lamination width is given by

$$Lmin = 2\sqrt{\frac{D}{2}^2 - \frac{H}{2}^2} \tag{4.8}$$

The maximum allowable width of central packet is usually core diameter less G mm

$$Lmax = D - G \tag{4.9}$$

4.2.8 Steps to optimize core construction

a. calculate diameter of core from area of core

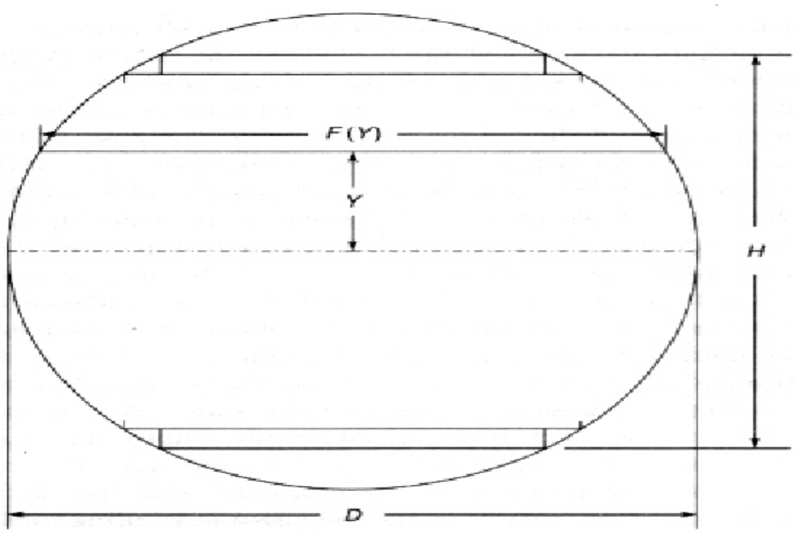

Figure 4.4: Circular cross section of core dimensional relationship

b. Take some random diameter D(optimized)

c. minimum core stack width should consider when adjusting core stack

d. Select number of steps of core stack

e. Core stacks should be arranged in 7*1,5*1 or any other pattern which mentioned by internal guide of industry.

f. Try to adjust steps in chosen core dia. and also obtain approximately near by value of core area

g. If above mentioned conditions come false iterate ones again

h. If above mentioned conditions come true calculate core weight(core weight calculations is discussed in below section)

i. Also calculate core losses from core weight(core loss calculations is discussed in below section)

j. core weight and core loss should match with costumers requirements.(check core weight first because if core weight is exceeding losses automatically exceeds.)

k. If any of above mentioned parameters violating their limits iterate once again.

4.2.9 LV Winding

- Foil winding An example for estimating eddy losses in LT for a 2000KVA 6600/433V Dyn11, 50Hz transformer with max guaranteed No-load loss 2.3kW , Load loss 20.7kW and 7.5% impedance indicates that GSP transformer has eddy losses less than 50Watts as compared to 450Watts in conventional transformer with layer winding and bunch of conductors.

- Selection of copper foil Width of copper foil should be less as it results in less quantity of copper which results in less load loss. It may also increase the lateral dimension of core but ideally width of window should be two-third of window height. and copper weight is also increase with it. Therefore, selection of copper foil should be done such a way that thickness should be kept as law as possible.

- Radial depth of LV winding Radial depth of LV winding is calculated by following equation,

$$Radialdepthoflvwdg = ((Th(foil) + Th(insu)) * totallvturns) * 2 \tag{4.10}$$

  Radial depth is necessary to find mean diameter.

- Mean diameter of lv wdg Necessities of mean diameter are to find length of conductor which is useful to find load loss and also to decide width od window.This is only find with simple geometrical formula depicted as below. formula,

$$Meandia.ofLVwdg = (Acore+(2*Cl(core-Lv))+(2*Radialdepthoflvwdg)) \tag{4.11}$$

4.2.10 Selection of conductor for winding

It is very well known fact that voltage is very high and current is very low compare to LV side at HV side.So,one can choose round conductor for HV winding as current passing through conductor is very less. Because of low current rating the diameter of conductor is also small.so,it is easy to wound a round copper wire for HV winding. First of all we have to calculate diameter of conductor from copper area of HV conductor formula,

$$Dcu(HV) = \sqrt{\frac{Acu(Hv) * 4}{\pi}} \tag{4.12}$$

where, Dcu(HV) is diameter of HV copper conductor

4.2.11 Arrangement of hv winding

Now we have HV turns,diameter of HV conductor and we have calculated height of leg(ch 5) from height of LV copper foil. so we can arrange turns of HV winding in different layers as cross over winding.

Number of turns in one winding is given by,

$$No.ofturninonelayer = \frac{legheight}{D(cond)} \tag{4.13}$$

Number of layers required is given by,

$$No.oflayers = \frac{totalno.ofturns}{no.ofturnsinonelayer} \tag{4.14}$$

4.2.12 Influence of parameters in hv winding construction

* Tapings can create changes in HV turns and height of winding as it needs extra turns to align HV voltage to grid voltage in case of deep

in voltage at LV side. This case we will see in next chapter of taping where existing HV turns in this chapter and height of winding that we have consider here will change due to influence of some parameters.

* Ampere turn balancing may also change arrangement of Hv winding. Ampere turn balancing is done to balance magmatic forces of winding. To balance magmatic forces of both winding, ampere turn per mm of both winding should be same. In short it is a procedure to equalize ampere turn of both windings.

4.2.13 Radial depth of hv winding

radial depth of HV winding is calculated as,

$$Radialdepthofhvwdg = ((D(cond) + Th(insu)) * No.oflayers) * 2 \tag{4.15}$$

4.2.14 Mean diameter of hv wdg

formula,

$$\begin{aligned} Meandia.ofHVwdg = A_core + (2 * Cl_(core - Lv)) + (2 * Radialdepthoflvwdg) \\ +(2 * (Cl_(Lv - shield) + Cl_(shield - Hv))) + (2 * Radialdepthofhvwdg) \end{aligned} \tag{4.17}$$

tc

4.2.15 Tapping

Transformers also provide the option of compensating for system regulation, as well as the regulation which they themselves introduce, by the use of tappings which may be varied either on-load, in the case of larger more important transformers, or off-circuit in the case of smaller distribution or auxiliary transformers. Consider, for example, a transformer used to step down the 132 kV grid system voltage to 33 kV. At times of light system load when the 132 kV system might be operating at 132 kV plus 10of 33 kV on the low-voltage side would require the high-voltage winding to have a tapping for plus 10132 kV system voltage has fallen to nominal it might be desirable to provide a voltage higher than 33 kV on the low-voltage side to allow for the regulation which will take place on the 33 kV system as well as the regulation internal to the transformer. In order to provide the facility to output a voltage of up to 10% above nominal with nominal voltage applied to the high-voltage winding and allow for up to 5would require that a tapping be provided on the high-voltage winding at about 13%. Thus the volts per turn within the transformer will be: 100/87 D 1.15 approx. so that the 33 kV system voltage will be boosted overall by the required 15It is important to recognise the difference between the two operations described above. In the former the transformer HV tapping has been varied to keep the volts per turn constant as the voltage applied to the transformer varies. In the latter the HV tapping has been varied to increase the volts per turn in order to boost the output voltage with nominal voltage applied to the transformer. In the former case the transformer is described as having HV tappings for HV voltage variation, in the latter it could be described as having HV tappings for LV voltage variation. The essential difference is that the former implies operation at constant flux density whereas the latter implies variable flux density. Except in very exceptional circumstances transformers are always designed as if they were intended for operation at constant flux density. In fixing this value of nominal flux density some allowance is made for the variations which may occur in practice. The magnitude of this allowance depends on the application.

4.2.16 Resistance calculation

Resistance is the property of material. Copper has very less resistance. Resistance is only responsible for copper loss in transformer. To know the total resistance offered by copper firstly we have to estimate quantity of copper required in transformer. We have all the necessary dimensions of active part from which we can estimate total resistance. list of parameters required in calculation are:

a. Height of hv winding in mm

b. height of lv winding in mm

c. radial depth of hv winding in mm

d. radial depth of lv winding in mm

e. mean diameter of hv winding in mm

f. mean diameter of lv winding in mm

g. resistivity of copper in $\omega * mm$

A very well known formula of resistance is used once again here.

