“Analysis of Power Distribution System in MRI & Transformer Design Optimization”

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Electrical Power System)

By

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Certificate

This is to certify that the Major Project Report entitled **"Analysis of Power Distribution System in MRI & Transformer Design Optimization"** submitted by **Yash Kaushikkumar Shah (Roll No: 21MEEE07)**, towards the partial fulfillment of the requirements for the award of degree of 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

A transformer plays many roles such as voltage conversion, isolation, and noise decoupling, and it is a vital element in electrical power distribution systems. In different countries we have different voltage level and frequencies. There are a few transformers in Magnetic Resonance Imaging (MRI) applications. The transformers employed in various countries face different voltage levels and frequencies. Further in MRI, components require specific voltage levels like 480V, 400V, 380V, 230V at 50/60Hz frequencies. This necessitates to step-up/step-down voltages and use relevant frequencies in different countries. This work proposes to reduce multiple transformers to a single multi-tap transformer and optimize the performance of latter. The main objective of this study is to design a single multi-tap transformer, optimize it for the maintenance, inventory cost & reduce complexity of the system. Thus, Single combined transformer can be used for any system and overall cost will be reduced. Design of 80kVA distribution transformer with calculation is presented. The design concepts and detailed design is presented, followed by the simulation results.

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Chapter 1

Introduction

1.1 What is MRI?

Magnetic resonance imaging (MRI) is a medical imaging technique used in radiology to create images of the body's anatomy and physiological processes. MRI scans generate images of the organs and tissues in the body by using strong magnetic fields and radio waves. The presence of water molecules with hydrogen atoms inside of our bodies aids the MRI scan. Each spinning hydrogen proton is like a little magnet that rotates around on its own axis, like how the Earth spins on its axis with north and south magnetic poles.

The billions of hydrogen protons that make up our bodies are constantly spinning on their axes and in random positions. Like how a compass needle aligns to the magnetic field of the Earth, the unpredictability of hydrogen proton changes when a human body is placed in an MRI scanner's strong magnetic field. These hydrogen protons, which spin at random, realign their axes with the increased magnetic field of the MRI scanner. The magnetic field of a scanner is known as the B0 field.

Figure 1.1: MRI Examination Room [13]

The body coils help the radio waves from the RF coils transmit signals to these protons and receive signals from the body. The computer attached to the scanner transforms these signal returns into images. A unit called a Tesla is used to express the magnet's strength (T). Hospitals and research facilities typically use 1.5 or 3T MRI scanners. The earth's magnetic field is around 0.00006T, which means that a 3T MRI scanner is approximately 60,000 times stronger than the earth's magnetic field.

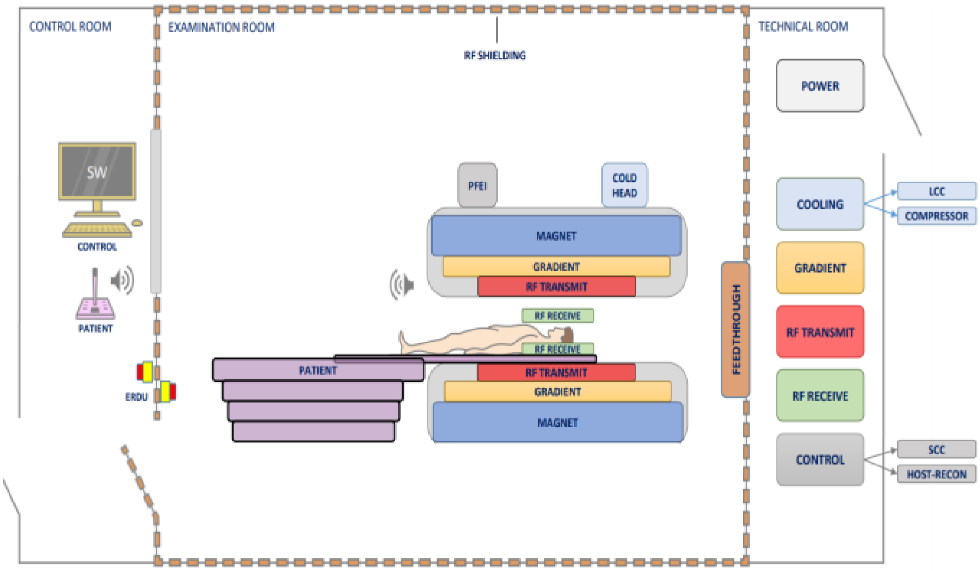


Figure 1.2: MRI Block Diagram

1.1.1 Different MRI Components

1. Magnet: The magnet is the MRI machine's most significant and substantial component. The MRI machine's ability to produce high-quality images is due to its magnet. MRI machines currently use superconducting electromagnets as their magnets. A niobium-titanium alloy transforms into a superconductor and loses resistance to the flow of electric current when cooled by liquid helium to 4 K (-269 °C, -452 °F).

Figure 1.3: Superconducting Magnet [13]

Superconductors can be used to build electromagnets with exceptionally high field strengths and very high stability. Consequently, although being more expensive, these superconducting magnets are still the most prevalent kind used in MRI scanners today.

2. Gradient Coils: By modulating the magnetic field linearly over the imaging volume with gradient coils, protons' locations are spatially encoded. To alter the primary magnetic field B0, three gradient coils are employed, one for each direction. By regulating and changing the primary magnetic field, the variable magnetic field can be raised or lowered to enable scanning of particular and various body sections. Before the signal is given to gradient coils, the gradient amplifier boosts its energy in such a way that the gradient field strength is strong enough to cause fluctuations with in main magnetic field.

Figure 1.4: Gradient coils [14]

3. RF coils: As a broadcasting station would, RF coils send and receive signals. A tiny magnetization coincides with the magnetic field as the patient is placed in the MRI scanner. A tiny magnetic field perpendicular to the main magnetic field is created by an RF pulse that is produced by an RF transmit coil.

Figure 1.5: RF coil [15]

A computer may create an image of the tissues by using the signals that an RF receiver coil picks up from the body. Both the TxCoil and the RxCoil are resonant circuits made up of electrical parts that store magnetic (Inductor L) and electric (Capacitor C) energy to produce a magnetic field when electric current flows.

4. Patient Table: For a precise diagnosis using any imaging modality, patient posture is crucial. Patient positioning is essential in magnetic resonance imaging to produce high-quality images and, ultimately, an accurate diagnosis. However, there are many methods for patient positioning that take anatomical reference and/or pathology into consideration.

Figure 1.6: Patient Table of MRI [13]

During examinations, patient tables improve security and comfort. They enable greater loads and decreased deflection. Automation and improved mechanisms provide the operator more control freedom.

5. Host Computer: Everything the MRI system does is coordinated by the host computer. All commands issued by the MR operator through the MR system software are handled by it, along with all image editing and display activities, photo and file management responsibilities, and the generation of control pulses during the scanning process.

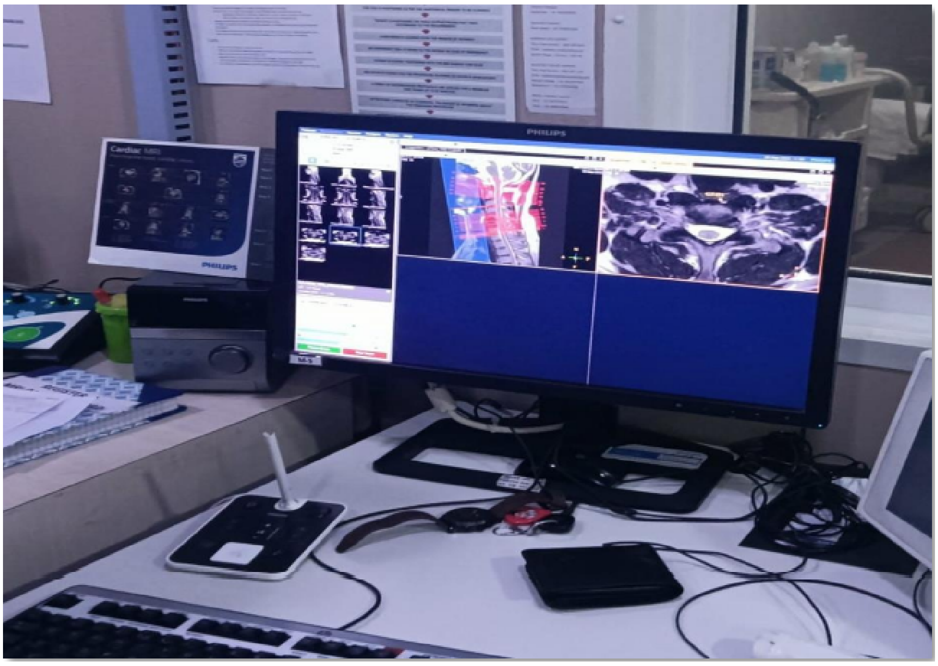


Figure 1.7: Host Computer

Host computers used by the current generation of MRI scanners come in a variety of speeds and capabilities. Large computational and storage resources are needed for these picture handling systems.

1.2 Need of Transformers in MRI System

1) If mains voltage is not compatible with Philips MRI system.

2) If neutral is required but not available at the hospital site.

3) Improvement of the mains quality as an insulation transformer generates a NEUTRAL. Any transformer does not improve the quality of protective earth.

