Kilowatt Three-phase Rotary Transformer Design for Permanent Magnet DC Motor with On-rotor Drive System

Ye Xu
MID SWEDEN UNIVERSITY
Department of Electronics Design (EKS)

Examiner: Göran Thungström, goran.thungstrom@miun.se
Supervisor: Peng Cheng, peng.cheng@miun.se
Co-supervisor: Bengt Oelmann, bengt.oelmann@miun.se
Author: Ye Xu, yexu1000@student.miun.se
Degree programme: Master of Science, 120 credits
Main field of study: Electronics
Semester, year: VT, 2016
Abstract

The aim of this thesis is to design a kilowatt three-phase step-down rotary transformer for a permanent magnet DC motor. The permanent magnet DC motor has an on-rotor drive system, and therefore requiring a power supply that can transfer power to its drive unit without mechanical contact. The rotary transformer has a detached magnetic coupling structure that qualifies it as a potential method for the wireless power transfer.

This thesis studies the rotary transformer as a static device, focusing on its core loss. By using a transient finite element analysis of COMSOL Multiphysics and an iron loss prediction model, the rotary transformer was optimized in terms of efficiency and power density for the on-rotor drive system through proper material selection and geometry exploration. After this, a mechanical design, which based on a literature review of the influences of manufacturing processes on electrical steels, was proposed for realizing the core fabrication and the rotary transformer assembly.

The results show that the rotary transformer can step down 400 V/50 Hz three-phase voltage to 13.15 V in a Delta-wye connection and output 1.17 kW power over an air-gap of 0.3 mm with 95.94% overall efficiency. The proposed mechanical design enables the transformer to minimize the core loss and the manufacturing cost. Without using resonant inductive coupling, this transformer design simplifies the power supply for the motor, thereby decreasing the motor manufacturing and maintenance cost.

Keywords: contactless energy transfer, transformer power loss, iron loss, iron loss model, rotary transformer, three-phase transformer, finite element method, COMSOL Multiphysics, electrical steel, electrical steel manufacturing process
Acknowledgement

I would like to, firstly, express my deep gratitude to Dr. Peng Cheng, my thesis supervisor, for his patient guidance, enthusiastic encouragement, and useful critiques of this thesis work. I also thank gratefully my assistant supervisor, Prof. Bengt Oelmann for helpful suggestions during the thesis development.

My special thanks are extended to Nazar ul Islam, Stefan Haller, Dr. Kent Bertilsson, Dr. Sebastian Bader and Mattias Kramer for their support, time in patiently listening to me and helping me work out my problems during this Master by Research. I am also indebted to Dr. Najeem Lawal for helping me out of some troubles about my student visa. (By the way, I am not Cheng 2.0...)

Additionally, I would like to take the opportunity to thank my Chinese friends in Sundsvall, Xinyu Ma, Hao Shi, Congrui Liu (cute baby deer), Hanxue Xu, Mengxuan Li, Dingding Sun, Jiayi Wang, Pengxiang Cheng, Tian Xie and Ziheng He, for their delicious Chinese food, help or bringing so much fun in my life.

Furthermore, special thanks go to Florian Gebben, Onyedika Sunday Okonkwo, and Till Dreier. You make me not feel alone because I can have some classmates in this programme of Master by Research.

I also owe my sincere gratitude to my two best friends, Yunxiang Jia and Xiaotian Li, who gave me their endless help, care, understanding and forgiving throughout my years of study and live in Sweden. Most importantly, my deepest gratitude goes to a very nice girl, Siwen An, for providing me with unfailing support and continuous encouragement.

Finally, I should like to, affectionately, express my gratitude to my parents who have always been helping me out of difficulties and supporting without any complaint through these years and, even, in future.

Ye Xu
Sundsvall, Sweden
May 2016
5 Two-dimensional Transient Finite Element Analysis 30
5.1 Model Definition ........................................... 30
5.1.1 Geometry Drawing and Material Assignment .......... 31
5.1.2 Analytic Function Definition for Using Iron Loss Model .... 33
5.1.3 Slitted O-ring Lamination Modelling .................. 34
5.1.4 Meshing of FEM Model .................................. 34
5.2 Transient Simulation ....................................... 35
5.3 Result ..................................................... 36

6 Review of Influences of Manufacturing Processes on Electrical Steels 41
6.1 Overview .................................................. 41
6.2 Mother Coil and Slitting Process ............................ 42
6.3 Losses Due to Cutting Techniques .......................... 42
  6.3.1 Wire Electrical Discharge Machining ................. 43
  6.3.2 Milling ................................................ 44
  6.3.3 Summary of Different Cutting Methods .............. 45
6.4 Losses Due to Stacking .................................... 46
  6.4.1 Sticking ................................................. 46
6.5 Annealing .................................................. 47
6.6 Losses Due to Frame Assembly .............................. 49
6.7 Summary .................................................... 49

7 Transformer Mechanical Design 51
7.1 Mechanical Design Overview ............................... 51
7.2 Winding and Core Design ................................. 53
  7.2.1 Rotor-radial Core ..................................... 53
  7.2.2 Rotor-axial Core ...................................... 55
  7.2.3 Secondary Winding ................................... 55
  7.2.4 Primary Winding and Stator Core ..................... 57
7.3 Transformer Assembly ...................................... 57
7.4 Summary of Mechanical Design ............................ 61

8 Conclusions and Future Work 64
8.1 Conclusions ............................................... 64
8.2 Recommendations for Further Work ........................ 65

Appendix 68
A HB-curve and specific iron loss of M235-35A given by ThyssenKrupp Steel 68
B Epstein Frame Measurement ................................. 69
C SPICE Model Coupled to the Magnetic Field Model of the Transformer 71
D Geometry of the Three-phase Rotary Transformer Drawn in COMSOL Multiphysics ........................................ 72
E Equations Used in COMSOL Multiphysics for Modelling the Three-phase Rotary Transformer .......................... 73
F Dimension of O-ring laminations in the rotor-radial core .... 74
G Dimension of O-ring laminations in the stator-radial core .... 75
H Magnet wire .................................................. 76
I  Frame and Terminal Box Assembly ............................... 77

References ...................................................... 77
Chapter 1

Introduction

This chapter describes the background, the objectives, and the scope of this Master by Research. Furthermore, the overview and outline of this thesis are presented.

1.1 Background of the Thesis Work

The permanent magnet DC (PMDC) motor with on-rotor drive system is still an ongoing project, which designs a new kind of PMDC motor that has a higher efficiency but a lower cost compared with industrial motors in the same power rating. However, for the usability of industrial applications, this motor must have a series of standard interfaces, including control, communication, power connection and even mechanical installation. This thesis work contributes a power supply by using the standard three-phase power (400 V/50 Hz) to this new PMDC motor.