$$R = \frac{\varrho * l}{A} \tag{4.18}$$

But we have to modify it corresponding to geometrical condition of core. As this is a circular core we have to use

$$R = \frac{\varrho * \pi * meandiameter * turns}{Acu} \tag{4.19}$$

4.2.17 Copper loss calculation

Maximum percentage of losses are owned by Copper loss in transformer.The classical formula of copper loss which is

$$Culoss = I^2 * Rwatts \tag{4.20}$$

List of Required parameters

a. LV resistance in ω

b. LV current in Amp

c. HV resistance in ω

d. HV current in Amp

4.2.18 Core loss calculation

Core loss is done due to internal property of core and leakage flux in transformer. Core material consume some losses and it define as watt per Kg losses.So,Core weight should be known. formula for core weight,

$$Wt(core) = corelength * density * Acore \tag{4.21}$$

where, length of core can find out by

$$corelength = 3 * A + 4 * (B + c) + 2 * Dcore \tag{4.22}$$

List of parameters

a. Leg length in cm

b. leg center in cm

c. max step in cm

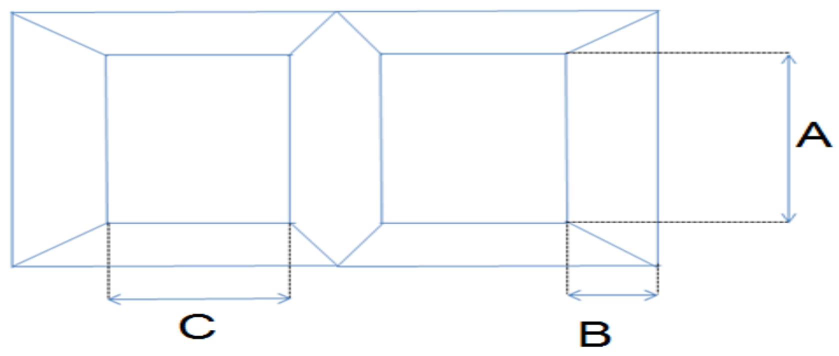

Figure 4.5: core dimension

d. area of core in cm^2

formula for core loss,

$$Coreloss = 1.1 * Wt(core) * wattsperkg \tag{4.23}$$

In this,watts per loss is mentioned by manufacturer of core material

4.2.19 Impedance

it was explained that the leakage reactance of a transformer arises from the fact that all the flux produced by one winding does not link the other winding. As would be expected, then, the magnitude of this leakage flux is a function of the geometry and construction of the transformer. Figure 10.1 shows a part section of a core-type transformer taken axially through the centre of the wound limb and cutting the primary and secondary windings. The principal dimensions are marked in the figure, as follows:

* l is axial length of windings (assumed the same for primary and secondary)
* a is the radial spacing between windings
* b the radial depth of the winding next to the core
* c the radial depth of the outer winding

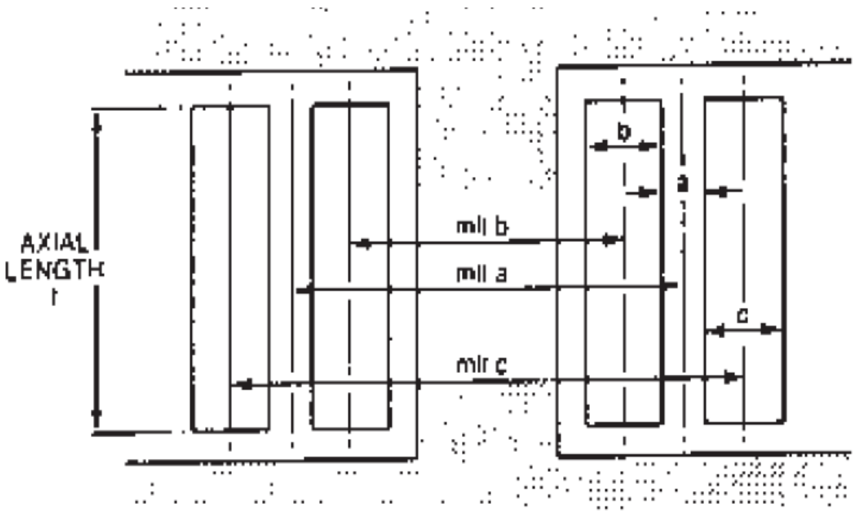

Figure 4.6: active part cross section

If mlt is then the mean length of turn of the winding indicated by the appropriate subscript, mltb for the inner winding, mltc for the outer winding and mlta for a hypothetical winding occupying the space between inner and outer windings, then the leakage reactance in per cent is given by the expression

$$\%X = 1.24 * f * 10^-5 * (\frac{Irated(Lv) * LVturns * Kr}{Electricalheight * Vt}) * \Sigma D \tag{4.24}$$

$$Kr = (\frac{Allraidaldepth + gap}{Elec.hight * \pi})$$

$\Sigma D = (1/3 * mltb) + (mlta) + (1/3 * mltc)(4.26)$

4.3 Calculation of parameters

4.3.1 Given parameters or Guaranteed technical parameters

* Type - Oil immersed (Hermetically sealed)
* Transformer Winding Type - Three
* Number of winding - 1HV + 2LV
* Number of phases - Three
* Normal continuous rating
  - HV winding - 1400 KVA
  - LV winding - 2*700 KVA
* Rated voltage
  - HV winding - 33KV
  - Lv winding - 0.315 - 0.315KV
* Rated current
  - HV current - 24.49 A
  - LV current - LV1-1283 A,LV2-1283 A
* Rated frequency - 50 Hz
* Connections
  - HV winding - star
  - Lv winding - LV1 delta,LV 2 delta
* Tappings
  - Taps provided on HV for HV variation? On HV for HV variation
  - Range +5
  - No. of steps nos 4 steps(5 positions)
  - Tap range

- Core and tank
  - Core type High grade non-aging cold rolled super grain oriented silicon steel laminate. Insulated level of 2kV for 1 minuit in air, winding and core shall be lifted through the lifting lug.
  - Core material CRGO STEEL M4
  - Core thickness mm 0.27 mm
  - Core weight kg 1500
  - watts /kg watts /kg 1.1
  - Working factor considered for calculation of no load current 1.1
  - Maximum flux density (at 110
  - Minimum flux density (at 90
  - Minimum flux density (at Rated Voltage) T 1.55 Max
  - Max. Internal pressure the tank is capable of withstanding PSI or KN/sqm(As per IEC) "Tanks with corrugations and without conservator shall be tested for leakage test at a pressure of 0.15kg/cm2 measured at the top of the tank."
  - Maximum flux density (at 110% Rated Voltage) T 1.705
  - Minimum flux density (at 90% Rated Voltage) T 1.395
  - Minimum flux density (at Rated Voltage) T 1.55 Max
- Winding Detail HV LV
  - Material Copper/Aluminium Copper (High grade electrolytic) Copper (High grade electrolytic)
  - Type of winding: Crossover/spiral
  - Max current density A/mm2 3.0 (at extream tap) 3.0 (at extream tap)
- Impedance voltage at rated current and frequency at 75 deg. C winding temperature

· Positive sequence impedance at rated current for the principal tapping HV-LV Nominal 6% (min.absolute 4% max.absolutr 6.6

4.3.2 Calculation

According to flow chart of design first of all selection of Vt,Bm and j should be made. Selection of this values are on the bases of trial and error method and here mentioned only a values of successful iteration.

* current density,j = 3 A/mm^2
* Flux density,Bm =1.5458 T(nominal) and 1.55T(max)
* Volt per turn = 20.20758

According to flow metioned in flow chart and equationary illustrated in Theory of design, different parameters of active part design of transformer are calculated here and mention in tabular format.

Calculation result of HV LV winding

Table 4.1: Calculation result of HV LV winding

Sr.no	subject	value	unit
1	Hv turn	1633	
2	Lv turn	9	
3	Hv current	7.0707	Amp
4	Lv current	1283.001	Amp
5	Acu(Lv)	427.66	mm^2
6	Acu(Hv)	2.35	mm^2
7	Lv foil dimension(Ht*T)	260*1.6	mm
8	Hv conductor diameter(bare)	1.73	mm

Ampere turn balancing

Ampere turn balancing is necessary to nullify magnetic forces of winding. For this ampere turn per mm should be same of both winding. Here, Lv winding hight is kept constant and calculate ampere turn per mm of Lv winding and it is 44.41 AT/mm Now, take 44.41 AT/mm for Hv winding and calculate hight of Hv winding and By it comes 259.99mm. So we can take 260mm.

Dimensions of winding

Table 4.2: Dimensions of winding

Sr.no	subject	value	unit
1	No. of layers(Hv wdg)	13	
2	No. of turns in one layer(Hv wdg)	122	
3	Hight of Hv wdg	260	mm
4	hight of Lv wdg	260	mm
5	clearance between two Hv wdg	40	mm
6	clearance between two Lv wdg	40	mm
7	Total ele. hight	570	mm
8	clearance from yoke(top and bottom)	10	mm

The visualization of arrangement of winding will be very clear by this durational figure.

Calculation results of core and core arrangement

According to theory of optimization of core design appropriate arrangement of core is presented here as tabular format and physical parameters of core is also mentioned in following tables.Find Ref figures in appendix.

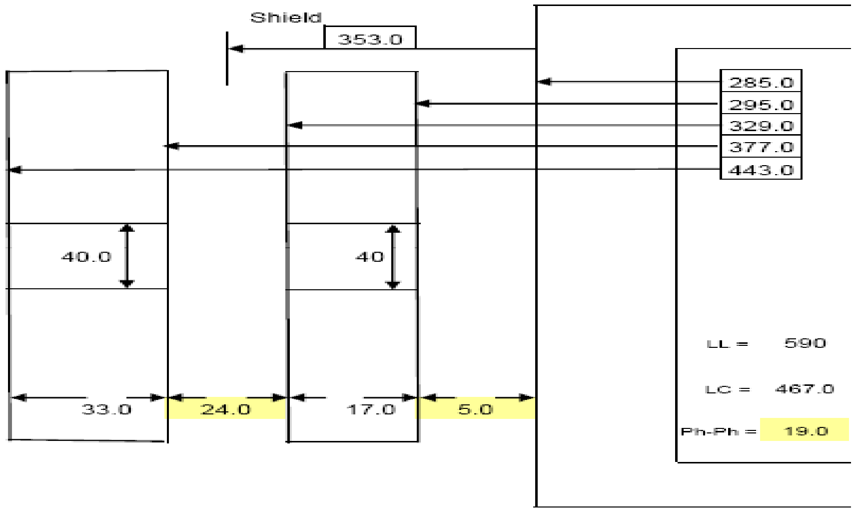

Figure 4.7: Layout Plan

Table 4.3: Calculation results of core and core arrangement

Sr.no	subject	value	unit
1	core area	588.862	cm^2
2	core diameter	285	mm
3	leg length	590	mm
4	leg center	467	mm
5	max. step	285	mm

The parameters of windings that may affected due to core design are mentioned in following table. It also contain Losses and %impedance of this design.