1.3 About Company

Philips India Limited is a leading health technology company in Personal healthcare having different business units like Magnetic Resonance Imaging, Computer Tomography, Image Guided Therapy, Mobile Devices, X-rays/DXR and Ultrasound. Company provides healthcare products as per user requirements with goal of improving 2.5 billion people by 2030. Philipsis a health technology company focused on improving There are three types of UPS design according to different applications: people's lives through meaningful innovation across the health continuum – from healthy living and prevention to diagnosis, treatment, and home care. Philips has a long history of breakthrough innovation. The company began in lighting and founded its first research lab in 1914. Applying its technical knowledge to healthcare, Philips introduced a medical X-ray tube in 1918. This marked the point when the company began to diversify its product range and to systematically protect its innovations with patents in areas stretching from X-ray radiation to radio reception. Along the way, we've been responsible for some truly ground-breaking discoveries and standards, such as the X-ray tube, the high-pressure mercury lamp, the triple-headed dry electric razor, the Compact Cassette, the 40-slice CT scanner, CD, DVD, Ambilight TV, and more recent innovations such as, portable ultrasound, and the all-digital PET/CT scanner.

1.4 Objective of project

- To understand and study of MRI system
- To optimize the power distribution system
- To reduce system Inventory and BOM cost through optimization

Chapter 2

Literature Review

This chapter provides an overview of specific studies that authors associated to the current project have conducted. It gives study related to latest technology in transformer and its design parameters. Also gives study related to power distribution system and transformer less system which is being used in many applications.

Kanakasabai Viswanathan, Jayanti N. Ganesh, Rajendra Naik, Juan Sabate, Mike Rose, and Yash Veer Singh [1]studied high frequency power distribution system for MRI. A change to the MRI system's current power architecture has been proposed in order to lower the cost and footprint of an MRI scanner setup in a hospital. There have been suggestions for a high frequency replacement for the frontend's large low frequency transformer. To prevent difficulty triggering of other hospital essential loads when an MRI cabinet ground fault occurs, the ground fault handling, a key idea of the LFPDU, has been integrated and experimentally proven for the HFPDU. HFPDU has observed steady state performance.

Yunfeng Liu, Juan Sabate, Margaret Wiza [2] focused on a new power supply with freely controlled multiple isolated-outputs, built on a phase-shift PWM control of a multi-leg bridge. For Magnetic Resonance Imaging (MRI) systems that require decent regulation during all operating situations for good image quality, the power supply was employed for a multi-level switching gradient amplifier. One half-bridge leg is included in the power supply circuit for each unique output, in addition to a further common leg. Phase shifting every leg with regard to the common leg and connecting two transformers with their primary between each leg's equivalent leg and the common leg are used to achieve control. Experimental results are obtained with 88interconnected, and the regulation is upheld even when the amplifier is used as a pulsating load. Ronnie Minhaz, P.Eng [3] provided a transformer design steps and design parameters selection procedure with detailed analysis. Also, each parameter are explained in detailed with their specifications.

Prasad N. Enjeti, Moonshik Kang, and Ira J. Pitel [4] focused on analysis and design of new electronic transformer. Some topologies utilizing magnetic core in series with primary and secondary side static converters have been researched. It has been found that an electronic transformer can handle three times as much power at 1000 Hz as it can at 60 Hz when typicalgrain-oriented silicon steel is used. We have looked at the topology of a high voltage electronic transformer with integrated static converters. Secure commutation is possible without the use of loss-producing snubber circuits by adopting a four-step switching approach.

BaoguiZhang, KunWang, TianziJiang [5] demonstrated the relationship between RF power and B1+ field implementation, and the overall requirements considered in RF subsystem design. The probabilities for system design optimization are demonstrated after systematically going over the RF design for the MR system, which includes the entire transmission chain, the sequence algorithm, and the RF pulse design. With an emphasis on the promising prospects offered by technologies like RF parallel transmission systems in the extreme high field, the radio frequency-related limitations of the human entire body 7T MR and animal MR systems are also investigated at the same time.

Mr. Vishal L. Tathe and Dr. S.A. Deokar [6] carried out new design of three phase auto transformer by which cost will be reduced and performance will also be improved. A hardware design and performance analysis are being conducted. It is less expensive and more feasible solution against the autotransformer. The existing collection method can be made better in the future by reducing harmonics and heating at brushes by employing a splitting method.

Young-Tae Jeon, Ashraf Ahmed, Joung-Hu Park [7] published transformer-less AC-AC system using dual inductor buck converter and multi-level inverter. Through the use of these SST devices, systems that formerly used transformers have made significant strides in recent years in terms of size and cost. However, given the use of high frequency transformers for galvanic isolation, the SST cannot be referred to as transformer-less topologies. The systems have a lot of benefits if the transformers are entirely eliminated from the circuit and can be used in a variety of power distribution systems. The following portion of this study offers an isolated topology using a twin inductor buck converter and multi-level inverter for topologies lacking magnetic transformers. With dual inductor buck converter leakage current is reduced to negligible leakage current which will work as isolation to the system. For 1kW power rating simulation is carried out and results are obtained according to the requirements.

Jonas E. Huber and Johann W. Kolar [8] conducted comparison between volume, weight, cost of 1MVA 10 kV/400V solid state against a conventional low frequency distribution transformer. The SST is discovered to have expenditures that are at least five times higher, losses that are around three times higher, a weight that is similar, but a volume that has been reduced by less than 80the comparison prefers the SST-based concept because its losses are only roughly half those of the LFT-based system, and its volume and weight are reduced by about one third. In contrast, the LFT's advantage in terms of material expenses is much less pronounced.

Peng Shuai, Jurgen Biela [9] evaluated design and optimization of medium frequency, medium voltage transformers. The design and optimization technique for MFTs is presented in this study, with a focus on thermal and insulation design. The optimization procedure takes into account the enhanced thermal model for multi-layer windings made of litz-wire as well as the analytical computation of the maximum electric field in the core window area. The methodology is used to examine the best designs for a 25 kW/4 kHz MFT with two widely used core materials. Investigated is the potential for volume reduction by an increase in operation frequency.

Essam Hendawi [10] focused on analysis, performance of operation, simulation and comparison of various versions of H6 transformer less inverters. This study aids in making an appropriate choice of an effective inverter in a real-world scenario. For each inverter, pulse width modulation (PWM) and selective harmonic elimination (SHE) techniques are used. When comparing inverters, factors such as inverter conduction losses, LCL filter size, leakage current, and electrical components are considered. MATLAB/SIMULINK is used to simulate the inverters with parasitic capacitance and an LCL filter. The comparison and results demonstrate that the modified H6 inverter with PWM is the preferable option in practical situations.

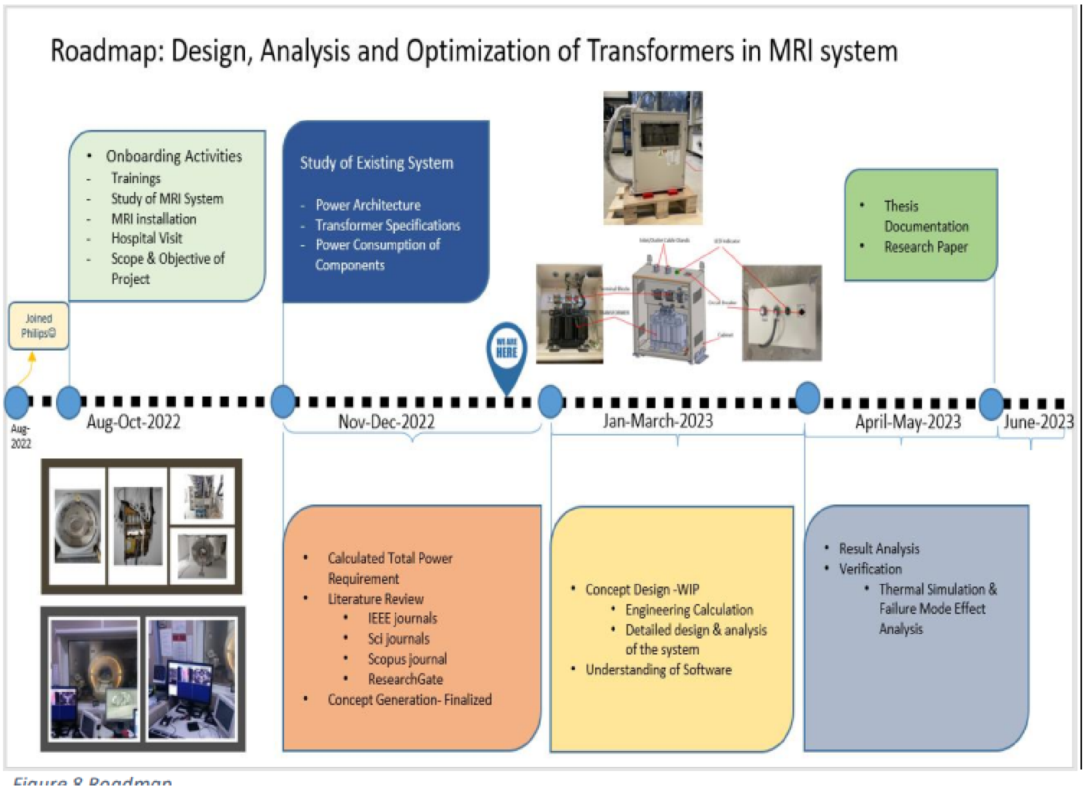
Ersan Kabalc [11] presents block diagrams and SST device configurations based on recent architectural concepts. Due to advancements in power electronics technology, SSTs have been the subject of intensive investigation for a few decades as potential alternatives for traditional magnetic transformers. An overview of the SST idea is given in the opening sections of this chapter, which are then followed by descriptions of the architectures and sets of the most typical SST topologies. The MLI topologies, which include input rectifiers, intermediate inverters and rectifiers, and output inverters for connecting to the power grid and incorporating distributed energy sources, are crucial circuit infrastructures for enhancing SSTs. The altered LV section in AC and DC waveforms makes up the output stage