![Figure 1.1: Functional modules of on-rotor drive system](image-url)

Permanent magnet brushed DC motor existed a long time ago and it had a lot of troubles with the mechanical commutation brushes and electromagnetic interference (EMI) generated by brush arcing [1]. Hence, it was never efficient compared with modern induction motors. However, the new PMDC motor has an on-rotor drive system shown in Figure 1.1, which includes several function modules to directly deliver the utility power from the stator and control the voltage and current of the motor drive unit to run the motor optimally at different speed and torque. This system eliminates the need of conventional brushes and drives the motor with much lower voltage (less than 20 V) and higher current...
Chapter 1. Introduction

(up to dozens of kA) using off-the-shelf multi-phase DC/DC step-down power regulators like the ones used in all the PCs for CPU power supply.

To sum up, the new PMDC motor requires a power supply that has a contact-free operation to transfer electrical power to its drive unit in the rotor without using slip rings or brushes. A rotary transformer, a transformer with an axial symmetry and an air-gap between the primary side and the secondary side, has a detached magnetic coupling structure that qualifies it as a potential method for avoiding the wear of the rotating parts, and therefore achieving a contactless energy transfer (CET) system.

CET offers significant advantages over conventional methods of electrical power transfer, such as contact rails or cable handling systems. Designing a power supply with CET can lower the system maintenance cost and higher the system availability. [2] presents a general classification of CET systems shown in Figure 1.2. The medium for power transfer in CET systems could be used acoustic waves, electromagnetic waves including light, as well as electric (capacitive) or magnetic (inductive) field. Typical applications of using acoustic waves and lights are powering wireless sensors combined with energy harvesting techniques [3, 4]. Capacitive CPT using electric coupling between conducting plates separated by a dielectric. Electric fields exhibit better directionality than magnetic fields, resulting in reduced EMI shielding requirements [2,5,6]. For most industrial applications, by means of inductive power transfer (IPT) techniques, achieving a CET system based on unconventional transformers, such as rotary transformers [7–10], linear transformers [11, 12] and sliding transformers [13–15].

![Classification of CET systems](image)

Currently, IPT is the most popular research topic and widely investigated and used in many applications, such as active implantable medical devices (AIMDs) [16,17], portable electronics 1), and electric vehicles (EVs) [18–20]. To reduce losses and maximize power transfer capability, designers add series or parallel capacitors to IPT circuits to compensate the inductance of coils to achieve resonant frequency IPT systems. To reduce the size of transformers and other passive components in an IPT system, the mains AC power (50 Hz or 60 Hz) is switched at a higher frequency by using switching mode power supplies (SMPS).

In recent decades, soft-switching technique and zero-voltage switching (ZVS) bridge continue to mature, and adopting them in a SMPS can reduce the switching losses and

---

1) Qi Standard, https://www.wirelesspowerconsortium.com/
even EMI. Hence, using an SMPS with soft-switching technique and ZVS bridge enable an IPT system to have a high power density with low loss and EMI, but complicating the IPT system (see Figure 1.3a), which results in increasing troubleshooting time and maintenance cost. Furthermore, like SMPS with loop compensation, a pick-up control unit is added to the receive circuit (secondary circuit) to send feedback to the primary control unit by a wireless commutation, which ensures the stability of the IPT system and can transfer and use the power optimally [2,21]. However, adding the pick-up control unit increases the complexity of the IPT system.

Transformer is the key unit in many industrial processes, and its reliability is the crucial factor to ensure uninterrupted power supply to motors in a wide variety of applications. This thesis work designs a simple and stable wireless power supply, similar to a linear power supply shown in Figure 1.3b, for the new PMDC motor. Without using the resonant and high switching frequency, this design results in a low power density and bulky transformer. However, it can focus on the study and investigation of the transformer core material and structure, which still is a challenge for the CET study.

1.2 Thesis Objectives and Scope

The main objective of this thesis work is to design a line frequency wireless power supply system, which achieves that a rotary transformer has a simple step-down power process and a detached magnetic coupling structure to transfer a three-phase electric power to the rotor drive unit of the PMDC motor without using brushes or slip rings.

The rotary transformer can have an output power up to 1.1 kW with the efficiency of over 90%, which steps down the mains three-phase power of 400 V/50 Hz to a low-voltage and high-current power with up to 20 V. The transformer design optimization is required to minimize the transformer volume to ensure that this rotary transformer can fit in an IEC 200 motor frame or a smaller standard size frame. Afterwards, a mechanical design for realizing the rotary transformer should be proposed, which presents the manufacturable
Chapter 1. Introduction

Transformer winding and core as well as necessary mechanical components for assembly and cooling.

In the aspect of the transformer material selection and transformer power loss, this thesis focuses on the study of electrical steel (Si-Fe steel) and iron loss.

In the aspect of the iron loss model study and the transformer finite element analysis, this design ignores the influences of manufacturing processes on electrical steels, and only uses the data-sheet to develop an iron loss model.

A complete power supply should consist of a transformer, a bridge rectifier, and filter capacitors or DC/DC regulators, but this thesis only studies the transformer part.

Thermal analysis and cooling solution are essential to the transformer design, but, in the finite element analysis, the factor of temperatures are not taken into account, and all the material properties are, hence, modelled as temperature invariant. Moreover, the mechanical design does not provide a cooling solution by means of a comprehensive and rigorous study.

The mechanical design and assembly of this thesis focuses on the rotary transformer, rather than the entire machine including the PMDC motor.

1.3 Thesis Overview and Methodology

Designing a rotary transformer is a nonlinear, multiphysics and multivariable problem, of which complexity requires a finite element analysis software to perform a large number of studies for the design and optimization. Moreover, many conventional methods of traditional transformer design cannot efficiently handle the very complex problem or accurately evaluate the rotary transformer performance. Therefore, this thesis work uses COMSOL Multiphysics to design the rotary transformer but does not give up using conventional methods if they are suitable for the performance analysis and optimization, such as the determination of transformer parameters including the efficiency, power factor and voltage regulation.

A complete study of transformer design should include two subsystems, magnetic subsystem and electrical circuit subsystem. The magnetic subsystem study involves the magnetic field of the transformer and the transformer core construction and material. The electrical circuit subsystem is coupled to the magnetic subsystem, providing external voltage/current sources, loads and even the configuration of the winding connection for a poly-phase transformer. This thesis work uses the Magnetic Field interface and Electrical Circuit interface of COMSOL Multiphysics to finish the transformer geometry drawing and the material selection and assignment, model the transformer, extract the relative data from the simulation and present the transformer parameters.

Because of the non-linear characteristics of transformer core materials, using an iron loss model is essential to the transformer design. The iron loss model embedded into the finite element analysis behaves the magnetic hysteresis mathematically or empirically, which can predict the transformer core loss and help designers to optimize the transformer in the terms of power density and efficiency.

However, even if an iron loss model can predict the core loss accurately, its accuracy is drastically reduced compared with the actual loss of the finally assembled transformer because various manufacturing processes degrade the magnetic properties of the trans-
former core. Hence, this thesis presents a literature review and studies the iron loss in the view of electrical steel manufacturing process. Furthermore, through the literature review, suitable methods and processes, which can minimize the core loss and manufacturing cost for producing the rotary transformer, are found, and they are presented in the transformer mechanical design proposal for the rotary transformer prototype.