Compressional study of spiral winding vs Foil winding

This comparison justify the use of foil winding over spiral winding.

Table 4.4: Table of Ref fig. 1

item no.	A	B	weight in kg	No. of lamination	T
1	1130	280	181.2	(95 + 95)*2	(25.7 +25.7)*2
2	1110	270	127.2	(70 + 70)*2	(18.9 +18.9)*2
3	1090	260	86.5	(50 + 50)*2	(13.5 + 13.5)*2
4	1070	250	57.5	(35 + 35)*2	(9.5 + 9.5)*2
5	1030	230	88.5	(60 + 60*)2	(16.2 + 16.5)*2
6	990	210	59.1	(45 + 45)*2	(12.2 + 12.2)*2
7	950	190	40.5	(35 +35)*2	(9.5 +9.5)*2
8	910	170	30.3	(30 + 30)*2	(8.1 + 8.1)*2
9	870	150	21.6	(25 + 25)*2	(6.8 + 6.8)*2
10	810	120	19.9	(30 + 30)*2	(8.1 + 8.1)*2
11	750	90	11.9	(25 + 25)*2	(6.8 + 6.8)*2

Table 4.5: Table of ref fig 2.

item no.	A	B	weight in kg	No. of lamination	T
1	850	280	75.7	(95 + 95)	(25.7 +25.7)
2	840	270	53.4	(70 + 70)	(18.9 +18.9)
3	830	260	36.5	(50 + 50)	(13.5 + 13.5)
4	820	250	24.4	(35 + 35)	(9.5 + 9.5)
5	800	230	37.9	(60 + 60)	(16.2 + 16.5)
6	780	210	25.6	(45 + 45)	(12.2 + 12.2)
7	760	190	17.7	(35 +35)	(9.5 +9.5)
8	740	170	13.4	(30 + 30)	(8.1 + 8.1)
9	720	150	9.7	(25 + 25)	(6.8 + 6.8)
10	690	120	9.1	(30 + 30)	(8.1 + 8.1)
11	660	90	4 5.5	(25 + 25)	(6.8 + 6.8)

Table 4.6: Table of ref fig 3.

item no.	A	B	weight in kg	No. of lamination	T
1	1214	280	184.2	(95 + 95)*2	(25.7 +25.7)*2
2	1204	270	131.2	(70 + 70)*2	(18.9 +18.9)*2
3	1194	260	90.5	(50 + 50)*2	(13.5 + 13.5)*2
4	1184	250	61.1	(35 + 35)*2	(9.5 + 9.5)*2
5	1164	230	96.9	(60 + 60*)2	(16.2 + 16.5)*2
6	1144	210	66.8	(45 + 45)*2	(12.2 + 12.2)*2
7	1124	190	47.3	(35 +35)*2	(9.5 +9.5)*2
8	1104	170	36.4	(30 + 30)*2	(8.1 + 8.1)*2
9	1084	150	26.9	(25 + 25)*2	(6.8 + 6.8)*2
10	1054	120	26.1	(30 + 30)*2	(8.1 + 8.1)*2
11	1024	90	16.4	(25 + 25)*2	(6.8 + 6.8)*2

Table 4.7: calculation results of losses and impedance

Sr.no	subject	value	unit
1	Radial depth of Lv	17.1	mm
2	mean dia. of Lv	312	mm
3	$R_L v$	0.00043317	
4	$I^2 R_L vloss$	4.278	Kw
5	Radial depth of Hv wdg	32.89	mm
6	Mean dia. of Hv Wdg	409.84	mm
7	$R_H v$	18.788	
8	$I^2 R_H vloss$	5.635	Kw
9	Total $I^2 Rloss$	9.913	Kw
10	No load loss	1.59	Kw
11	% impedance	5.9	

Table 4.8: Spiral winding Vs. Foil winding

	Spiral winding	**Foil winding**	unit
Winding hight	288	260	mm
Leg length	635	590	mm
total weight of core	2028.1	1816.8	Kg
Core loss	1.90	1.59	Kw
Copper loss	12.55	9.915	Kw

Chapter 5

Simulation results

Transformer design theory explained in very disciplinary manner in chapter 4. It also contains calculation results based on theory. 3D model of active part of SAT is developed in AUTODESK INVENTOR and physical parameters are taken from calculation results in chapter 4. This geometry is imported to ANSOFT MAXWELL,a FEM analysis based simulation tool,for analysis purpose.Analysis results of this geometry for different conditions and parameters are presented here.

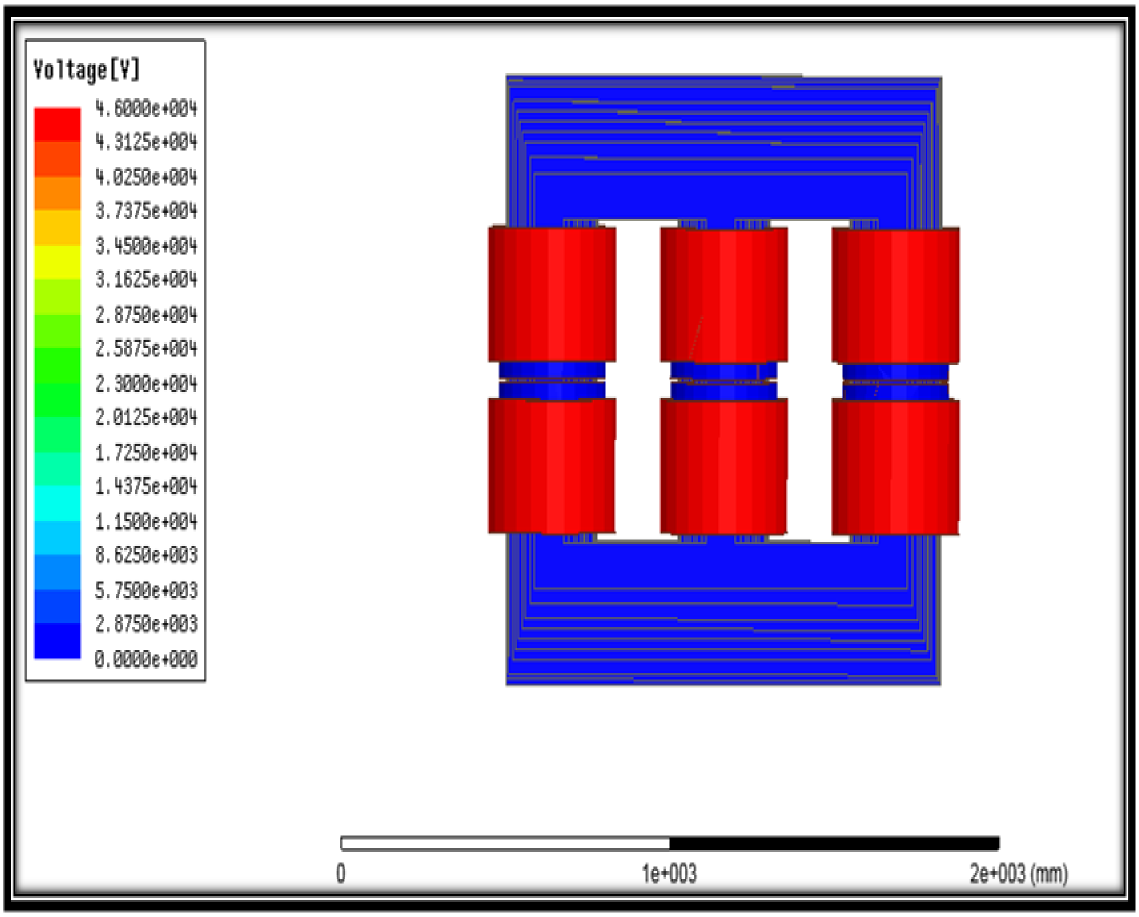

Figure 5.1: Plot of Rated voltages

HV is rated with 33 Kv . This simulation results Hv winding plot energized with 33 Kv and because of this result it conforms that in normal rated condition model analysis gives required results