Chapter 3

Methodology

3.1 Roadmap

Gantt Chart with timeline of the project is shown in Figure 8 :



Roadmap: Design, Analysis and Optimization of Transformers in MRI system

Joined Philips©

Aug-2022

Aug-Oct-2022

- Onboarding Activities
  - Trainings
  - Study of MRI System
  - MRI installation
  - Hospital Visit
  - Scope & Objective of Project

Nov-Dec-2022

Study of Existing System

- Power Architecture
- Transformer Specifications
- Power Consumption of Components

- Calculated Total Power Requirement
- Literature Review
  - IEEE journals
  - Sci journals
  - Scopus journal
  - ResearchGate
- Concept Generation- Finalized

WE ARE HERE

Jan-March-2023

- Concept Design -WIP
  - Engineering Calculation
  - Detailed design & analysis of the system
- Understanding of Software

April-May-2023

- Result Analysis
- Verification
  - Thermal Simulation & Failure Mode Effect Analysis

June-2023

- Thesis Documentation
- Research Paper

Figure 3.1: Roadmap

3.2 Power Architecture of MRI

Figure 9 Shows the power architecture of MRI. According to the system mains input transformers are required. Overall MRI requires 80kVA-110kVA Power.

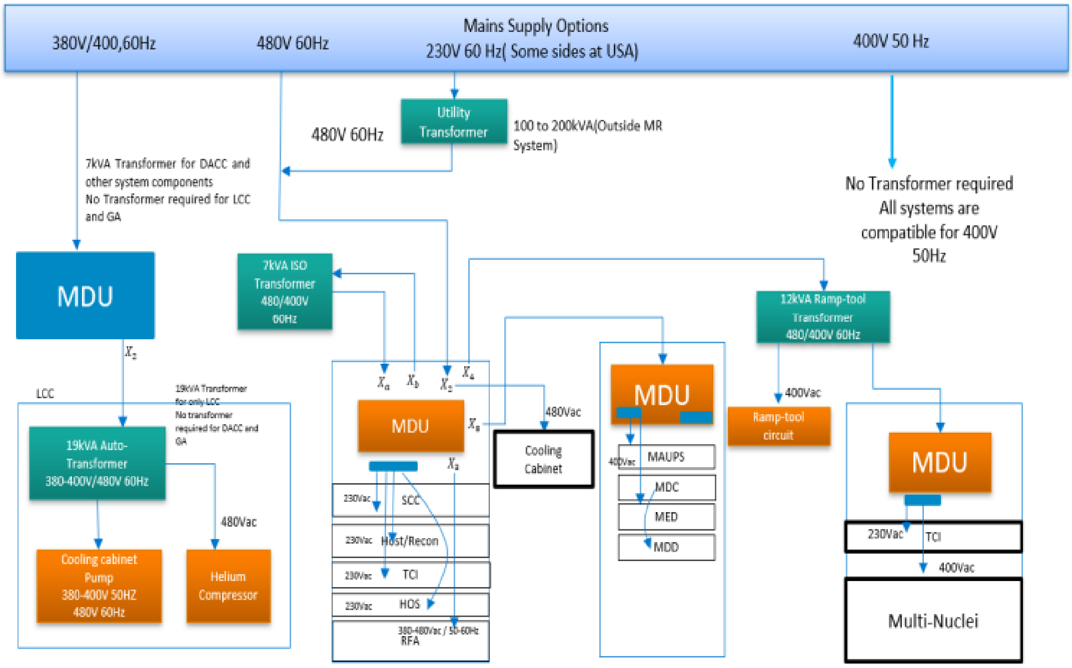


Figure 3.2: Power Architecture of MRI

3.2.1 Detailed Specifications of Each Transformer

Specifications	**Transformers**		
Power Rating	7kVA	12kVA	19kVA
Type	Isolated (3-Ø)	Isolated (3-Ø)	Auto-Transformer (3-Ø)
Input Voltage	480V ± 10%	480V ± 10%	400V ± 10%
Output Voltage	400V ± 5%	400V ± 5%	480V ± 10%
Connection type	Delta-Star	Delta-Star	Star-Star
Efficiency	97%	96.5%	98%
Frequency	60Hz ± 1Hz	60Hz ± 1Hz	60Hz ± 1Hz
Load Current	10.1 A	17.3 A	22.9 A
Voltage Regulation	<3%	<3%	<5%
Insulation Type	Class H (180 °C)	Class H (180 °C)	Class B (130 °C)
Weight	55kg	95kg	37kg
Core material	Cold Rolled Grain Oriented	Non-oriented magnetic steel plate and steel strip	-
Leakage Current	<100µA	<100µA	<100µA

Table 3.1: Transformer Specification

3.2.2 Calculation of power requirement for each transformer

Power rating of each transformer are estimated from the load requirement of connected components. Each transformer load requirement is shown in table below:

For 7kVA Isolated Transformer:

Components Connected	Max. Load required
MDC(MAUPS)	500W (400Vac)
MED	6300W (400Vac)
HOS	765W (230Vac)
TCI	25W (230Vac)
SCC	400W (230Vac)
Host/Recon	600W (230Vac)
Total Load (During Normal Condition)	2315W
(During Energize Mode)	6300W

Table 3.2: Load calculation for 7kVA transformer

For 12kVA Isolated Transformer:

Components Connected	Max. Load required
Ramp-tool circuit	12kVA (400Vac)
TCI	25W (230Vac)
Multi-Nuclei	4kW (400Vac)
Total Load (During Ramping of Magnet)	12kVA
(During Normal Mode)	4025W

Table 3.3: Load Calculation for 12kVA Transformer

For 19kVA Isolated Transformer:

Components Connected	Max. Load required
Pump	3kW, 4300VA (480Vac)
Helium Compressor	12kVA (480Vac)
Total Load	16.3kVA

Table 3.4: Load Calculation for 19kVA transformer

3.2.3 Advantage & Disadvantage of combine Transformer

Advantages:

- It will eliminate the various transformers used in MRI which will reduce the system inventory and BOM cost.
- It can be used for any system of Philips MRI
- Easy to operate
- Galvanic Isolation

- Higher Efficiency
- Higher Reliability
- Less maintenance

Disadvantages:

- More Weight
- Larger Size
- Input range not supported
- Output range not supported
- High capital cost

Chapter 4

Concept Generation

As per requirements, morphology was created, and then different ideas generated according to the requirement. With the help of PUGH Matrix concept idea is finalized which was shown in Table 4.1 below.

S.No.	**Selection Criteria**	**Weightage**	**Combine Transformer**	**Transformer less system**	**High Frequency Transformer**	**Solid State Transformer**
1	Weight	9	3	9	5	5
2	Size	9	3	7	5	5
3	Cost	1	5	3	3	3
4	Efficiency	9	9	3	9	5
5	No. of components	5	9	3	7	5
6	reliability	9	7	1	5	3
7	Maintenance	9	9	5	9	7
8	Heating	3	9	5	7	5
9	Audible Noise	3	7	9	5	5
10	Input range supported	9	3	9	3	9
11	Output range supported	9	3	9	3	7
12	Leakage Current	5	7	7	7	7
13	Interference due to high frequency switching	9	9	3	3	3
14	Isolation	5	9	3	9	9
15	Feasibility compared to MRI	9	9	5	7	5
16	Safety	9	9	7	9	9
	Total Weightage		**754**	632	676	660

Table 4.1: Pugh Matrix

From Pugh Matrix, Combine Transformer was selected as we can clearly see it has more weightage compared to other ideas. In Combine Transformer also there are two options which was presented below.

4.1 Proposed Concept

- Concept 1: Combine Transformer with Utility Transformer

Input Voltages (in V)	Output Voltages (in V)	Load to be supplied	Power Ratings (in kVA)		Current ratings (in A)	
220			60 Hz	50 Hz		
230	480 (3-Phase 4-wire)	LCC	20	NA	24.05	NA
240	400 (3-Phase 4-wire)	All other components	60	80	72.17	115.47
380						
400						
415						
440						
460						
480						

Table 4.2: Requirement Specifications of Concept 1

- Concept 2: Combine Transformer without Utility Transformer

Input Voltages (in V)	Output Voltages (in V)	Load to be supplied	Power Ratings (in kVA)		Current ratings (in A)	
			60 Hz	50 Hz		
400	480 (3-Phase 4-wire)	LCC	20	NA	24.05	NA
480	400 (3-Phase 4-wire)	All other components	20	NA	28.86	NA
	230 (1-phase)					

Table 4.3: Requirement Specifications of Concept 2

Option 1 is being selected because the requirement of utility transformer is increased. And by adding it we can have only one transformer i.e., combine transformer for all MR variants which reduces the component BOM, inventory and maintenance of the system.