1.4 Thesis Outline

This thesis is organized in eight chapters with the following content:

- **Chapter 1**, the current chapter, briefs the introduction about the background and scope of the thesis work. The overview and outline of the thesis are also presented in this chapter.

- **Chapter 2** gives a general introduction of transformers about the principle, various types, power loss and materials. A short review of rotary transformers is presented as well.

- **Chapter 3** presents the three-phase rotary transformer structure, power loss and core material selection.

- **Chapter 4** introduces iron loss models and develops an iron loss model for predicting the core loss of the three-phase rotary transformer.

- **Chapter 5** implements a two-dimensional transits finite element analysis on the power loss of the three-phase rotary transformer and presents a series of performance parameters of this rotary transformer.

- **Chapter 6** is a literature study of influences of the manufacturing process on the magnetic properties and iron losses in electrical steels. The manufacturing processes that are suitable for the rotary transformer prototype are presented in more detail in this chapter.

- **Chapter 7** proposes a mechanical design and assembly for realizing the three-phase rotary transformer.

- **Chapter 8** presents the main summary and conclusion about this thesis work and also suggests the possible future works on the three-phase rotary transformer design.
Chapter 2

Background

In 1830s-1880s, transformer was invented, developed and used in the real world, and it creates a milestone in the history of electrical engineering [22]. Transformers have been around in many electronic and electrical applications for quite a while, but fundamentals of them are still being investigated. A transformer, a static electrical device, transfers electrical signals or energy between two circuit networks by means of electromagnetic induction. It can have a single winding, or two or more coupled windings with or without a magnetic core for introducing mutual coupling between electric circuits. Magnetic flux couples the primary and secondary windings, so two circuit networks that locate in primary and secondary separately are not connected to each other. A transformer can modify levels of voltage and current, but it does not modify the frequency or, ideally, the amount of power being transferred from one winding to another.

2.1 Theory of Transformer

**Principle** The principle of a transformer depends on Faraday’s law of electromagnetic induction. As shown in Figure 2.1, a varying current $I_p$ in the primary winding $N_p$ creates a varying magnetic flux $\phi_m$ in the core by the applied voltage $V_p$, and a varying magnetic field impinging on the secondary winding $N_s$. The magnetic field induces an electromotive force (EMF) $E_2$ in the secondary winding.

![Figure 2.1: Ideal transformer](image)

The EMF of $E_1$ is

$$E_1 = N_p \frac{d\phi_p}{dt} \quad (2.1)$$
where $\phi_p$ is the varying magnetic flux produced by $V_p$, and $\phi_p = \phi_m \cos(2\pi ft)$.

**Turns ratio** A transformer can achieve the difference in voltage between the primary and the secondary circuits by changing the turns ratio between the primary and secondary windings. The voltage ratio between primary and secondary windings is directly proportional to the turns ratio, which is expressed by

$$n_{TR} = \frac{N_p}{N_s} = \frac{V_p}{V_s}$$

(2.2)

where $N_p$, $N_s$, $V_p$ and $V_s$ are coil turns and voltages of primary and secondary windings.

The turns ratio dictates the operation of the transformer and the corresponding voltage available on the secondary winding. The apparent load of primary $Z_p^l$ is dependent on the turns ratio, which is expressed by

$$Z_p^l = \frac{V_p}{I_p} = n_{TR}^2 \frac{V_s}{I_s} = n_{TR}^2 Z_s^l$$

(2.3)

where $Z_s^l$ is the apparent load of the secondary circuit.

**Efficiency** An ideal transformer has a coupling coefficient of 1.0 and no internal losses; the powers in the secondary and primary windings are exactly equal. In real transformers, however, because of losses the secondary power is less than the primary power. The efficiency of a transformer is the ratio of the output power to the input power.

$$\eta(\%) = \frac{P_{out}}{P_{in}} \times 100\%$$

(2.4)

where $P_{out}$ and $P_{in}$ are the real output and the input powers, which are expressed by

$$P_{out} = Re\{V_s I_s\}$$

$$P_{in} = Re\{V_p I_p\}$$

(2.5)

where $V_p$, $I_p$, $V_s$ and $I_s$ are voltages and currents of the primary and secondary windings. It should be noted that the active power is used for the power efficiency calculation rather than the item of apparent power or reactive power. A real transformer cannot achieve an efficiency of 100%, which leads designers to analyse the losses and influencing factors.

**Power Factor** Power factor is the relationship between active power and apparent power, which is expressed by Equation 2.6.

$$\cos \varphi_{PF} = \frac{P}{S}$$

(2.6)

where $P$ is the active power in W and $S$ is the apparent power in VA, which are expressed by Equation 2.7 and 2.8, respectively. In case of transformer, the active power is the real power transmitted from the transformer to load, and the apparent power is the basis for the transformer power rating.

$$P = IV = I^2R \text{[W]}$$

(2.7)
\[ S = I_{\text{rms}} V_{\text{rms}} [\text{VA}] \]  

(2.8)

**Voltage Regulation** The voltage regulation of a transformer is defined as the change in secondary terminal voltage when the transformer loading is at the full-load applied while the primary supply voltage is kept in a constant. The voltage regulation determines the voltage drop that occurs in the transformer as the load voltage becomes too low as a result of the transformers loading being too high which therefore affects its performance and efficiency.

The voltage regulation, expressed in Equation 2.9, is the percentage of voltage difference between no load and full load voltages with respect to the full load voltage.

\[ VR = \frac{V_{\text{no-load}} - V_{\text{full-load}}}{V_{\text{no-load}}} 100\% \]  

(2.9)

### 2.2 Transformer Types

Depending on purpose, use and construction, transformers can be categorized in different ways. Generally, types of transformer are:

- **Power/distribution/instrument transformer** (Power rating and purpose)
  - **Power transformer** is generally used in transmission networks of higher voltages (up to 36 kV) for step-up and step-down applications, and it is generally rated above 2.5 MVA. It transfers electric energy in any part of the circuit between the generator and the distribution primary circuits [23].
  - **Distribution transformer** is used in lower voltage (e.g., 11 kV, 6.6 kV, 3.3 kV, 440 V, 220 V and 110 V) distribution networks as a means to end user connectivity, and it is generally rated less than 200 MVA.
  - **Instrument transformer** is used for instruments or measuring high voltage or high current. It isolates the secondary control or meter circuitry from the high voltage or current circuit that is connected to its primary winding.
  - **Step-up/down transformer** is used for stepping up or down the voltage level of power in power transmission or distribution networks.

- **Single/poly-phase transformer** (Electrical structure)
  - **Single-phase transformer** is typically used for single-phase power transmission or distribution. It has only one primary winding and one or more than one secondary windings.
  - **Poly-phase transformer** is constructed by multiple single-phase transformers. A poly-phase transformer can have a two-phase, three-phase, six-phase or even 24-phase that is used for DC rectification [24].