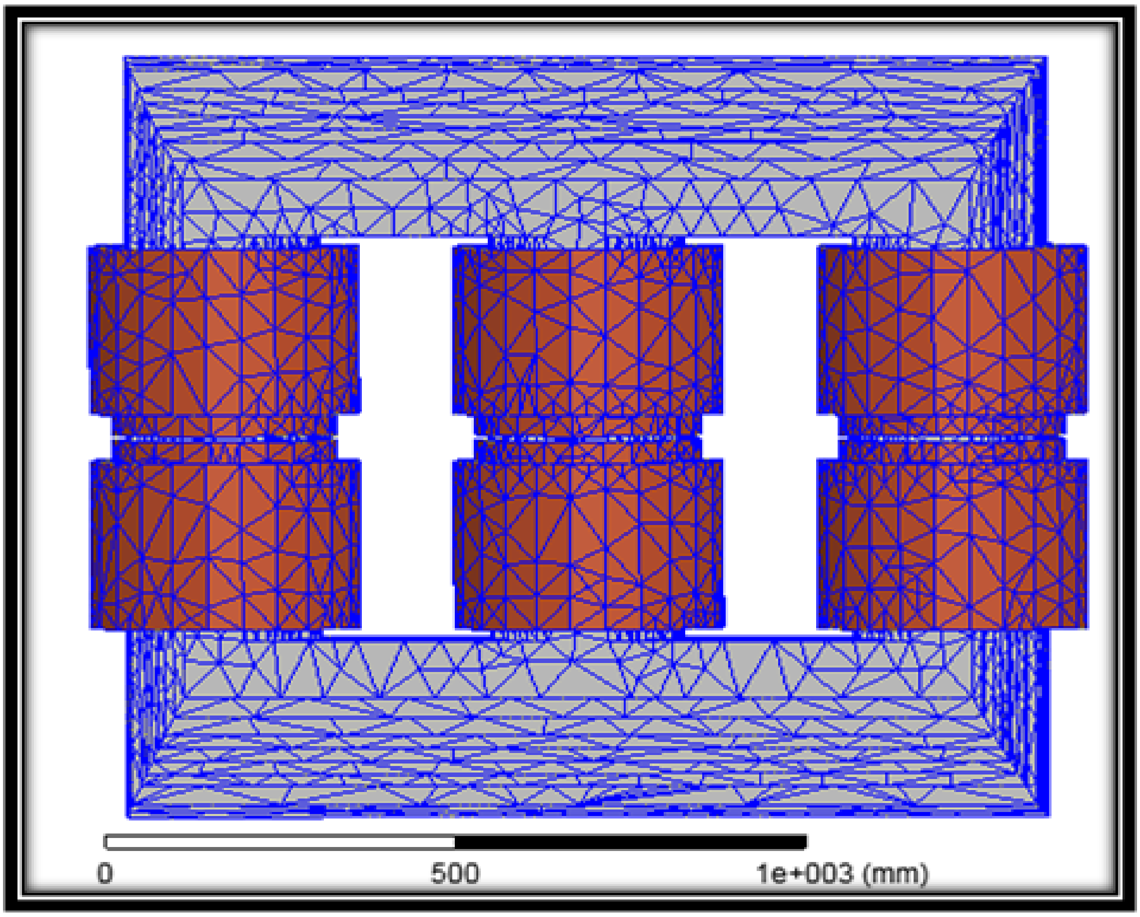

Figure 5.2: Meshing of model

This plot gives the idea about meshing of geometry. meshing plays important role in analysis. and from above plot result it is clear that meshing is good.

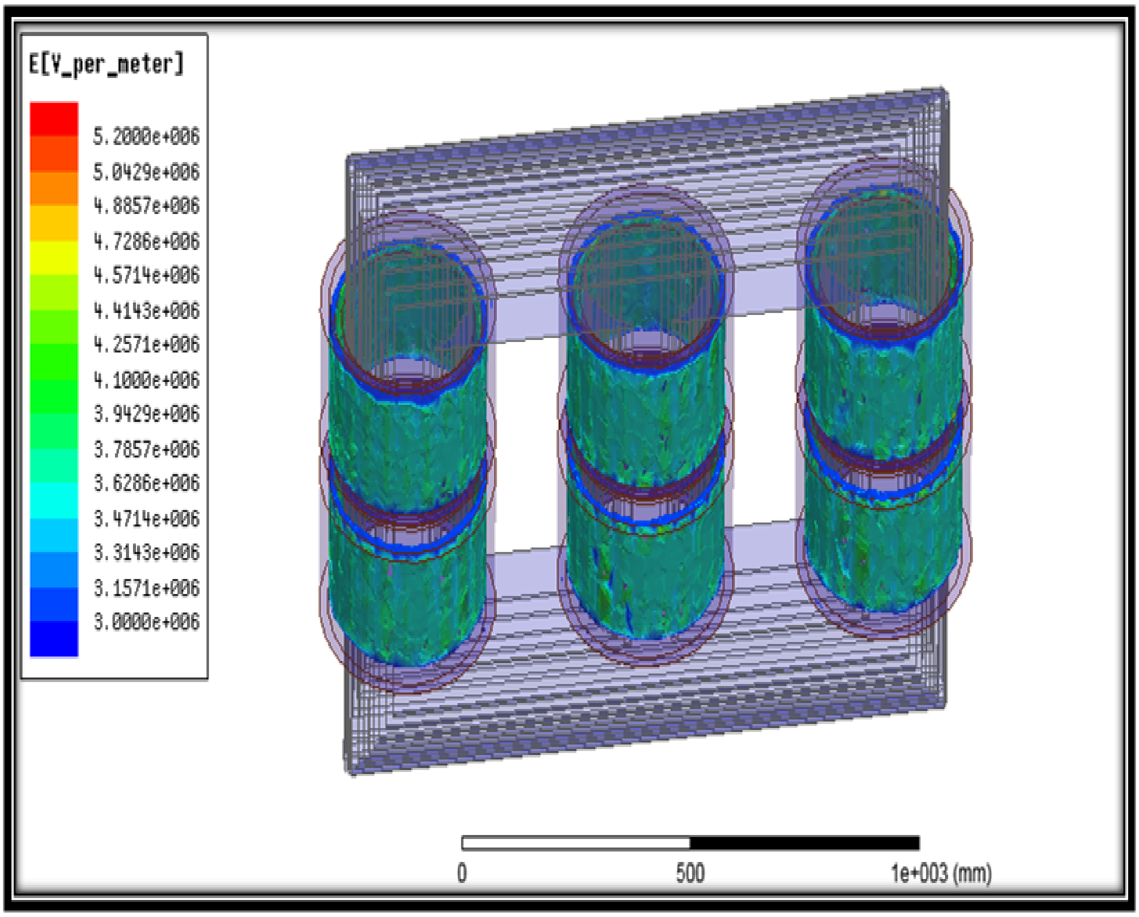

Figure 5.3: Voltage stress plot between two winding at peek voltage

In this plot Hv and LV both rated to its peak value.From the results it can be clarify that the voltage distribution between two windings is very much symmetrical i.e. the voltage stress is very evenly distributed between winding and any point between wind does not reach up to red zone and this conclude that in this arrangement chances of failure due to voltage stress at peak voltage condition is very rare.It validates design for peak voltage itself.

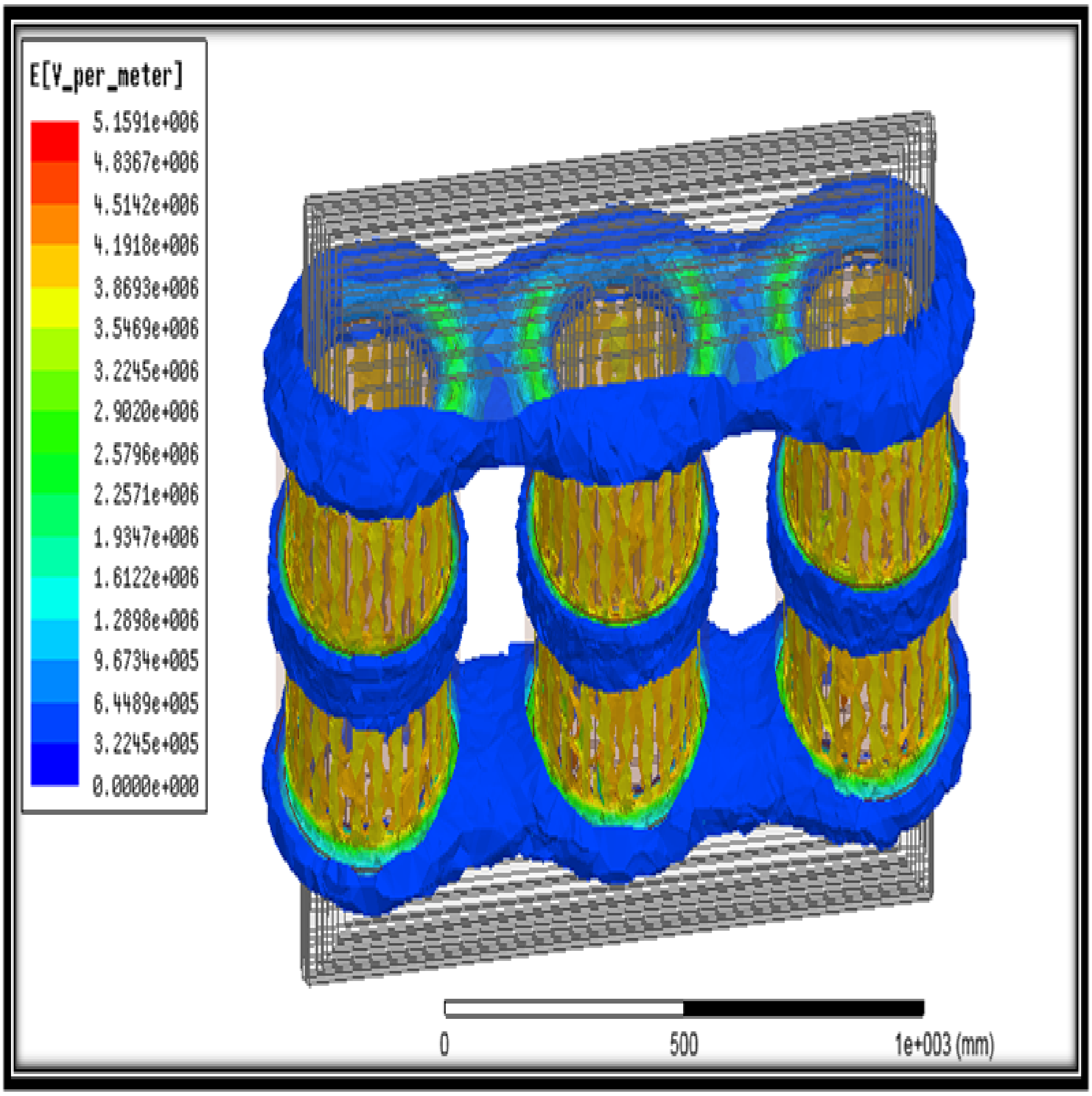

Figure 5.4: Voltage stress plot on surface of two winding at peek voltage

It is a plot of voltage distribution on each winding which are rated to their peak voltages. The symmetrical and even distribution is seen from this plot.