Chapter 5

Concept Design

- Constraints which need to consider while designing are heat, space, vibrations etc.

- Steps for designing a transformer are listed below:
  1. Selection of type of transformer
  2. Design of Core
  3. Design of Window & Yoke
  4. Design of Windings & Insulation
  5. Design of Tappings & Tank
  6. Calculation of Losses & Efficiency

5.1 Selection of type of transformer

The transformers are of two types. 1) Core type transformer & 2) Shell type transformer.

Core Type Transformer	**Shell Type Transformer**
Simple in design	Complex design
Easy for maintenance	Maintenance is difficult because core will be inside, and windings are outside
Poor mechanical strength	During short-circuit, it has higher mechanical strength compared to core type
Offers better heat dissipation facilities	Better cooling in core compared to windings
Better cooling in windings compared to core	Difficulty in inspection & repair of coils
Easily accessible except for small portion of window	

Table 5.1: Comparison between core type and shell type transformer [16]

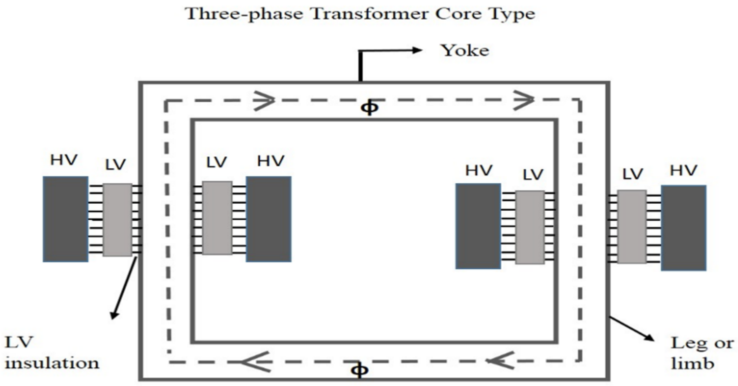


Figure 5.1: Circuit diagram of three phase core type transformer [17]

For this design, core type transformer is being selected.

5.2 Design of Core

The transformer core creates a closed magnetic circuit through which the mutual flux passes and links with both windings. It's important to minimize the magnetizing current and core losses in the core material and structure. To cut down on eddy current losses, transformer cores are laminated. The square of the lamination thickness determines the eddy current loss. The maximum practicable thickness is 0.3mm. The thickness of the laminations is 0.33 to 0.5 mm. It becomes mechanically fragile and has a tendency to buckle below 0.3 mm. These laminations are constructed from steel that is supposedly of transformer quality and contains 3-5% silicon. As the core's resistivity rises due to the greater silicon concentration, eddy current loss is decreased. Due to the material's high permeability, the magnetizing current is likewise minimal. Transformer core steel can be either hot-rolled or cold-rolled. Flux densities up to 1.8 $\mathrm{Wb/m^2}$ are much greater because to the thick cold-rolled steel. However, the price is 25–35% more than that of hot rolled steel. Reducing the amount of core material is made feasible by an increase in flux density.

Cold-rolled grain-oriented (CRGO) steel has the following benefits:

- Maximum magnetic induction and a large BH curve loop.
- The transformer's core loss is minimal while it is operating without a load.
- The transformer operates with a modest reactive power input when there is no load.

- Low magnetostriction.
- Excellent mechanical qualities.

5.2.1 Core Cross-Section:

Transformers with small cores typically have rectangular limbs and coils, while larger transformers are designed with circular cores to optimize the use of core material. This is because a circle has the smallest possible perimeter for a given area, which results in shorter winding lengths and less conductor material required, ultimately leading to lower costs. To maximize the net sectional area of a transformer core, the core section is often divided into steps and arranged in a circular pattern that corresponds to a preset diameter known as the circumscribing circle. This approach strikes a balance between the number of steps used and the available space, resulting in an optimized design.

Figure illustrates a two-stepped core, also referred to as a cruciform core. Two sizes of laminations are required for a two-stepped core. However, there are more varied lamination sizes as the number of stages grows. When there are several steps, the mean turn of the windings is shorter, which leads to the shearing and assembly of laminations of various sizes. Therefore, while constructing a core section, a balance between the price of the conductors and core and the work costs must be achieved.

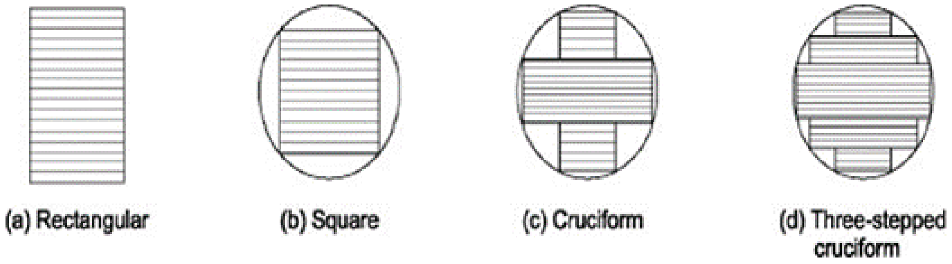


Figure 5.2: Types of Core [18]

I type laminations are utilized in big core type transformers, and the joints between the limbs and yokes are interleaved. The optimal configuration is achieved by interleaving one plate at a time if the magnetic characteristics of the circuit are the sole factor taken into account. It should be noted that the higher layer thickness increases the transformer's iron loss and no-load current due to the greater resistance provided to magnetic lines of force that avoid the joints between the laminations. The interleaving at the joints of the laminations should be done with the utmost care in order to minimize magnetizing current. Laminations must not have gaps that are wider than 1-2 mm.

5.2.2 Choice of core area and type of core:

To achieve the optimal core area within the core's circumscribing circle, a stepped core cross-section is chosen. The number of steps, steel grade, insulation or laminations, and clamping style all affect the core area. Core area grows as the number of steps rises, but costs rise as well. High tensile strength clamps are used to clamp the core lamination for bigger rated transformers, which increases the core area for any constant core diameter. Enough ducts must be installed in order to keep the hot spot temperature within the defined range.

The choice of core type is based on the rating, operating duty, and transport restrictions. To get around the issue of the core's larger height, five or six limbed cores are suggested for big three phase transformers.

5.2.3 Choice of Flux Density:

The core area is determined by the flux density value inside the core. Higher flux density values result in a smaller core area, which lowers the cost of iron. Additionally, the length of the mean winding turn is shorter due to the smaller core area. As a result, conductor expenses are also reduced. However, when the flux density increases, the iron losses increase as well, creating a significant temperature differential across the core. The need for a strong magnetizing current with unfavorable harmonics arises from high flux density.

The service circumstances of the transformer have an impact on the value of flux density that should be selected. Since a distribution transformer must be built with a high overall efficiency, the flux density value should be low to minimize iron losses. The value of flux density for use of CRGO steel for distribution transformers varies from 1.1 to 1.55 Wb/m^2.

5.2.4 Calculation of Core Area:

- Voltage per turn is calculated from Eqn.[16]

$$E_t = K * \sqrt{Q} volts.$$

- Find net cross-sectional area of the core A_i from Eqn.[16]

$$E_t = 4.44 * f * \phi_m = 4.44 * f * B_m * A_i; Where, A_i = E_t/(4.44 * f * B_m)m^2$$

- Determine the diameter of the circumscribing circle using the Eqn.[16]

$$A_i = K * d^2; Where, d = \sqrt{(A_i/K)}m$$

- From the above Eqn., Calculated parameters are shown in Table 5.2:

Parameters:	**Calculated Value**
K =>	0.45
Power (Q in kVA) =>	80
E_t (Voltage per turn) =>	4.0249
Frequency (f in Hz) =>	60
B_m (Wb/m^2) =>	1.2
Flux Ø (Wb) =>	0.0181
A_i (in m^2)	0.0126
A_i (in mm^2)	12590.47
d (in mm) =>	139.176
Core Material =>	35HP110
# of core stage	6 Stage
Max. Specific iron loss (W/kg)	1.45

Table 5.2: Calculated parameters for core

5.3 Design of Window & Yoke

The ratio of the copper area within the window to the overall window area is known as the window space factor. The calculation of a transformer's window space factor depends on the proportions of copper and insulation used, which are determined by the transformer's voltage rating and output. The empirical formula for determining the window space factor, denoted as K_w, is 10 divided by 30 added to the voltage of the high-voltage winding (in kilovolts), where the value of kV is substituted accordingly. The aforementioned calculation applies to transformers with a rating of 50 to 200 kVA.

The spacing between neighboring limbs affects the leakage reactance. If this distance is short, the winding's width will be constrained; to compensate, the winding's height must be raised. The windings are lengthy and thin as a result. With this configuration, the leakage reactance is minimal. To achieve a suitable level of leakage reactance and an appropriate winding arrangement, adjustments may be made to the height and width of the transformer window. The window area is affected by both the overall conductor area and the window space factor.

Area of window $A_w = H_w * W_w$; where $H_w/W_w = 2$ to 4 represents the window's height to width ratio. It is possible to determine the window's height and width by assuming a suitable ratio value.