The most common poly-phase transformer is the three-phase transformer used for electrical power generation, transmission, distribution and many industrial applications. A three-phase power system is advantageous over a single-phase power system, which requires a lesser amount of conductors for transferring the same amount of energy as compared to the single-phase power [25]. The primary and secondary
windings of a three-phase transformer can be connected in different configuration (e.g. Delta, star or interconnected star) to meet practical requirements [26].

- **Isolation/auto transformer (Electrical structure)**
  - **Isolation transformer**: There is no direct electrical connection between two windings. They are independently isolated and insulated from each other but are coupled by mutual induction to transfer power or signals. An isolation transformer can be a two-winding transformer or three-winding transformer.
  - **Auto transformer** has the usual magnetic core but only one single winding; the primary and secondary circuit are electrically and magnetically linking together by the transformer [27]. Therefore, it is an economy and high efficiency transformer used in voltage step-up/down applications; however, the primary and secondary windings do not have an isolation coupling of a conventional double-wound transformer [28].

- **Ordinary/rotary transformer (Mechanical structure)**
  - **Ordinary transformer** (or static transformer) is the general transformer widely used in the world. The primary and secondary winding are using a common core to achieve power and signals transmission and electrical isolations.
  - **Rotary Transformer** has the particularity of an air-gap to enable the rotation between the primary and the secondary. Comparing an ordinary transformer, the primary and secondary windings of a rotary transformer have separate cores to transfer power and signals over a physical distance, which can replace slip rings or brushes across the rotary interface [7].

- **Shell/core structure transformer (Magnetic circuit structure)**
  - **Shell transformer**: The windings of a shell type transformer are completely surrounded by transformer core.
  - **Core transformer**: The coils are wrapped around the core.

As shown in Figure 2.2, three-phase cores are constructed in three-, four- or five-leg construction [26].

![Figure 2.2: Three-phase core construction](image)

The three-leg type three-phase transformer is the most common method of three-phase transformer construction allowing the three phases to be magnetically linked. Flux of each leg uses the other two legs for its return path. However, compared with the four-leg and five-leg type, three-leg core does not provide a low reluctance path for flux, which causes more core losses.
liquid-immersed/dry-type transformer (Cooling solution)

- **Liquid-immersed transformer**: It is an insulating oil filled or synthetic insulating liquid filled transformer. Its magnetic circuit and windings are immersed in the liquid. Those insulating liquids can help cool the transformer. Some high-power rating transformers may have external active or passive cooling units such as cooling fans, pumps and oil-to-water heat exchangers to improve the heat emission efficiency [29].

- **Dry-type transformer**: Its cooling system is implemented with natural air circulation. A dry-type transformer has a mechanical enclosure with a low ingress protection (IP) rating with comparing a liquid-immersed transformer [30].

The enclosure of both types of transformers is made of high thermal conductivity metals such as aluminium alloy. Furthermore, the outer surface of an enclosure has many fins (heat sinks) that can increase the area of heat dissipation.

### 2.3 Power Loss in Transformer

#### 2.3.1 Winding Loss

Winding loss is resistive loss or copper loss, which is created by an electrical current in the winding. Equation 2.10 presents the relation between the copper loss and current.

\[
P_{\text{cu}} = I^2R
\]  
(2.10)

The total copper loss of the primary or secondary in a poly-phase transformer is the sum of losses of all phase windings, which is expressed by Equation 2.11.

\[
P_{\text{cu-total}} = \sum_{n=1}^{N} I_n^2(R_{\text{coil}_n} + R_{\text{ter}_n})
\]  
(2.11)

where \(n\) is the index for every phase, \(N\) the total amount of phases, \(R_{\text{coil}_n}\) and \(R_{\text{ter}_n}\) the resistance of the \(n\)th phase winding and its terminals, receptively, and \(I_n\) the RMS current in the \(n\)th phase winding. Since the both primary and secondary currents depend upon the load of a transformer, copper loss in the transformer vary with the load.

In Equation 2.11, the resistance is dependent on the material and geometry of the conductor, and it is

\[
R = \frac{l\rho}{A}
\]  
(2.12)

where \(l\) is the conductor length, \(\rho\) is the conductor resistivity, and \(A\) is the cross-sectional area of the conductor.

Furthermore, in AC power system, depending on the conductor cross-sectional area and frequency, the skin effect and proximity effect have to be taken into account. When an AC flows through an electrical conductor, the outer surface of that conductor carries more current as compared to its center, which results in higher resistance to AC and is called skin effect. Proximity effect is that the alternating flux in a conductor is caused by
the current of the other nearby conductor. The description of these effects’ calculations can be found in [31].

### 2.3.2 Iron Loss

The iron losses are also referred as core losses. They are created by the varying magnetic field in the iron parts of the machine. The two basic components of the iron losses are the hysteresis and the eddy current losses. Both of these components result in the same physical phenomenon which is Joule heating.

**Hysteresis Loss**  Hysteresis loss is a part of loss of a transformer, which depends upon the following factors [32]:

- The hysteresis loss is directly proportional to the area under the B-H curve i.e area of the hysteresis loop.
- It is directly proportional to magnetization frequency.
- It is directly proportional to volume of the material.

Hysteresis losses originate from the molecular magnetic domains in core laminations, resisting being magnetized and demagnetized by the alternating magnetic field [33]. Because poles of magnetic field in the core of a transformer is alternately shifted by the magnetizing of alternating current. Each magnetizing cycle two poles of the core is magnetized to their opposite poles, i.e. the direction of magnetic field is changed. The process of magnetizing needs power to change the two poles, but the power to finish this magnetizing comes from the input power and is not transferred to the secondary winding. Additionally, this magnetizing causes power losses that are dissipated as heat [34]; if the heat is transferred to windings, it will increase the electrical resistance and lead to more ohmic losses.

In one cycle of magnetizing, the hysteresis loss (\(P_h\) in W) is expressed by Steinmetz Formula [35, 36]:

\[
P_h = K_h f V (B_{max})^n
\]  

(2.13)

where

- \(K_h\) – It is the constant dependent on the characteristics of core.
- \(f\) – the frequency of a varying magnetic field (Hz)
- \(B_{max}\) – the maximum flux density of the magnetic field (T)
- \(n\) – the Steinmetz index, it depends on the structure of a transformer core.
- \(V\) – the volume of magnetic material (\(m^3\))

**Eddy current Loss**  The eddy current is applied to an electric current which circulates within a mass of conductor material, when the material is situated in a varying magnetic field. In a transformer, according to Faraday’s Law, it is caused by a changing magnetic flux that passes through the transformer core.

Eddy current loss comes from two phenomenons. First, a transformer core is a kind of electrical conductor, and a current will be induced by a changing magnetic flux in the core; The eddy current can result the heating because the core has an ohmic resistance. Second, eddy current essentially is a kind of electric currents, and it can generate a magnetic field
that has an opposite direction force to against the power of the magnetic field produced by the primary. To reduce these losses, higher resistivity core material and thinner lamination of transformer core are used.