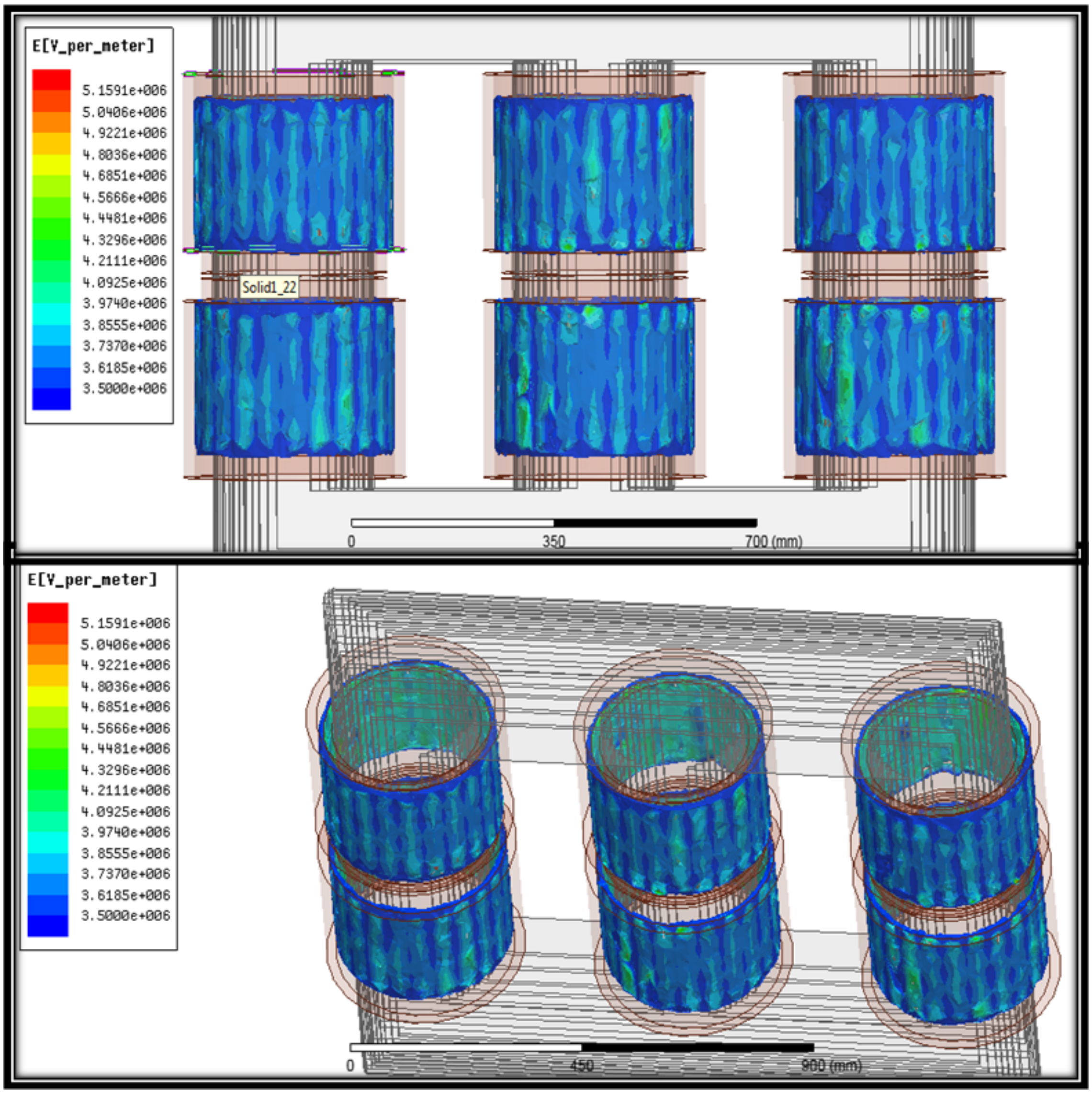

Figure 5.5: Layout Section Elevation

This plot both windings are energized to their rated voltages and a very identical distribution of voltage can shown from plot and voltage stress is less compared to simulation at peak voltage. Voltage stress at peak voltage is more than rated voltages,and similar results can find here.

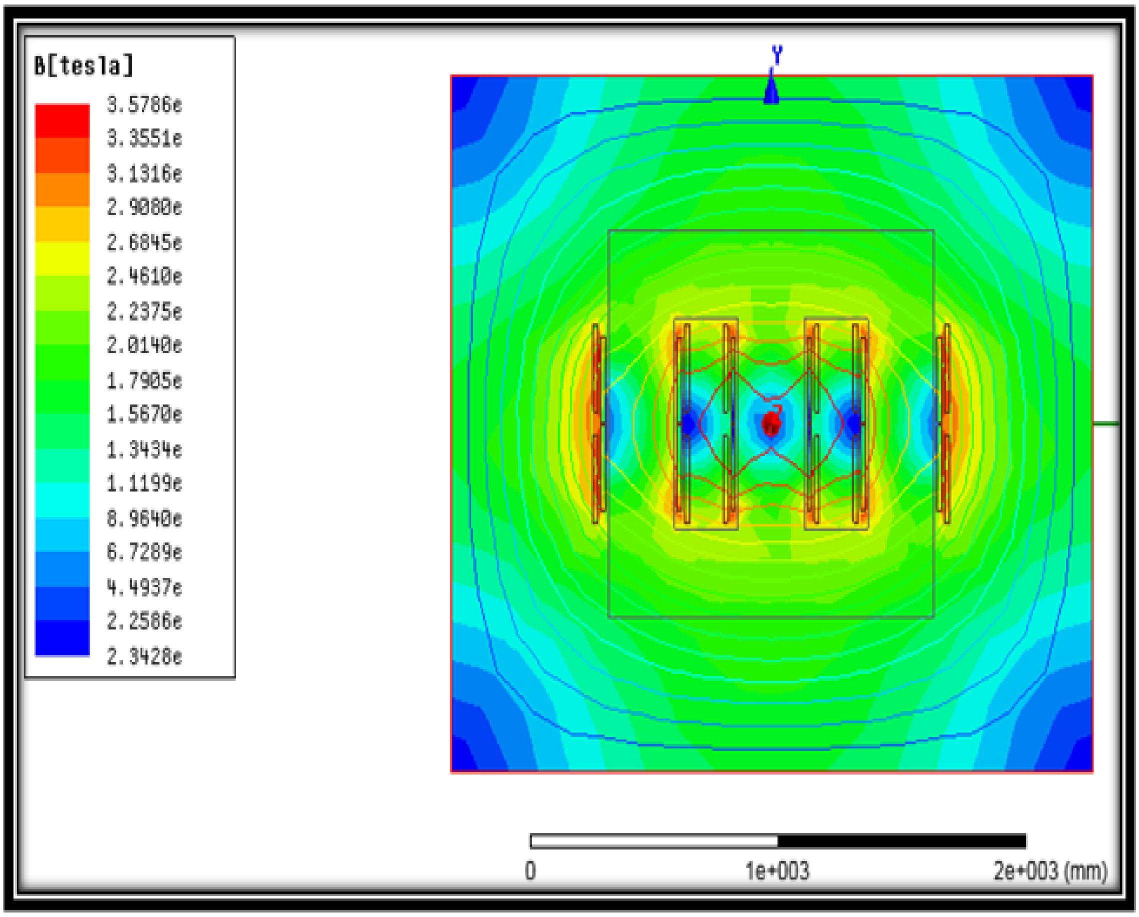

Figure 5.6: Flux density plot

Flux density plot for rated voltages are presented here. In design,value of flux density is taken 1.5458T and in this plot the Flux density in core area is between 1.5T to 1.65T.