5.3.1 Yoke area and overall dimensions

For transformers made of hot rolled silicon steel, the area of the yoke is assumed to be 15–25% bigger than the area of the core. As a result, the iron losses and the magnetizing current are reduced together with the value of flux density that is obtained in the yoke. The area of the yoke is considered to be equal to the size of the core for transformers made of cold-rolled grain-oriented steel.

The yoke portion can be seen as either rectangular or stepped. When using yokes with a rectangular section, the depth of the yoke and the depth of the core are the same. When square or stepped cores are utilized, the depth of the core is equal to the width of the biggest stamping.

- D_y (depth of yoke) $= a$, H_y (height of yoke) $= a$, Where a is the width of largest stamping.

- For three phase core type transformers [16], $W_w = D - d; H = (H_w + 2H_y)\ m$; $W = (2D + a)\ m$.

5.3.2 Calculation of window area and yoke area and overall dimensions:

Parameters	**Value**
Window Space Factor =>	0.33
Window Area (in m^2) =>	0.03
Window Area (in mm^2) =>	34567.23
Width of Window =>	107.34
Height of Window =>	322.03
Area of Window provided (in mm^2) =>	34567.23
Distance between adjacent core center D =>	246.52
Area of Yoke (in m^2) =>	0.0126
Area of Yoke (in mm^2) =>	12590.47
Flux density in yoke=	1.20
Stacking Factor Kw =>	0.9
Gross area of yoke (in mm^2) =>	13989.41
a (in mm)	133.61
b (in mm)	122.47
c (in mm)	107.17
d (in mm)	89.07
e (in mm)	66.80
f (in mm)	38.97
Taking the section of yoke as rectangular.	
Depth of yoke Dy (in mm)	133.61
Height of yoke Hy (in mm)	104.70
Height of Frame H (in mm)	531.44
Width of Frame W (in mm)	626.65
Depth of Frame Dy (in mm)	133.61

Table 5.3: Calculated Parameters for Window & Yoke

Acc. to the analytical calculation, Simulated Model is created with the help of solidworks & ANSYS Maxwell Software.

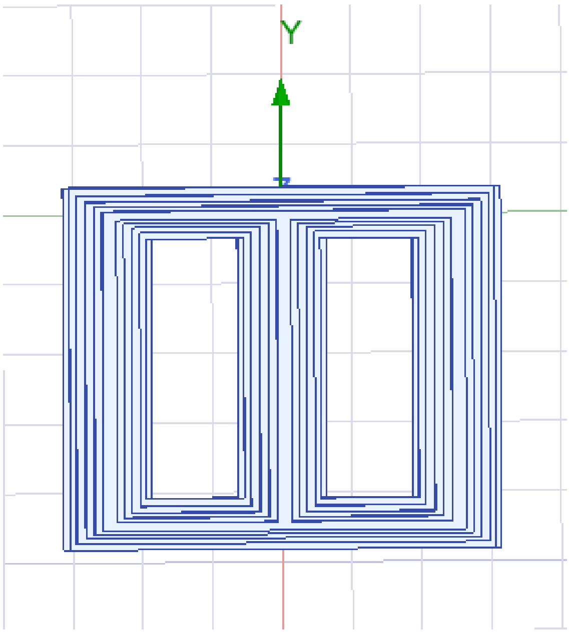


Figure 5.3: Simulated 6-Stepped Core

5.4 Design of Windings & Insulation

Different types of transformer windings with various coil configurations are employed. Concentric windings are used in core-style transformers. Every limb has coiled wind around them which consist of concentric coils having both windings primary and secondary. The high voltage winding is located outside, whereas the low voltage winding is positioned close to the core. To lessen the leakage reactance, the upper voltage and lower voltage windings might be alternatively tangled.

Connection Type for windings: Delta-Star

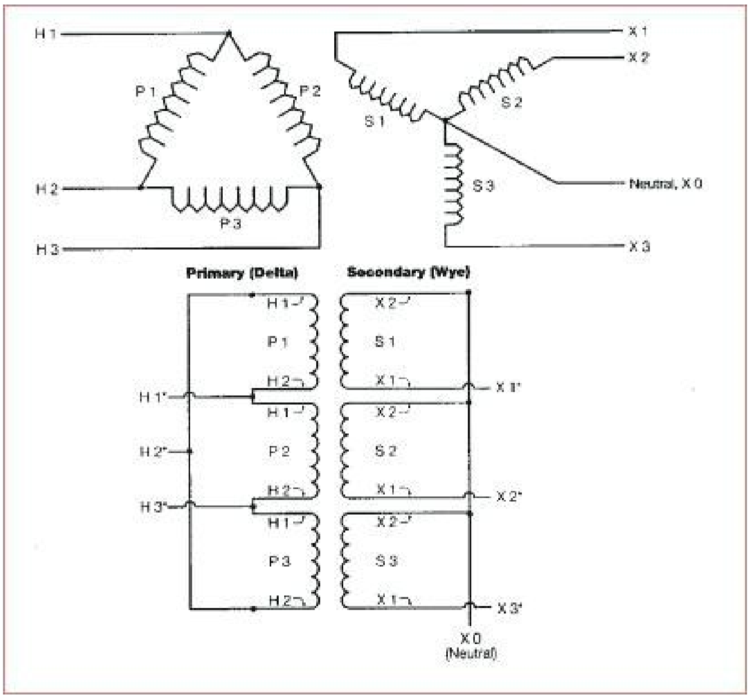


Figure 5.4: Connection Type [19]

There are several variables that affect the kind and arrangement of windings utilized in core type transformers. Current rating, short circuit power, temperature increase, impedance, surge voltages, and transportation facilities are a few of these variables.

The following sorts of windings are employed in core-type transformers: Aluminium foil windings, disc and continuous disc windings, cross-over windings, double helical windings, multi-layer helical windings, and cylinder windings are some examples of winding types.

Low voltage, high-capacity transformers use **helical** windings, also known as spiral windings, due to their ability to accommodate larger current flow with fewer winding turns. The conductor may be made up of up to 16 strips when they are used in parallel. Single Helical Windings are windings that run in an axial direction along a screw line at an angle. Each of these windings contains just one layer of turns. The eddy current loss within conductors is decreased by the double-helical type winding. Therefore, they are employed in a radial orientation because to the decreased quantity of parallel conductors. The strips in the disc-helical winding are joined side by side in a radial pattern to occupy the winding's whole radial strength.

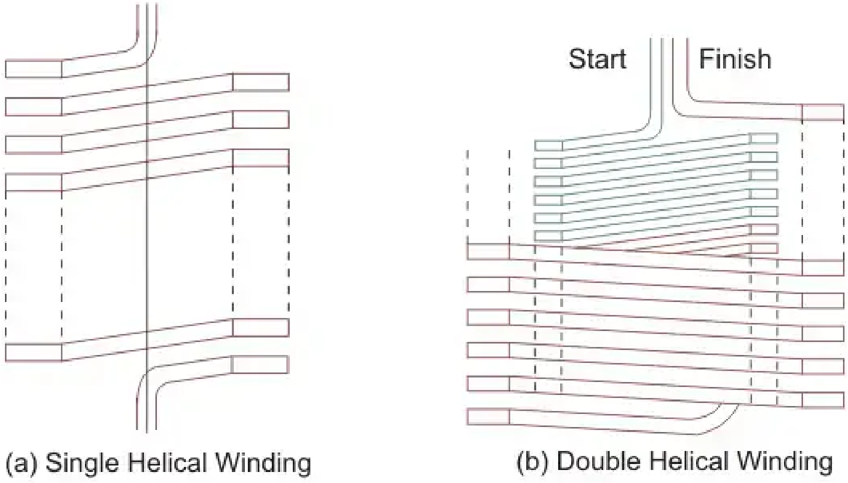


Figure 5.5: Single And Double helical winding [20]

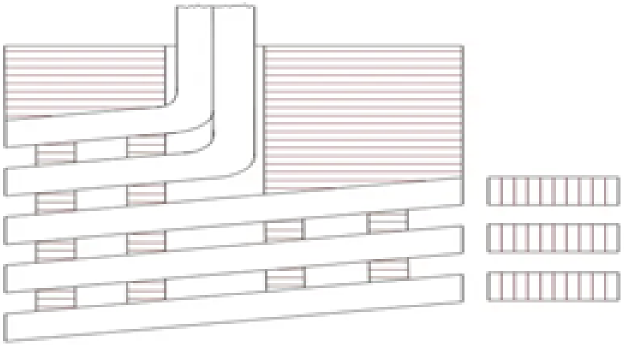


Figure 5.6: Disc Helical winding [20]

High voltage rating-based transformers, such as those rated at 110 kV and beyond, are the major application for multi-layer helical windings. Many cylindrical layers are coiled and joined in sequence in these kinds of windings. In these transformer windings, the outer layers are designed to be shorter than the inner layers in order to ensure uniform distribution of capacitance. This winding configuration is primarily intended to enhance the surge behavior of the transformer.

The current rating of **cylindrical** windings spans from 10 to 600 A and they require low voltage up to 6.6 kV. Multi-layer transformers often utilize these windings, which are comprised of circular conductors coiled on vertical strips to enhance cooling.