The eddy current loss is expressed by

\[ P_e = K_e f^2 (B_{\text{max}})^2 (\tau_l)^2 V \]  

(2.14)

where

- \( K_e \) – It is the eddy current coefficient dependent on magnetic materials.
- \( f \) – the frequency of a varying magnetic field (Hz)
- \( B_{\text{max}} \) – the maximum flux density of the magnetic field (T)
- \( \tau_l \) – the thickness of laminations (m)
- \( V \) – the volume of a transformer core (m³)

### 2.4 Transformer Materials

#### 2.4.1 Winding Conductor

Windings of a transformer are constructed by magnet wires. Magnet wire or enamelled wire is a copper or aluminium conductor has a thin insulation layer.

**Insulation** The insulation layer for a magnet wire that has different sizes, temperature ratings and applications. TEMCo Industrial Power Supply ¹ lists some common insulation types and their specifications.

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Thermal Class</th>
<th>Diameter [mm]</th>
<th>Diameter [in.]</th>
<th>AWG Wire Size Range</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane</td>
<td>120°C, 130°C, or 155°C</td>
<td>0.08 to 1.00</td>
<td>0.0031 to 0.0064</td>
<td>20-18</td>
<td>Transformers, meters, and communication devices.</td>
</tr>
<tr>
<td>Polyester</td>
<td>155°C</td>
<td>0.08 to 1.00</td>
<td>0.0031 to 0.006</td>
<td>20-14</td>
<td>Motors in household appliances.</td>
</tr>
<tr>
<td>Polyester-imide</td>
<td>180°C</td>
<td>0.1 to 1.00</td>
<td>0.0039 to 0.0054</td>
<td>36-18</td>
<td>High powered motors.</td>
</tr>
<tr>
<td>Polyesterimide</td>
<td>220°C</td>
<td>0.1 to 1.0</td>
<td>0.0094 to 0.013</td>
<td>36-14</td>
<td>Small motors and transformers.</td>
</tr>
<tr>
<td>Self-bonding polyester</td>
<td>130°C</td>
<td>0.08 to 1.2</td>
<td>0.0031 to 0.0472</td>
<td>20-16</td>
<td>Communication apparatus and small motors.</td>
</tr>
<tr>
<td>Self-bonding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester-imide</td>
<td>180°C</td>
<td>0.1 to 0.8</td>
<td>0.0039 to 0.031</td>
<td>38-20</td>
<td>Used in magnetic coils and deflection yoke application.</td>
</tr>
<tr>
<td>Polyesterimide</td>
<td>150°C or 180°C</td>
<td>0.08 to 1.0</td>
<td>0.0031 to 0.003</td>
<td>20-14</td>
<td>Small motors and transformers.</td>
</tr>
<tr>
<td>Polyesterimide</td>
<td>155°C or 180°C</td>
<td>0.1 to 1.0</td>
<td>0.0039 to 0.003</td>
<td>36-14</td>
<td>Used in small motors.</td>
</tr>
<tr>
<td>Polyesterimide</td>
<td>200°C</td>
<td>0.1 to 1.0</td>
<td>0.039 to 0.063</td>
<td>36-14</td>
<td>Microwave oven transformers and air-conditioning motors.</td>
</tr>
</tbody>
</table>

¹) www.temcoindustrialpower.com/

**Conductor Material** The windings consist of the current-carrying conductors wound around the sections of the core, and these must be properly insulated, supported and cooled to withstand operational and test conditions. Copper and aluminium are the primary materials used as conductors in transformer windings. Because the electrical conductive of aluminium is lower than that of copper, a larger cross-sectional area of aluminium conductor is required to carry a current with similar performance as a copper
conductor. Copper has higher tensile strength (TS), 220 MPa, and is used almost exclusively in all but the smaller size ranges, where an aluminium conductor may be acceptable because of its low expense (approximately 25-40% in cost savings) and lightweight nature (low density, 2.70 g/cm³). Additionally, pure aluminium is not used as an electrical conductor in equipment since it is too soft for mechanical assemblies and is thus alloyed with other materials [37].

**Utilization Factor** The window utilization factor can determine the amount of a conductor that occupies the window area of the transformer, which is expressed by:

\[
K_u = \frac{S_1}{S_2} \frac{S_3}{S_4}
\]

(2.15)

where

- \(S_1\) — conductor area or copper area
- \(S_2\) — the window area
- \(S_3\) — the usable window area
- \(S_4\) — the sum of the usable window area and insulation area

Theoretically, a coil wound by a round wire in square winding pattern has the square magnet wire has less space between the wires when wound in a coil. The round wire has the fill factor of 0.785 in square winding pattern, the fill factor of 0.907 in hexagonal winding pattern, and the square wire has the fill factor of 1. Thus, the square wire has a high lay fill factor and can be used in confined spaces.

### 2.4.2 Electrical Steel

For low frequency designs (50/60 Hz), where the losses produced by eddy current and hysteresis effect are low, the materials used are usually silicon-steel laminations.

**Introduction to Electrical Steel** Electrical steel is a ferromagnetic material which has enhanced soft magnetic properties (such as having a small hysteresis area, high permeability, low coercivity and high saturation magnetization) and is used for the magnetic flux-carrying cores of electrical machines, transformers and generators, in which it is used to amplify the magnetic flux. The characteristics of electrical steel have direct impact on the performance and efficiency of above electromechanical devices.

When a transformer core is magnetised and then demagnetised due to an alternating magnetic field, it absorbs energy and causes hysteresis loss and eddy current loss. Electrical steel is an alloy material that has a low power loss, which is achieved by adding silicon (Si) to the molten steel (Fe). Si can increase the electrical resistivity of the steel to decrease the induced eddy currents and narrow the hysteresis area [38]. However, the electrical steel is still a good conductor that has a low electrical resistivity in the range of \(12 - 50 \times 10^{-8} \Omega \cdot m\) [38]. To minimize eddy current loss a transformer core is stacked together by thin lamination sheets with the thickness of 0.1 – 1.0 mm and a thin electrical insulation coating with approximately 1µm thick [39–41].

In a transformer core manufacturing, different cutting methods, such as laser cutting, punching, wire electrical discharge machining (WEDM), water jet cutting, etc, also influence on the magnetic properties of steel material. Electrical steel cutting procedure is an
unavoidable step in a transformer core manufacturing, and more details are presented in Chapter 7.

**Texture of Electrical Steel** Crystallographic texture is one of the most important parameters determining the magnetic properties of steel sheets, which divides electrical steel into two groups, the grain oriented (GO) electrical steel and non-oriented (NO) electrical steel.

The texture of NO electrical steel is a Cube texture. The Cube texture is its (001) or (110) plane parallels to the sheet plane (i.e., the [100] direction normal to the sheet plane) and has a uniform distribution of the [100] direction. Hence, NO electrical steels have uniform magnetic properties in all directions with respect to the rolling direction (RD) [42]. They are used in rotating machines where the direction of magnetic flux is circular, such as motors, generators and alternators.