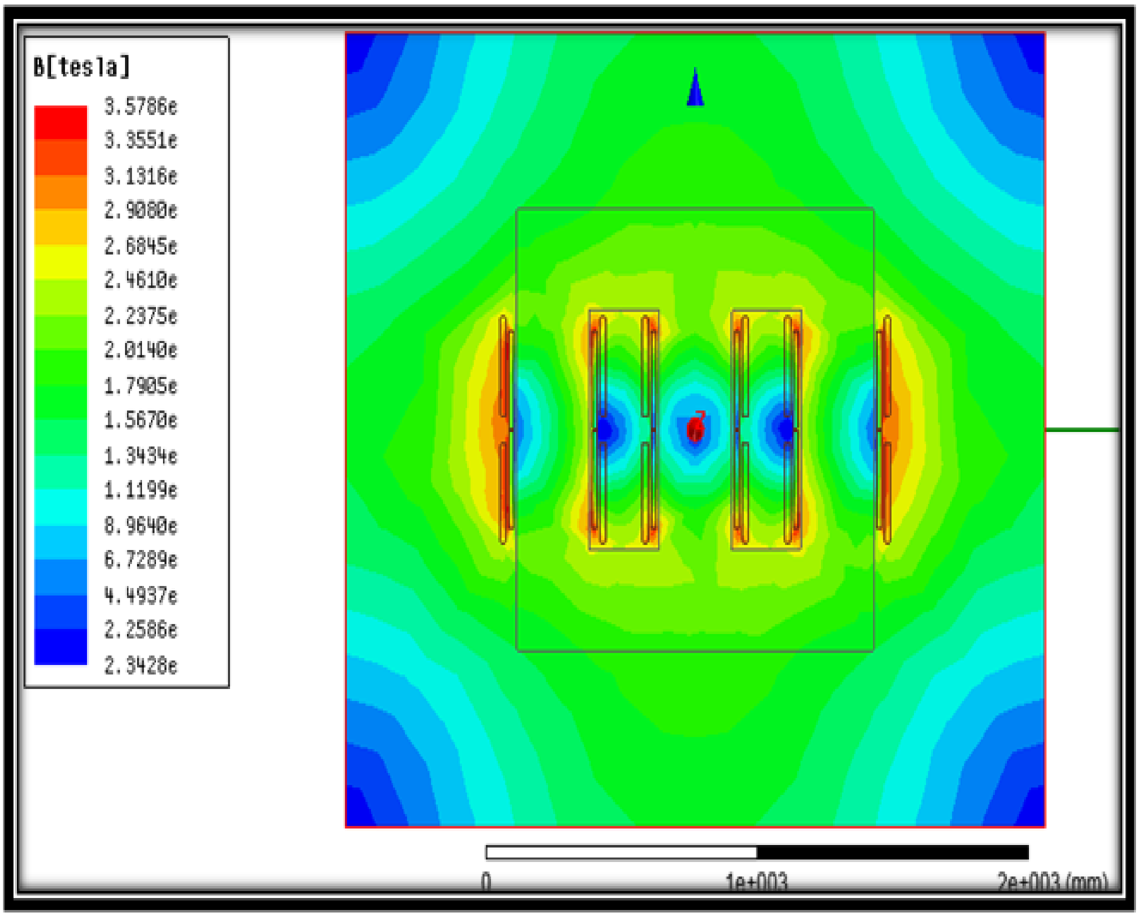

Figure 5.7: Magnetic field lines

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

Design of transformer is differ as per its application.This project appropriate change in is done design of its active part due to special requirements.flow chart development of design procedure is developed and detail design which includes required parameters calculation according to flow chart is done.

The application of Foil winding theocratically seems beneficial from references and calculated results of this design gives reduced losses than previous design with traditional winding.

In the last phase of this project simulation results of created 3D model,based on design of active part of transformer,under different conditions and for different plots are presented which itself validate the design of transformer.

6.2 Future Scope

* Design of HV winding may change with pan cake winding technique for better results.

* Effect of force constrains may analyze and compare for all changes in design.
* Effect of electrostatic shield at different positions between two winding can analyze.

References

[1] Martine J. Heathcote,CEng, FIEE, The J P Transformer

[2] The late L F Blume,A.boyajiyan,C.Camilli,T.C.Lennox,S.Minneci,V M Montsinger, The Blume Transformer Engineering

[3] S.V.Kulkarni,S.A.Khaparde, Transformer Engineering Design and Practices

[4] Zoheb Akhtar, Hari N Varrier,K.Bheema prakash, Devlopment of efficient and compact GSP Transformer

[5] Transformer book,BHEL Transformer

[6] G.N.Mathur,R.S.Chadha, CBIP manual on transformer, by central board of irrigation and power

[7] Indian Standard 2026 (Part 5),Ability to withstand short circuit current

Appendix A

Transformer Design Calculation

Data required for design are:-

* Type - Oil immersed (Hermetically sealed)
* Transformer Winding Type - Three
* Number of winding - 1HV + 2LV
* Number of phases - Three
* Normal continuous rating
  - HV winding - 1400 KVA
  - LV winding - 2*700 KVA
* Rated voltage
  - HV winding - 33KV
  - Lv winding - 0.315 - 0.315KV
* Rated current
  - HV current - 24.49 A
  - LV current - LV1-1283 A,LV2-1283 A
* Rated frequency - 50 Hz
* Connections
  - HV winding - star
  - Lv winding - LV1 delta,LV 2 delta
* Tappings
  - Taps provided on HV for HV variation? On HV for HV variation
  - Range +5
  - No. of steps nos 4 steps(5 positions)
  - Tap range
* Core and tank

- · Core type High grade non-aging cold rolled super grain oriented silicon steel laminate. Insulated level of 2kV for 1 minuit in air, winding and core shall be lifted through the lifting lug.
- · Core material CRGO STEEL M4
- · Core thickness mm 0.27 mm
- · Core weight kg 1500
- · watts /kg watts /kg 1.1
- · Working factor considered for calculation of no load current 1.1
- · Maximum flux density (at 110
- · Minimum flux density (at 90
- · Minimum flux density (at Rated Voltage) T 1.55 Max
- · Max. Internal pressure the tank is capable of withstanding PSI or KN/sqm(As per IEC) "Tanks with corrugations and without conservator shall be tested for leakage test at a pressure of 0.15kg/cm2 measured at the top of the tank."
- · Maximum flux density (at 110% Rated Voltage) T 1.705
- · Minimum flux density (at 90% Rated Voltage) T 1.395
- · Minimum flux density (at Rated Voltage) T 1.55 Max

∗ Winding Detail HV LV

- · Material Copper/Aluminium Copper (High grade electrolytic) Copper (High grade electrolytic)
- · Type of winding: Crossover/spiral
- · Max current density A/mm2 3.0 (at extream tap) 3.0 (at extream tap)

∗ Impedance voltage at rated current and frequency at 75 deg. C winding temperature

- · Positive sequence impedance at rated current for the principal tapping HV-LV Nominal 6% (min.absolute 4% max.absolutr 6.6

∗ $V_t = 20.20758 Bm = 1.5458T$

∗ $j = 3\ A/mm^2$

Calculation For Winding

Step 1:- Calculate number of turn of HV and LV winding

$$N = \frac{E}{4.44 * f * Bm * Acore} \tag{A.1}$$

$$N_H v = \frac{33}{4.44 * 50 * 1.5458 * 588.862} 10^7 \tag{A.2}$$

$N_H v = 1633$

$N_Lv = 0.3154.44 * 50 * 1.5458 * 588.86210^7$(A.3)

$\mathrm{N}_Lv = 9$

step2 : $-$**Calculatecurrents**

$$I_Hv = \frac{700}{3 * 33} \tag{A.4}$$

$\mathrm{I}_Hv = 7.0707A$

$$I_Lv = \frac{700}{\sqrt{3} * 0.315} \tag{A.5}$$

$\mathrm{I}_Lv = 1283.001A$

Step 3:- Copper area of winding

$$A_Lv = \frac{1283.001}{3} \tag{A.6}$$

$\mathrm{A}_Lv = 427.66mm^2$

$$A_Hv = \frac{7.0707}{3} \tag{A.7}$$

$\mathrm{A}_Hv = 2.35mm^2$

Step 4:- Dimension of winding

* $\mathrm{Ht}_Lv = 260mmTh_foil = 1.6mm$

Hv cond. dia=1.733 mm(bare) 2.13(covered)

Step 5:-Turns arrangement of Hv winding

$$No.ofturnsinonelayer = \frac{260}{2.13} \tag{A.8}$$

No. of turn in one layer= 122

$$No.oflayers = \frac{1633}{122} \tag{A.9}$$

No. of layers= 13

Step 6:- Physical dimensions of winding

$$Radialdepth_Lv = 1.64 + 0.25 * 9 \tag{A.10}$$

Radial depth$_L v = 170.01mm$

$$Radialdepth_Hv = 2.13 + 0.4 * 13 \tag{A.11}$$

Radial depth$_H v = 32.89mm$

$$meandia_lv = 285 + 2 * 5 + 17 \tag{A.12}$$

Mean dia$_L v = 312mm$

$$Meandia_Hv = 285 + (2 * 5) + (2 * 17) + (2 * 24) + 32.89 \tag{A.13}$$

Mean dia$_H V = 409.84mm$

$$lengthofcopperfoil_Lv = \{pi * 312 * 9 \tag{A.14}$$

Length of copper foil$_H v = 8821.59mm$

$$lengthofcopperconductor_Hv = \{pi * *409.84 * 1633 \tag{A.15}$$

length of copper conductor$_{H}v = 2,102,569.69mm$

Step 7:- calculate copper loss

$$R_{L}v = \frac{0.021 * 8821.5}{427.66} \tag{A.16}$$

$R_{l}v = 0.00043317\Omega$

$$R_{H}v = \frac{0.021 * 21,02,569}{2.35} \tag{A.17}$$

$R_{H}v = 18.788\Omega$

$I^2R_{L}v = 3 * 2 * (1283.001 * 1283.001 * 0.00043317)$

= 4.278 Kw

$I^2R_{H}v = 3 * 2 * (7.0707 * 7.0707 * 18.788)$

= 5.635 Kw

Step 8:- core loss calculation

$$Coreloss = 1.1 * Wt(core) * wattsperkg \tag{A.18}$$

core loss= 1.1* 1816.8 *0.8

= 1.598 Kw

Step 9:- Impedance

$$\%X = 1.24 * f * 10^{-}5 * (\frac{Irated(Lv) * LVturns * Kr}{Electricalheight * Vt}) * \Sigma D \tag{A.19}$$