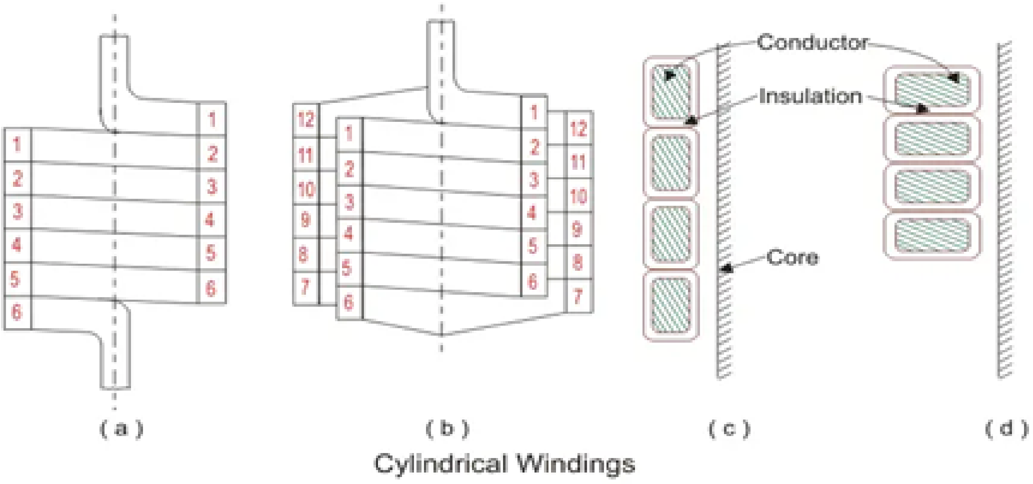


Figure 5.7: Cylindrical windings [20]

To create multi-layer spiral windings, thin insulated sheets of aluminum or copper are typically used in the design of foil windings. This winding may be created on the plane side using one or more sheets coiled parallel to each other. These can be used in large capacity transformers with currents between 12 and 600 A.

Cross-over windings are used in small transformers. These windings are separated into several coils to decrease the voltage among contiguous layers where these coils are divided axially through 0.5 to 1 mm of distance. Voltages between adjacent coils shouldn't be greater than 800 to 1000 V.

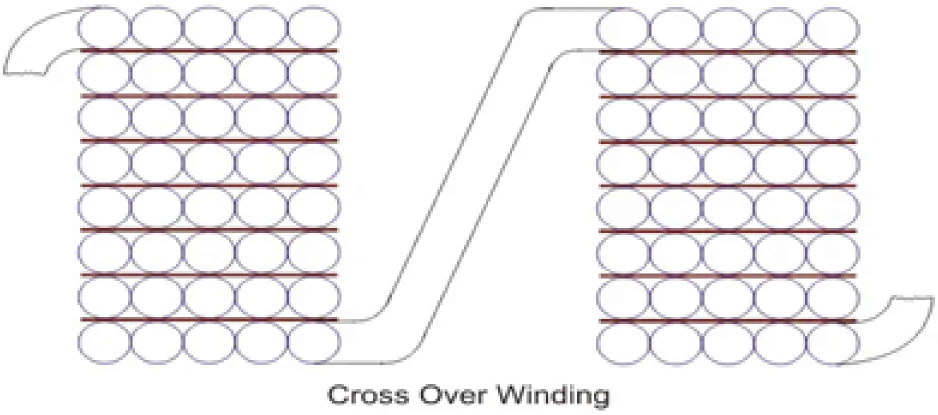


Figure 5.8: Cross over windings [20]

Continuous disc and layer windings are frequently utilized in high-capacity transformers. This type of winding involves arranging multiple discs or flat coils in series or parallel, which can be formed by spirally winding rectangular strips in a radial direction. These windings consist of conductors coiled on the flat side in the form of one or more parallel strips. Thus, the development of this conductor will result in a highly sturdy structure. The discs in these windings are divided from each other with pressboard sectors where these sectors are connected to vertical stripes. The conductor size in this case spans from 4 to 50 mm square, and the current from 12 to 600 A. The transformer oil conduit has a minimum width of 6 mm, which is primarily for 35 kV. The main benefit of these types of windings is that they provide maximum mechanical axial strength.

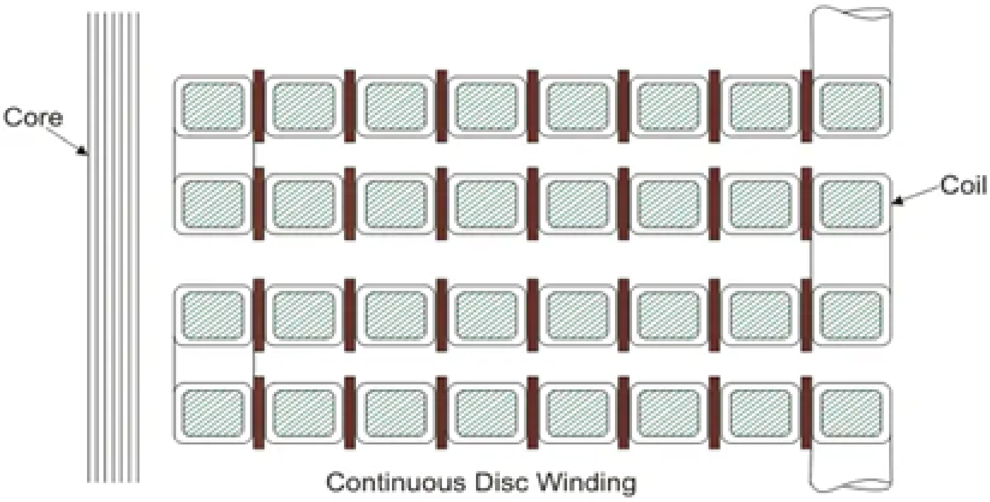


Figure 5.9: Continuous Disc winding [20]

The copper winding is the main winding material but the main reason to choose this **aluminium** winding is its initial cost is low. Compared to copper, aluminum winding is more flexible, making it simpler. The high resistivity of aluminum naturally leads to reduced eddy losses in the windings. This lessens the likelihood of hot spots. Transformers with aluminium winding or copper winding have the same losses & performance. Aluminium wound coils are bigger as compared to copper coils.

5.4.1 Selection of type of winding

The winding design must be selected in a way that yields the appropriate electrical properties and sufficient mechanical strength. There are occasions when more than one kind of winding is appropriate for the transformer.

Rectangular conductors are used in cylindrical winding and helical winding (often double helical). For voltages up to 433V and kVA ratings up to 800, cylindrical windings are employed. The helical winding can be employed for voltages up to 15 kV and occasionally up to 33 kV and ratings up to tens of MVA.

Type of winding	Conductor cross-section mm^2	Rating kVA	Maximum current/conductor A	No. of conductors (strips) in parallel	Voltage kV
Helical	75 to 100 and above	From 160 to tens of thousands	From 300 and above	4 to 16 (sometimes more)	Upto 15 but sometimes upto 33
Cylindrical (circular conductors)	Upto 30	5000-10000	Upto 80	1 to 2	Upto 33
Cylindrical (rectangular conductors)	5-200	5000-8000	10-600	1 to 4	Upto 6 (usually 0.433)
Continuous disc	From 4 to 200 and above	From 200 to tens of thousands	12 and above	1 to 4 (sometimes more)	3.3-220
Cross over	Upto 15	Upto 1000	Upto 40	1	Upto 33

Table 5.4: Selection of type of windings [16]

Helical winding is being selected because of low voltage and high current rating having small number of turns.

5.4.2 Calculation of windings

Here there is no l.v. or h.v. windings because transformation ratio is 1:1 (i.e., 480/480V). And vector group is selected as Dyn11. Primary winding is delta connected and secondary winding is star connected.

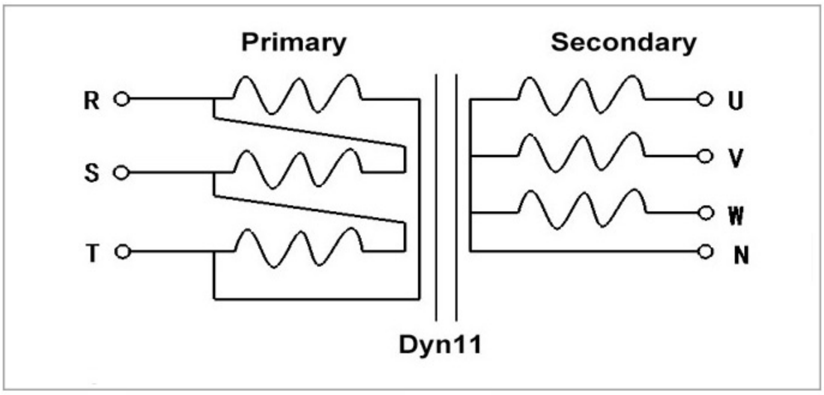


Figure 5.10: Vector Group [21]

Calculating number of turns/phase using the Eqn. [16], $T_s = V_s/E_t$; where V_s = Secondary Voltage E_t= Voltage per turn.

- Secondary Phase Current, I_s:

$$I_s = kVA * 10^3/3 * V_s$$

The cross-sectional area (in mm^2) of the secondary conductor given by

$$a_s = I_s/\delta_s$$

where δ_s is the assumed current density in Amp/mm^2.

If the cross-sectional area of the secondary conductor surpasses 50 $mm2$, stranded parallel conductor (many layers) should be used. Also, the secondary current density $delta_s$ must be calculated yet again with the chosen conductor area (because the conductor dimension is chosen from the standard based on availability, the area chosen may be slightly larger than the mathematically calculated area; thus, the current density will need to be obtained again).