The texture of GO electrical steel is a Goss texture with (110)[001] orientation in which cubic crystals are all arranged in the RD. Hence, a GO steel is very anisotropic and has much better permeability properties in the RD than it has at 90 degree to RD (i.e., transverse direction (TD)) [43]. GO steels are used in transformers, transducers and magnetic amplifier cores. GO steels can be used also in small electrical machines, but it is ensured during a core construction that the lamination sheets are stacked at random so the permanence of the machine does not very in different directions [44].

**Grade of Electrical Steel** The grade of electrical steels is classified by many standards. For example, as presented in European Standard EN 10106 2), the grade of M800-50A means that an electrical steel has a dissipation power of 8 W/kg at a peak flux density of 1.5 T and a frequency of 50 Hz. Figure 2.4 shows the details of M800-50A nomenclature.

![Figure 2.4: Nomenclature of M800-50A presented in European Standard EN 10106](image)

Electrical steel manufacturers and researchers use a standardized method named Epstein frame experiment 3) to characterize and investigate the magnetic properties and iron loss of electrical steels over a range of frequency and induction level. The working principle of an Epstein frame is similar to an unload transformer. It has a primary winding, a secondary winding and the specimen of electrical steel strips as the transformer core. The iron loss is measured by using watt-meter method. An Epstein frame is applicable to GO and NO electrical steel sheets for AC measurements up to 400 Hz and also for DC measurements [45–47].

---

2) European Standard EN 10106 specifies cold-rolled NO electrical steel strip and sheet in nominal thickness of 0.35 mm, 0.50 mm, 0.65 mm and 1.00 mm

3) International Electrotechnical Commission, IEC 60404-2
2.5 Review of Rotary Transformer

A rotary power transformer is used to couple the electrical power between two units that rotate in relation to each other. It has the particularity of an air-gap to enable the rotation between the primary and the secondary. The principle of a rotary transformer and a conventional transformer has no difference, which is that both of them can transfer electrical power between two galvanic isolation circuits by means of electromagnetic induction. Thus, the rotary power transformer can be developed to replace slip-rings and brushes to achieve that the power transfer can implement over a physical distance. Using rotary power transformer is one application of CET system for loads located in rotor part. A contactless transformer has a large air-gap as compared to conventional transformer. So its construction causes large leakage inductance, small magnetizing inductance and low coupling coefficient. Therefore, due to the small magnetizing inductance a large amount of magnetizing current flows through the entire primary windings, and it lowers the overall system efficiency. Additionally, the large air-gap causes a high probability of noncompliance with electromagnetic compatibility (EMC) and safety regulations.

Though a contactless power transformer has the low coupling coefficient and brings unsafely matters on EMC, it can be used in some particular applications where conventional connection solutions such as cable, slip-rings and brushes that are either impractical or cause dangerous of friction, wear and intermittent contact. Thus, the rotary power transformer that is used for powering the new DC motor with on-rotor drive system can avoid the problems above, extremely improve its power efficiency and working life and reduce maintenance cost of the entire system.

As shown in Figure 2.5, [48–52] present rotary transformers with different structures for their particular researches. (a) flat plane type and (b) axial type are the most common and easy way to insert coils. Because the air-gap is completely free, and it can be very small. It should be noted that both types have “two” air-gaps in the cross-section view, and they can aggravate the high magnetic flux leakage. [51] presents (c), a core geometry with single air-gap, which can achieve a high magnetic coupling. [52] presents (d) another kind of core construction that employs double windings on stator side to improve the coupling coefficient. Furthermore, because there are no any cores in the rotor, (c) and (d) can extremely lower the rotor’s weight, but they also have an expensive cast on the assembly of a three-phase rotary transformer. Comparing the four structures above, (a), (c) and (d) cause a complex assembly for the three-phase transformer, while (b) can be considered in

![Figure 2.5: Cross-sectional view of rotary transformer constructions](image-url)
this transformer design.

![Diagram of transformer design](image)

**Figure 2.6**: Single phase pulsating magnetic field-based system [54].

Considering the core manufacturing on rotary transformer design, [9, 51, 52, 54–57] use many U-shaped cores to constitute a circular array (Figure 2.6). Because cores are rectangular cuboid, they leave many unshielded sector areas between each of two cores. Therefore, this topology cannot cover all parts of windings and causes much more fringing and leakage flux. As presented in [52], this core structure uses an extra high permeability sheet around the primary and secondary for shielding to improve the magnetic coupling. According to these studies above, this thesis work explores a new geometry in core design to build a rotary transformer to have a completely shielded construction.

Most of contactless transformers are used to supply power [8–14] or transfer signals [7, 9] for a movable target located on a rotary shaft [7–10, 13] or a linear track [11, 12, 14]. Only few examples illustrate how to power the rotor unit of a motor system.

[48–50] present an application of three-phase rotary transformer used for powering the rotor unit of a brushless doubly fed induction machine. It shows that using a rotary transformer for the doubly fed induction machine can substitute the many disadvantages of brushes and slip-rings. However, it connects to a variable frequency drive (VFD) with working frequencies higher than hundreds of Hz rather than directly connects to the electric grid and using the mains voltage frequency. Those three papers also show the magnetizing flux behaviour obtained via an FEM software and present the unavoidable common problem of air-gap that can cause high a leakage/magnetizing reactance ratio.

[58, 59] present a design of an iron silicon axial rotary transformer for a wound rotor synchronous machine (WRSM) for an integrated starter generator (ISG). It adopts a sequential quadratic programming algorithm (SQP) and a coupled multi-physic model of a FEM program FLUX 2D to optimize a rotary transformer. It achieves that a coupled multi-physic models associated with the SQP optimization algorithm demonstrate that the rotary transformer is a good challenger for the gliding contacts system in WRSM. This paper also reveals that the choice of magnetic material for such applications mainly relies on the thermal conductivity, losses properties and mechanical strength of the material instead of the saturation flux density level.
2.6 Summary

First, the basic concept of the transformer was introduced as well as the different transformer types. Second, general losses of the transformer were presented briefly, including the theory and calculation formulae for determining winding losses and iron losses in transformers. Third, transformer materials, winding conductors and electrical steels, were introduced. Last, a short review of the design and utilization of rotary transformer was presented. Those basic concepts can assist the three-phase rotary transformer design that is presented in the next chapter.
Chapter 3

Three-phase Rotary Transformer Design

Nowadays, designing and achieving a high-performance and low-cost transformer is still a complex task. In electrical power transmission system, in order to minimize transmission losses many electrical grids deliver a high-voltage and low-current power over a long distance, and transformers are key units that can change the voltage level for different requirements of transmission systems and ultimate users. Reducing transformer losses and improving transformer reliability and performance have many challenges in scientific and engineering works. Olivares presents several challenges in a transformer design [60]: (a) to prevent transformers from too-high temperatures, (b) to provide sufficient insulation and to design the transformers so that they will withstand voltage conditions that are indicated on standards, (c) to manufacture transformers with low losses, (d) to produce transformer designs that can be manufactured, (e) to maximize transformer sales and to minimize transformer total owning cost, (f) to minimize transformer weight, (g) to minimize noise, etc. Because of energy shortage and environmental concerns Olivares also points out that (c) is a critical problem, and it is necessity to improve the efficiency of transformers [61].