where$\Sigma D = 1/3(mltb) + mlta + 1/3(mltc)$

=60.03 cm

$$K_r = 1 - \frac{(3.2 + 1.7 + 4.8)}{2.60 * \{pi} \tag{A.20}$$

$K_r = 0.8212$

put values in eq. of %X ,result will be

%X= 5.9%

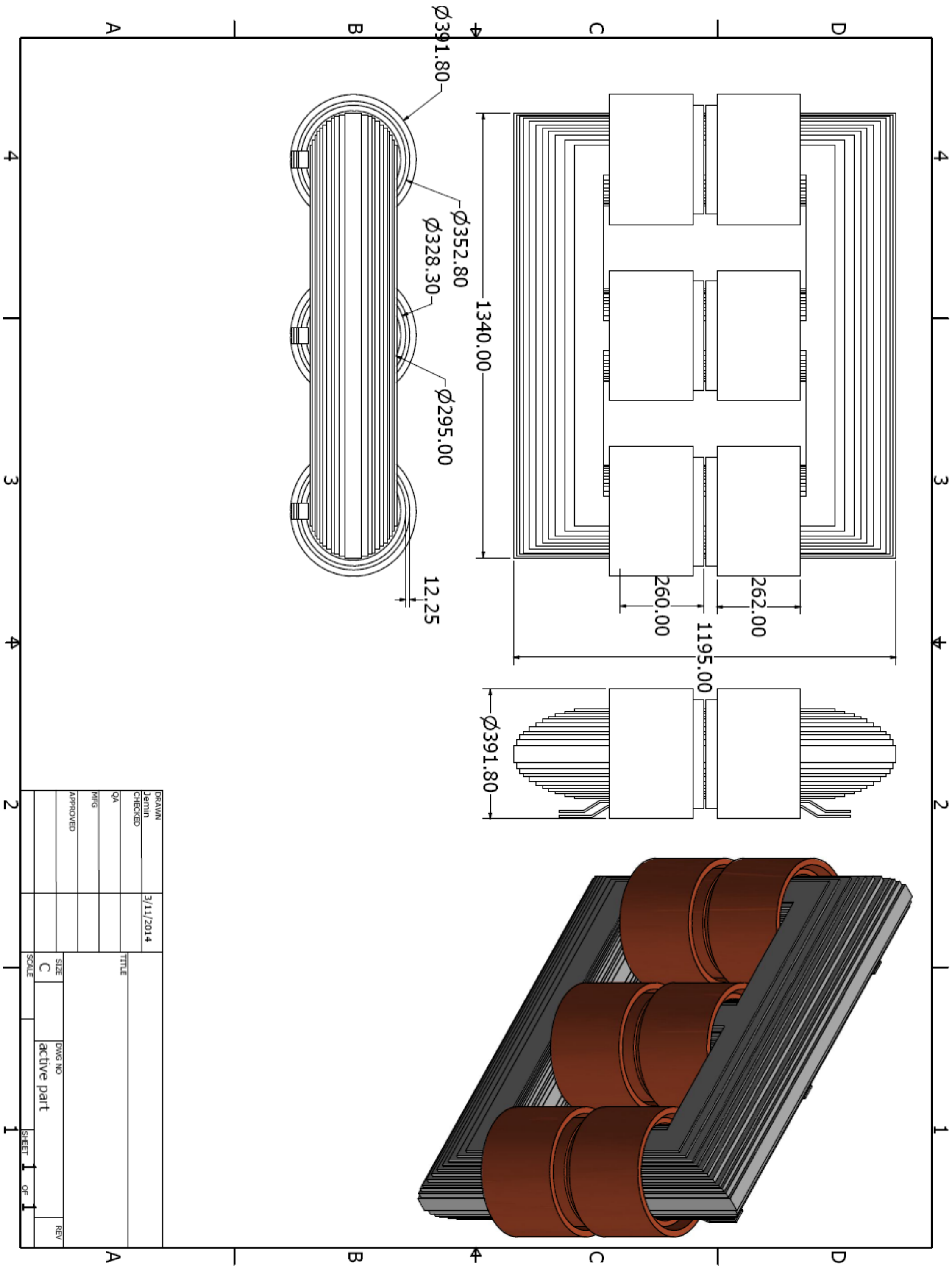

Figure A.1: Active part