The conductors are insulated with paper. This increased the conductor's thickness. Allow for a 0.5mm increase in conductor thickness for single paper covering. [Conductor width x (conductor thickness + 0.5mm)] becomes the conductor dimension. From the Table 5.4, the type of winding is selected. If it is a helical winding keep 1 turn more along the axial depth.

Axial depth of l.v winding [16]: L_s = number of secondary turns * axial depth of conductor (width of conductor).

Window clearance = (height of the window- L_s)/2 [Minimum clearance is 6mm for windings having voltage below 500V.]

Radial depth of l.v winding [16]: b_s=number of layers * radial depth of conductor + insulation between layers.

Inside Diameter & Outside Diameter of l.v. winding [16]:

- Inside dia. = dia. of circumscribing circle + 2 * pressboard thickness for insulation between core and l.v. winding. Outside dia. = inside dia. + b_s.

Here, similar process can be used for h.v. winding calculation because there is no big difference in voltages & currents.

Parameters	**Values**	
Secondary Line Voltage (in V):	480	400
Secondary Phase Voltage (in V):	277	231
Number of turns per phase:	69	58
Secondary Phase Current (in A):	96.27	115.44
Current Density (in A/mm^2):	2.3	
area of secondary conductor (in mm^2)	41.86	50.19
Winding material		Copper
Acc. to IS: 1897-1962, using a bare conductor of (in mm^2):		12x4.5
Area of bare conductor (in mm^2):		53.4
Current Density in secondary windings (in A/mm^2):		2.1617999
Dimensions of Insulated Conductor (in mm^2):	Note: The conductors are covered with paper, which results in an increase in their dimensions by 0.5mm.	12.5x5
Helical Winding is selected		
Axial depth of l.v. winding (in mm)	No. of secondary turns x width of conductor	300
Clearance on each side of the winding will be (in mm)		11
Using pressboard cylinder between layers (in mm)	0.5	
Radial depth of l.v. winding bs (in mm)	16	
Diameter of circumscribing circle d (in mm)	139	
Using pressboard wraps 1.5mm thick as insulation between l.v. winding and core		1.5
Inside Diameter of l.v. winding (in mm)	142	
Outside Diameter of l.v. winding (in mm)	174	

Table 5.5: Calculated Parameters for Secondary Winding Design

- For primary winding calculated parameters are:

Parameters		Values
Primary Line Voltage (in V):		480
Primary Phase Voltage Vp (in V)		480 (delta)
Number of turns per phase:		69
H.V. Winding Phase Current Ip (in A)		121.21
Helical Winding is selected		
Current Density (in A/mm^2):		2.3
Area of primary conductor (in mm^2)		52.70
Acc. to IS: 1897-1962, using a bare conductor of (in mm^2):		12x4.5
Area of bare conductor (in mm^2):		53.4
Current Density in primary windings (in A/mm^2):		2.270
Dimensions of Insulated Conductor (in mm^2):	Note: The Conductors are paper covered. The increase in dimensions on account of paper covering is 0.5mm.	12.5x5
Axial depth of h.v. winding (in mm)	No. of primary turns x width of conductor	300
Clearance on each side of the winding will be (in mm)		11.01
Clearance between winding and window will be (in mm)		22.027
Radial depth of h.v. winding bs (in mm)		26.00
Diameter of circumscribing circle d (in mm)		139.18
Using pressboard wraps 5.5mm thick as total insulation between h.v. winding and l.v. winding which includes the width of oil duct also.		5.5
Inside Diameter of h.v. winding (in mm)		185.00
Outside Diameter of h.v. winding (in mm)		237.00
Clearance between windings of two adjacent limbs will be (in mm)		9.52

Table 5.6: Calculated Parameters for Primary Winding Design

5.4.3 Design of Insulation

A transformer experiences mechanical, electrical, and thermal events as it transfers power from a specific circuit to another. Winding voltages create an electrostatic field in the dielectric, which stresses the insulation; winding currents create magnetic fields, which cause electromagnetic forces on the windings and mechanical stressing of insulation; and transformer losses cause temperature rise, which causes thermal stressing of insulation.

As a result, the essential issues in transformer insulation design are those of integrating windings, insulation, and core to achieve desirable mechanical, electrical, and thermal characteristics under steady-state and transient situations.

The three basic considerations in the design of insulation are: 1) Thermal considerations 2) Electrical considerations & 3) Mechanical considerations [16]

The transformer structure should be designed so that the losses developed in the windings and core generate temperature rises in the various parts that never exceed the allowable limits, either under normal and over fault/load conditions, and that, for economic reasons, come as close to those boundaries as possible.

Class A insulation is utilised for conductors in oil-immersed transformers. The conductors are normally coated in paper. The paper coating adds 0.25 mm to the size of rectangular conductors.

Pressboard or a synthetic resin bound paper cylinder insulates the low voltage windings of medium and small size transformers from the core. Axial bars positioned around the cylinder provide a cooling duct between the interior and the core cylindrical surface of the core. The bars can be put around the outside of the l.v. winding alongside the helical winding layers. Additional pressboard or synthetic resin bonded paper cylinder serves as the primary insulation across the high voltage and low voltage windings, and the bars are positioned around it. [16]

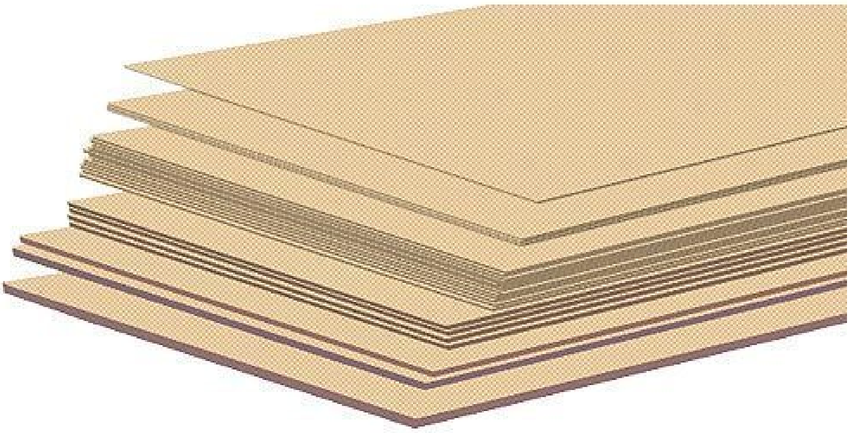


Figure 5.11: Pressboard Insulation [22]

The following is a realistic formula for estimating the thickness of insulation between a earth windings and h.v. and l.v. windings: Insulation thickness $= (5 + 0.9kV)mm$, where kV is the voltage in kilo volts between the earth and windings or between the windings. This thickness comprises the width of any oil conduit installed in the middle. An oil duct is approximately 6mm wide in smaller capacity transformers and 7.5-12 mm wide in bigger high voltage transformers.

The bars in helical disc and disc windings feature a wedge form to allow inter coil or interturn integrated spacers to be inserted to them. Blocks linked to the axial bars provide insulation at both ends of the windings. These blocks are aligned with the axial spacers and form a series of columns that can be used to clamp the winding.

Insulation thickness at either end of the winding ranges from 6mm for windings less than 500V to around 150mm for 66kV transformers.

The insulation of a transformer is divided into four types: (1) Insulation between phases (2) Insulation relative to tank (3) Minor insulation and (4) Major insulation

Major insulation refers to the insulation between grounded core and windings,as well as the insulation between windings of the same phase. Minor insulation is insulation between different portions of a winding, such as insulation between coils, layers and turns.

With the help of above analytical calculation and detailed design, simulation model is created with the help of Solidworks & Ansys Maxwell Software.

Here Cylindrical winding is created and terminal on each winding is also created. Between both windings 5.5mm gap was taken for duct and pressboard insulation. Final Simulated Model with windings and core is shown below:

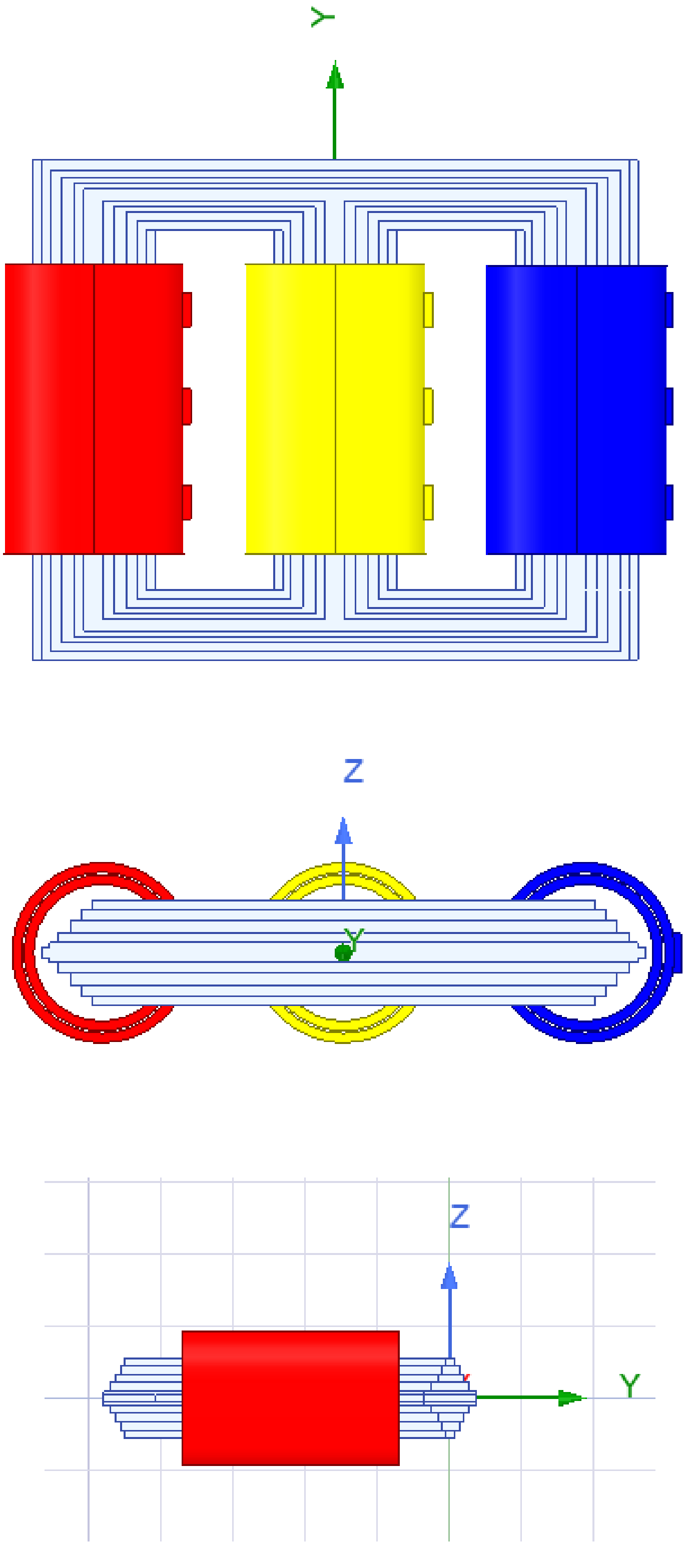


Figure 5.12: Transformer Model with Front view, Top view and Side view

5.5 Design of Tapping & Tank

By adjusting the transformers' transformation ratio, the voltage of power networks provided by transformers may be adjusted. By adding tapping to the transformer windings, the transformation ratio can alter. The connections, known as tapping, are placed at various points in the windings; as a result, the number of turns in the circuit at one tap differs from the number of turns at another tap.

If the transformer is detached from the supply, the tapping can be altered. Off-circuit tap changing is what this is known as. When making sporadic changes, such as in distribution transformers equipped with 5% and 2.5% taps, off-circuit tap changing is employed. It is also possible to modify the tapping while the transformer is powered up or under load. On load tap change is the term for this action. On-load tap altering gear is used to make routine and temporary voltage changes. Vertical tapping switches and face-plate switches are the most often used switches for altering the tap on an off circuit. A contactor is fixed on an arm that is connected to the shaft, and six brass or copper terminals are mounted on an insulating base.

On primary windings to balance the ampere-turns on both windings. Two windings of 240V max are being connected in series to get the desired 480V output. In this way only ampere-turns can be balanced otherwise according to normal tapping procedure between windings each tap being given then ampere-turns will not balance on both windings. And during short-circuit or overload condition core of the transformer may get damaged.

Existing utility transformer is having the same tapping provision and the electrical diagram of same is shown in fig. 5.10 below to understand how tapping is provided in this design also.

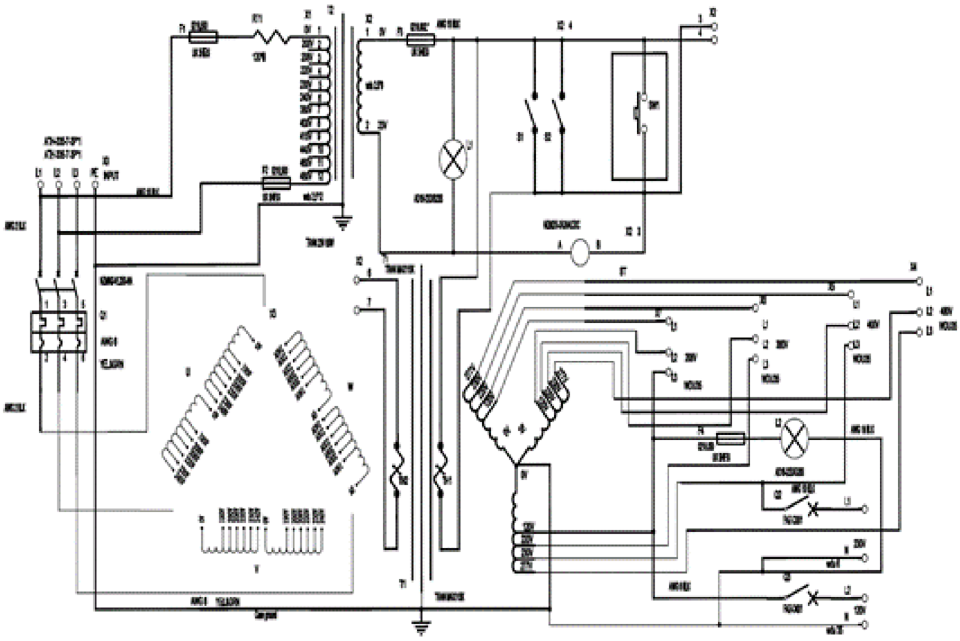


Figure 5.13: Electrical diagram of Existing Utility Transformer

5.5.1 Calculation for tappings

Parameters	**Values**		
Primary Line Voltage (in V):	220	230	240
Primary Phase Voltage Vp (in V)	127.01	132.79	138.56
Number of turns per phase:	32	34	35

Table 5.7: Calculated Parameters for Tapping

- Two windings of 3-phase 240V connected in series to get the desired 3-phase 480V supply.

5.5.2 Design of Tank

There are several things to take into account while building transformer tanks. These considerations include minimizing cost, stray load losses, and weight, all of which are obviously incompatible criteria.

Tanks need to be sturdy enough to withstand the strains caused by raising and jacking. The tank's dimensions must provide for cores, windings, internal connections, as well as the necessary distance between the windings and the walls.

Cast aluminum components set on a thin mild steel tray typically make up aluminum tanks. The primary lifting and jacking components are configured to be carried by the mild steel tray. Electromagnetic screens or shunts are employed to reduce eddy current losses in high-leakage flux units when mild steel tanks are used.

The tank width (W_t) of a transformer can be calculated by adding twice the distance between adjacent limbs (D), the external diameter of the high-voltage winding (D_e), and twice the clearance (b) between the high-voltage winding and the tank.

The tank length (L_t) is calculated by adding the external diameter of the high-voltage winding (D_e) and twice the clearance (l) on each side of the winding along the width.

Finally, the tank height (H_t) is calculated by adding the height of the transformer frame (H) and the clearance (h) between the assembled transformer and the tank.

Parameters:	Values
Width of tank W_t (in mm) =>	810.04
length of tank L_t (in mm) =>	337
height of tank H_t (in mm) =>	981.44

Table 5.8: Calculated Parameters for Tank Design

5.6 Calculation of losses & efficiency

Resistance:	Mean diameter of primary winding (in mm)	211
	Length of mean turn of primary winding Lmtp (in m)	0.663
	Resistance of primary winding at 75°C, rp (in Ω)	0.018
	Mean diameter of secondary winding (in mm)	158
	Length of mean turn of secondary winding Lmts (in m)	0.496
	Resistance of secondary winding at 75°C, rs (in Ω)	0.013
	Total resistance referred to primary side Rp	0.031
	P.U. resistance of transformer	0.008
Leakage Reactance:	Mean Diameter of windings	189.5
	Length of mean turn Lmt (in m)	0.595
	Height of winding Lc (in mm)	300
	Leakage reactance of transformer referred to primary side	0.087
	P.U. leakage reactance	0.022
	P.U. impedance	0.023
Regulation:	P.U. regulation	8.404E-05
Losses:	Cu loss at 75°C (in W)	1386.490
	Taking stray load loss 15% of above	
	Total Cu loss including stray load loss (in W)	1594.463
	Total Core loss (in W)	413.86
	Efficiency at full load and unity p.f. (in %)	97.551
	For maximum efficiency, x (in %)	50.947

Table 5.9: Calculated Parameters for Losses & Efficiency

- At 50.95 percent of the full load, maximum efficiency is achieved. For distribution transformers, this is a decent figure.

Chapter 6

Conclusion & Future Scope

The design process involves calculating the core size, determining the conductor size and number of turns, selecting the appropriate multi-tap configuration, considering the cooling system, estimating losses, selecting insulation materials, ensuring proper mechanical design, performing detailed calculations and analysis, conducting testing and validation, and preparing comprehensive design documentation.

Here in this project, detailed calculations and analysis being carried out. From calculation & analysis, by selecting proper core and winding material and insulation material obtained efficiency of 97.14% at full load with unity power factor and maximum efficiency at 50.95 percent of full load and it was good figure for distribution transformers.

In future , further validation through simulation & testing can be done with the help of above detailed design calculations and analysis.

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