Until 2009, the major source of electricity generation is still the fossil fuel and has 67% of the total source in the world [62]. The fossil fuel includes coal, peat, oil and natural gas, which cause emissions of carbon dioxide during the electricity generation. Low-efficiency transformers influence the environment because they require more power to support their work, which causes more emissions of carbon dioxide, and furthermore, these low-efficiency transformers also contribute to the greenhouse effect [63]. Contrary, a high-efficient transformer can reduce the energy consumed by itself and deliver more power for further purposes, which can optimize the electricity usage and reduce the environmental impact of electricity generation.

Hence, first of all, understanding the loss components of the rotary transformer is an essential requirement for achieving a high-efficient transformer in this design. Second, the high-efficient transformer will extremely improve the performance of the permanent magnet DC motor with on-rotor drive system. This chapter presents the structure of the three-phase rotary transformer and then analysis its power loss in more detail. Furthermore, this chapter also presents available materials used in the transformer and proposes an achievable core construction to use the transformer materials effectively.
### 3.1 Three-phase Rotary Transformer Structure

![Diagram of three-phase rotary transformer structure](image)

Figure 3.1: Three-phase rotary transformer structure

Figure 3.1 illustrates the construction of the permanent magnet DC motor with on-rotor drive system and the three-phase rotary transformer. More details are described as follows.

1. Because of the working principle of (a) the DC motor all electrical power consumption units (i.e., motor drive unit) of the motor are in the rotor side. The motor eliminates the usage of conventional brushes or slips ring, which requires a transformer to transfer power over a physical distance. Hence, in this rotating machine, the air gap is unwanted but unavoidable due to the necessity of physical movement required between the stator and the rotor.

2. (c) A single-phase transformer is viewed by three-dimensional form to example and present the structure of (b) the three-phase rotary transformer.

3. (f) Terminal box is the electrical connection interface between (d) the three-phase electric grid and (b) the rotary transformer.

4. (b) The rotary transformer with (e) the AC/DC unit achieves a wireless power transmission and converts the power from (d) the three-phase electric grid to a low-voltage and high-current DC power for (g) the motor drive unit.

5. (h) An external fan is added to blow outside air over the frame of the entire system to lower the transformer temperature.

This transformer can be categorized by:

- **Distribution and step-down transformer**: This transformer is used for low voltage application and decreases the input voltage of 230 V to a low voltage for every power phase to achieve a low-voltage and high-current transformer.

- **Three-phase transformer**: Three-phase power system is widely used in industrial applications. The motor must have a standard power interface and use a three-phase transformer for its usability of industrial environments.
• **Rotary Transformer**: To avoid the fraction and wear caused by slip rings or brushes, the rotary transformer can perform a non-contact operation to transfer three-phase utility power to the rotor side.

• **Dry-type Transformer**: The transformer has the power rating of 1.5 kVA with the efficiency of over 90%, and a few parts of the power is dissipated as heat. Thus, the dry-type cooling method can limit the temperature to a permissible range and ensure the long life and stable operation of the transformer and the DC motor. Hence, the entire machine is similar to a totally enclosed fan cooled (TEFC) motor.

### 3.2 Air-gap

The air-gap needed to separate the rotor from the stator should be as small as possible to minimize the magnetizing power loss, but a large air-gap, which can have an enough space, allows bigger manufacturing tolerances on their dimensions and the rotary movement resulting from mechanical deflection and looseness in their supporting bearings. Practical, the smallest air gap for industrial machines is around 0.2 mm. Considering the tolerances of the transformer manufacturing and assembly, this rotary transformer uses an air-gap with the thickness of 0.3 mm.

The permeability of a transformer core is related to copper loss through magnetizing current, which is reciprocally proportional to the square of permeability [64]. The approximation of copper loss is expressed by:

$$ P_{cu} = a(\mu')^{-2} + b $$

where $a$ and $b$ are constants in [65], and $\mu'$ is called apparent permeability that is the permeability of the transformer core with an air-gap and is expressed by Equation 3.2.

$$ \mu' = \frac{\mu_{core}}{l_{mag} + \mu_{core}\left(\frac{\delta_{air}}{l_{mag}}\right)} $$

where $\mu_{core}$ is the core material permeability, $l_{mag}$ the total magnetic path length, and $\delta_{air}$ the air-gap length.

The permeability of the core is not utilized fully since there is an air-gap in the magnetic path of the rotary transformer core. As expressed in Equation 3.2, the apparent permeability ($\mu'$) increases with increase of the permeability of the core itself ($\mu_{core}$). However, due to the air-gap has a low permeability, the $\mu'$ hardly changes when $\mu_{core}$ changes in a high range, but it can change remarkably if $\mu_{core}$ changes in a low range. Because the low $\mu_{core}$ range corresponds to the higher induction range, electrical steel sheets that have a high permeability at a high induction is required to reduce the copper loss due to the exciting current. In summary, an electrical steel sheet with a high magnetic permeability can improve the average permeability of transformer core and decreases the copper loss. Therefore, both low iron loss and high magnetic permeability are important for electrical steel sheets used in the high efficiency rotary transformer.
3.3 Configuration of Transformer Connection

This rotary transformer, due to the three-phase, is configured as a Delta-wye (Δ-y) connection. A Δ-y connected transformer has the following advantages for the design and application of the three-phase rotary transformer.

- The primary windings due to Δ connection can deliver the same power in a higher voltage and a lower current, which enables the copper conductors to have less cross-section area than that of conductors used in Y connection. Therefore a Δ connected primary can minimize the stator volume.
- A load connected phase-to-neutral or a phase-to-ground fault produces two equal and opposite currents in two phases in the primary circuit without any neutral ground current in the primary circuit [66].
- The neutral of the Y grounded is referred to as a grounding bank, because it provides a local source of ground current at the secondary side that is completely isolated from the primary circuit. Therefore, phase-to-ground faults or current unbalance in the secondary circuit will not affect ground protective relaying applied to the primary circuit [66].
- The Δ-y connection provides harmonic suppression [66]. The magnetizing currents have significant quantities of odd-harmonic components for the induced voltages to be sinusoidal. In a Δ-y connection, the third harmonic currents, being equal in amplitude and in phase with each other, are able to circulate around the path formed by the Δ-connected windings. However, in a Y-y transformer connection, the only path for the third harmonic current is through the neutral.

3.4 Power loss Analysis

The three-phase rotary transformer is a part and parcel of the permanent magnet DC motor, which transfers utility power to the drive system located in the DC motor’s rotor. The rotary transformer also contributes extra mechanical power losses (e.g., windage and friction loss) to the DC motor during the rotation. Figure 3.2 outlines various losses in the three-phase rotary transformer.

This thesis studies the rotary transformer as a static device and only investigates its copper loss and iron loss. Other kinds of electrical losses are briefly introduced in this section as well as the mechanical rotational losses.