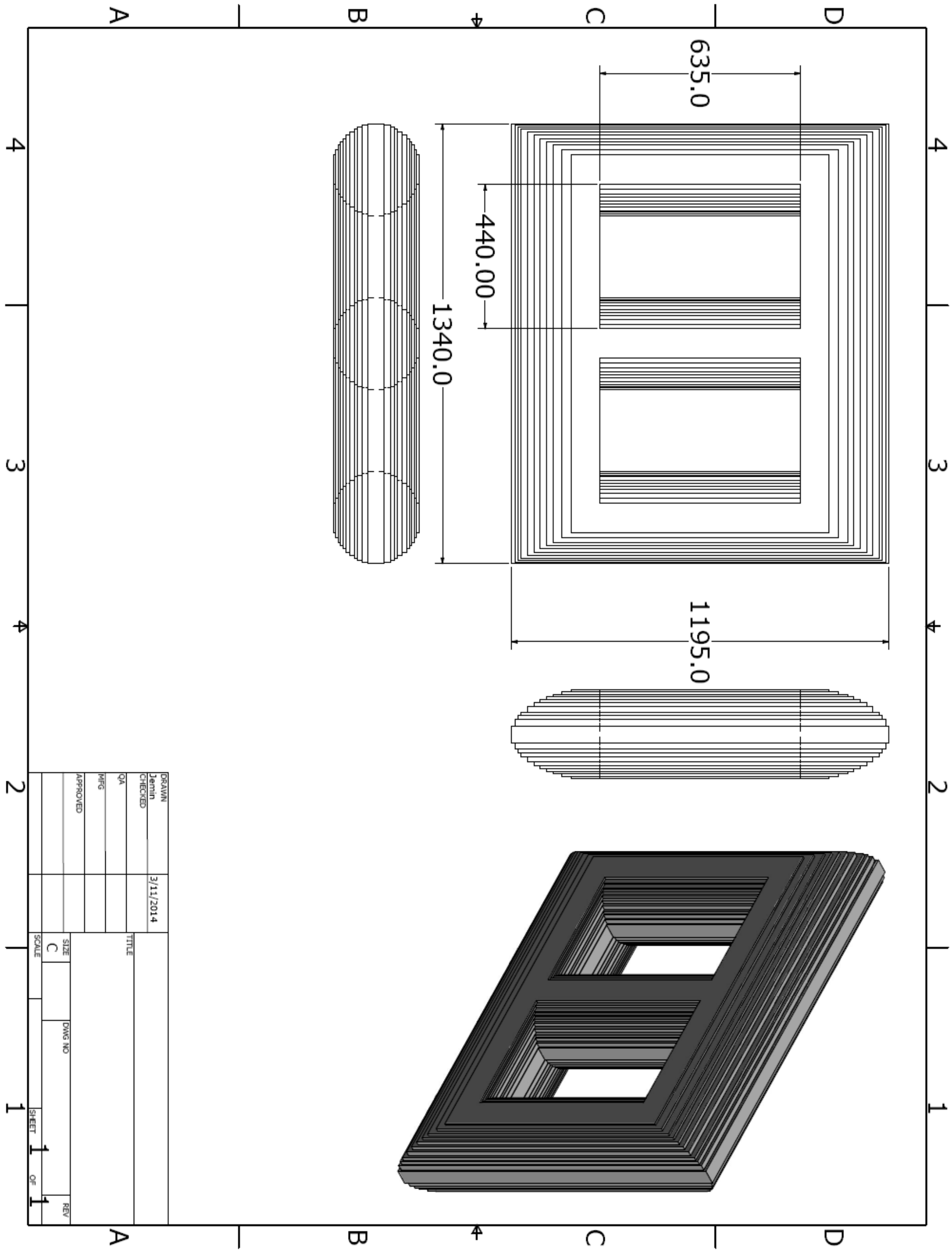

Figure A.2: Magnetic core

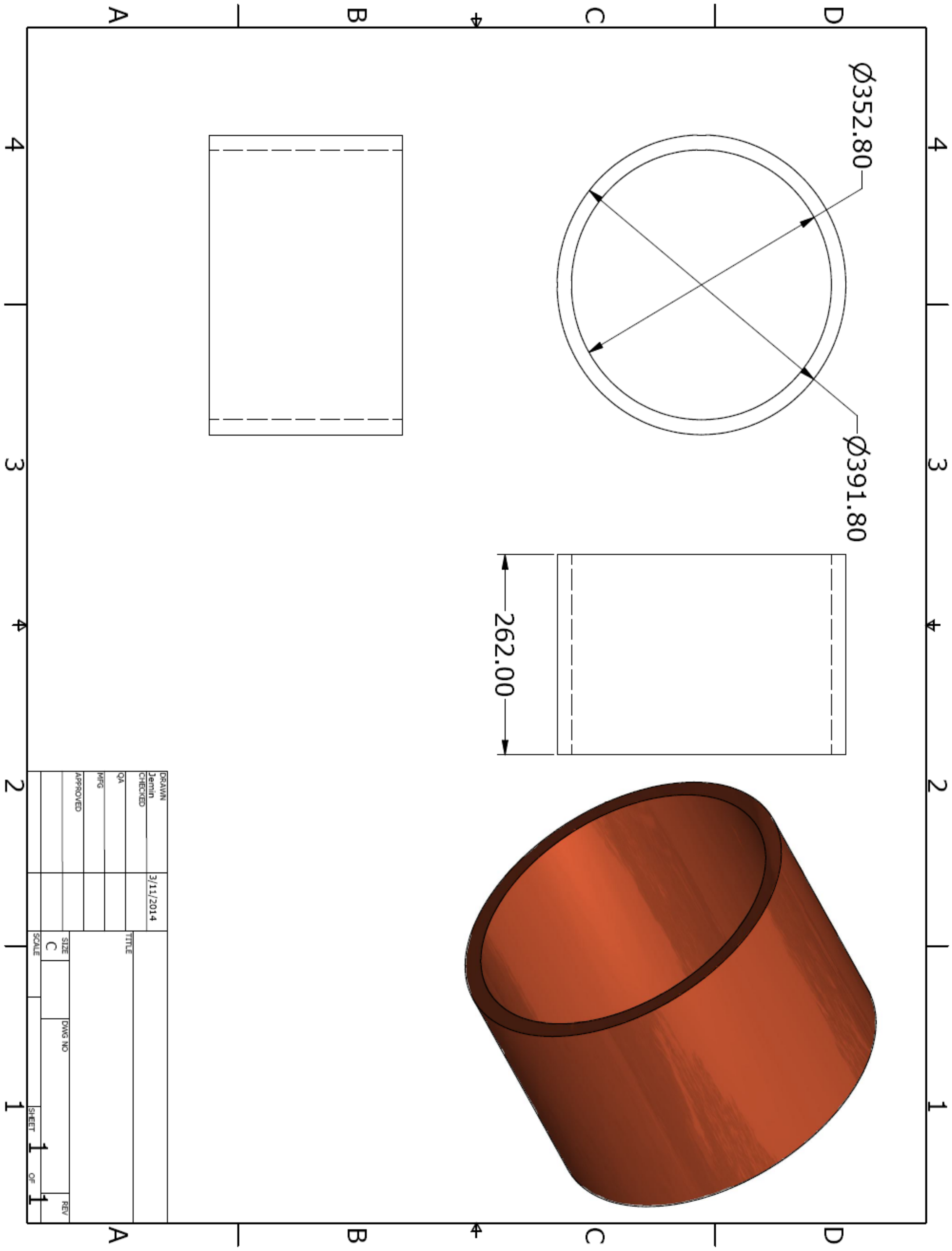

Figure A.3: Hv winding

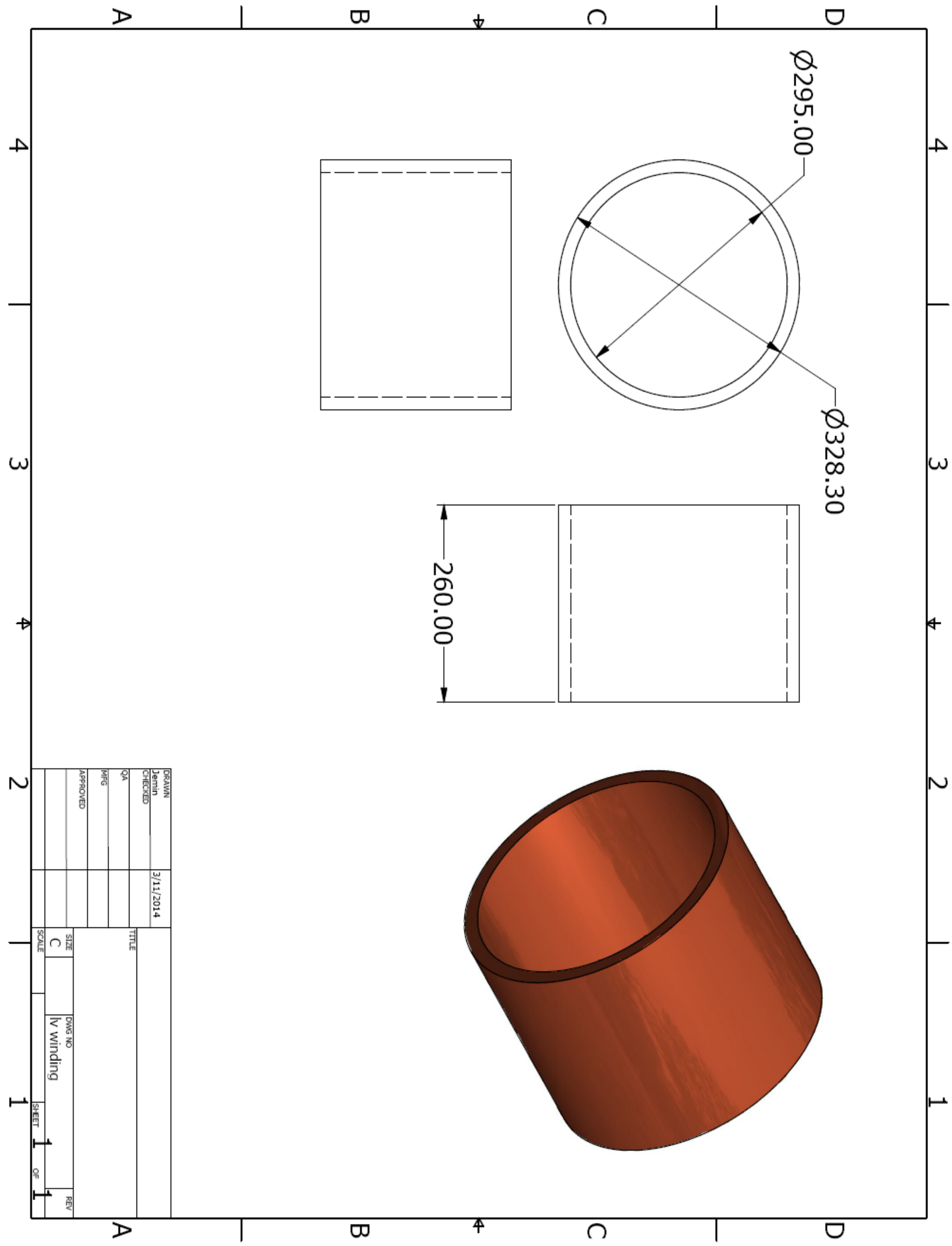

Figure A.4: Lv winding

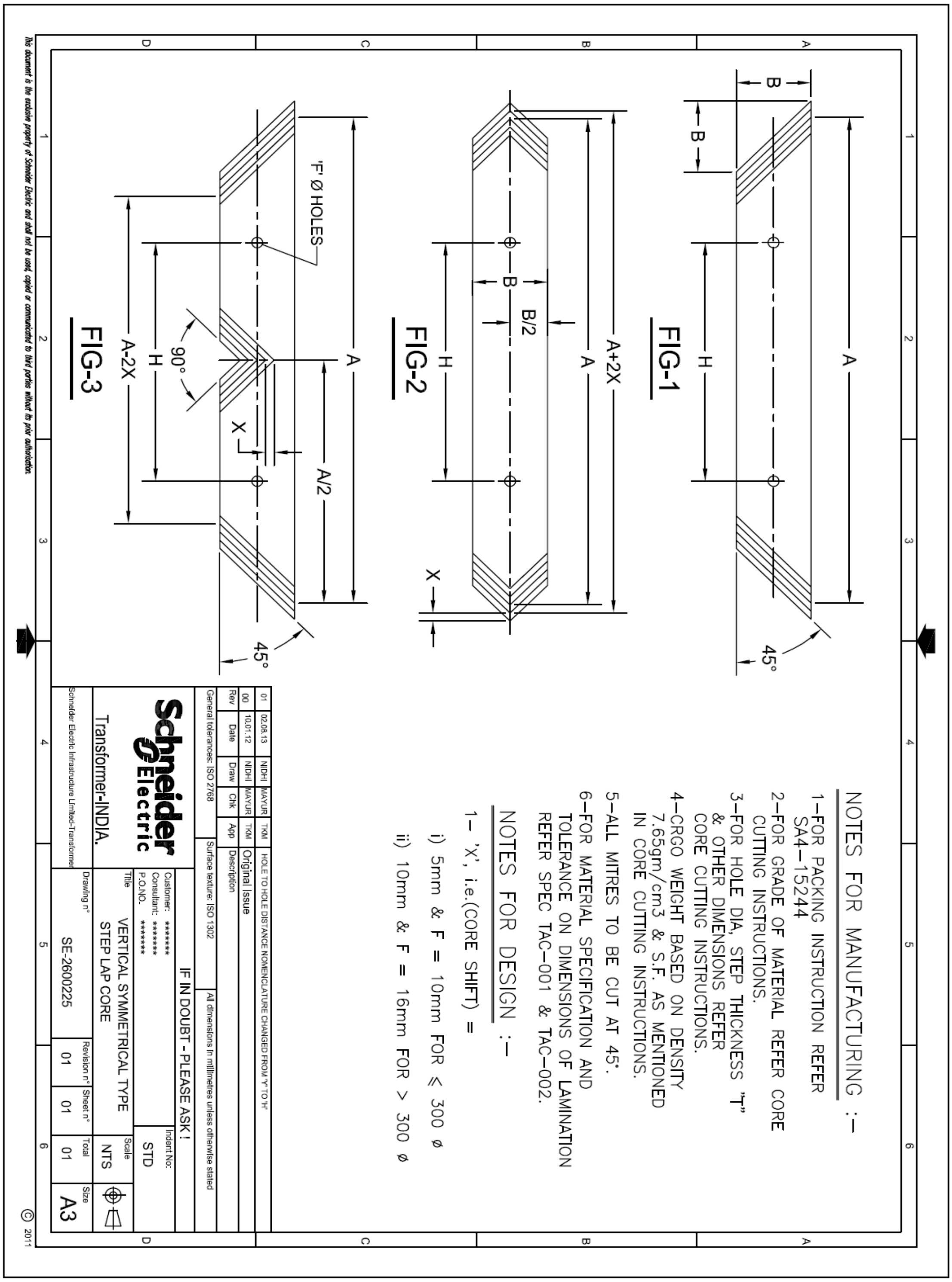

Figure A.5: Reference drawing for core construction