- Electrical losses: They are caused by the power conversion between electrical and magnetic energy in the rotary transformer.
  - Winding loss and iron loss: The electrical operating principle of the rotary transformer is same as that of a conventional transformer. Electrical current flowing through the primary and secondary windings causes resistive heating of the magnetic wires. The iron loss includes hysteresis loss and eddy current loss. They depend upon the magnetic properties of the material used for building a transformer core. More details of both loss components have been presented in Section 2.3.1 and 2.3.2.
Stray loss: Stray loss is kind of power loss that remains after windings and iron loss and is originate from the mechanical construction parts in a transformer [67–69]. Not all the magnetic field produced by the primary couple to the secondary and some fluxes link with the mechanical structure and windings. These leakage fluxes may induce eddy currents within nearby conductive mechanical parts, such as fasteners for machine assembly and the rotary shaft in the rotor. Because the rotary shaft is an essential mechanical component in the rotary transformer, the stray loss caused by it should be taken into account for the transformer power loss study.

Magnetostriction: Magnetostriction is a property of electrical steels that can deform them during the magnetization [70]. In a transformer, because of alternating magnetization magnetostriction can vibrate the cores and windings to produce audible noise and friction heating, thereby causing power losses.

Mechanical losses: As in the complete permanent magnet DC motor, they are caused by the power conversion between electrical and mechanical energy. When the motor delivers the mechanical power to a load some mechanical losses occur in the motor.

Friction loss: The friction loss occurs in bearings and an air cooling fan of the motor. This loss is attributed to the force that it takes to overcome the drag and air resistance associated with rotating the rotor and cooling fan. The frictional loss depends upon the rotor speed, the diameter of the shaft at the bearing and coefficient of friction (COF) between the shaft and bearing [71].

Windage loss: The windage loss is due to the turbulence of a medium among the air-gap as the motor's rotor and stator move past each other. In more details, the windage loss is divided into three components: a) friction on the disks of the rotor spider, b) friction on the cylindrical surface in the air-gap and c) pumping of medium through unit [72].
3.5 Core Construction and Material Selection

The main parameters for selecting a core for the transformer are material, shape, and size. The frequency of the transformer to be operating is important for its material to be determined. This is due to the materials indifference in resistivity, which in turn would influence eddy current existence and behaviour.

Figure 3.3 shows the O-ring core structure of a single-phase. It is a shell type structure, which surrounds the winding completely. However, because of the fringing flux phenomenon caused by the air-gap, this shell type core can not reduce the EMI prorogation effectively. To prevent excessive eddy current loss within the metal of the core itself it must be laminated in a plane parallel to the flux path (More details are presented in Section 7.2). According to the flux direction respect to the rotary transformer axis, each core of the single-phase transformer has an unique name shown in the cross-sectional view.

![Figure 3.3](image)

**Figure 3.3:** Single-phase O-ring core structure. Left: axial view. Middle: cutaway view. Right: cross-sectional view. In the cross-sectional view, the flux passes through all cores in the counterclockwise by assuming the current flow of the primary winding is the out-of-plane direction. Hence, in all axial cores, the flux direction is parallel to the axis of the rotary transformer and, as shown in the axial view, it is parallel to the radial direction in all radial cores.

Figure 3.4 examples laminations that are cut from a roll of electrical strip. (a), the radial lamination, in which the magnetic flux may flow in any direction, is similar to a lamination used for producing an electric motor core. The axial core is produced by winding a long sheet strip cut from the electrical steel in TD or RD (see (b) or (c) in the figure). Due to the finite width of electrical steel, using many short discontinuous strips cut in the TD to form the axial core may complex and expensive in a strip-wound core manufacturing if the total length of all used axial laminations is bigger than the width of electrical steel. Contrary, the strip slitted in RD can have a relative infinite length, which is suitable for producing the axial core. It should be noted that, as illustrated in (b), the flux direction in the axial lamination is perpendicular to the RD, which results that the axial core does not use the electrical steel effectively, because the magnetic properties in the RD are superior to those in other directions.

ThyssenKrupp PowerCore M235-35A is used for the rotary transformer core study, and three reasons are presented as follows.

a) M235-35A is a NO electrical steel, in which the iron loss and magnetic properties are practically similar in any direction of magnetization in the plane of the sheet.
b) As presented in the given data-sheets of ThyssenKrupp PowerCore NO and GO electrical steels, although GO electrical steel has a lower iron loss than NO electrical steel, its low permeability limits the maximum magnetic flux density that can
be achieved in a transformer core. Section 3.2 presents that the air-gap lowers the transformer core permeability. However, using the NO electrical steel, due to its high permeability, can weaken the effects of air-gap as much as possible. By applying the same external $H$, using NO electrical steel can induce a higher magnetic flux density in the transformer core than using a GO electrical steel, thereby increasing the rotary transformer performance.

c) The electrical steel of M235-35A has the lowest inherent iron loss with 2.35 W/kg at 50 Hz and 1.5 T and the thinnest thickness with 0.35 mm in the series of PowerCore NO electrical steel. Thus, using the M235-35A can minimize the core loss and eddy current loss of the rotary transformer.

### 3.6 Summary

In this chapter, the structure and transformer category of the three-phase rotary transformer structure were introduced as well as the transformer winding connection. Then, according to the structure, the power losses were presented in more detail. Last, an achievable core structure and core material selection were presented.

This thesis studies the rotary transformer as a static electrical device, focusing on the electrical loss study. However, compared with the copper loss, the iron loss is the most complicated loss to predict in transformers. Therefore, it is discussed in more detail in the next chapters.
Chapter 4

Iron Loss Model Development for Three-phase Rotary Transformer

4.1 Iron Loss Model

To predict the iron losses during the design or optimization process of electric machines, engineers can choose from a wide range of models. [73] presents an overview of iron loss models, which categorizes different iron loss models into three types that are described as follows.

- The first type based on Steinmetz Equation and the loss separation models are preferable and best suited for fast and rough iron loss prediction. The models in first type can be easily integrated into an FEM simulation. Once the magmatic flux density is obtained, these models can present the iron loss for a certain electric machine.

  The iron losses based on Steinmetz Equation can be separated into three main components, referred to as hysteresis, eddy-current and excess losses. First two of them have been presented in Section 2.3.2. The last one, the excess loss, is due to dynamic losses of the Weiss domains caused by block walls discontinuous movements with the production of the Barkhausen jumps [74].

- In the second group, the models try to separate the total iron losses in several terms based on the influence of the physical variables (frequency dependency, alternating and rotational flux density behaviour, harmonic analysis, etc.)

- The third type is a more complex mathematical hysteresis model that can preform a higher accuracy of the iron loss prediction. This model needs much more information about the material data, prior material measurements and magnetic flux density waveforms in an electrical machine. Additionally, the integration into an FEM is more complicated, which is not just a post-possessing. This model is a part of the solving process, which takes into account the influence of the history of flux density waveform on the iron losses.
4.1.1 Iron Loss Prediction Errors

To predict the iron loss of an electric machine core, designers use the HB curve and specific core loss data set obtained from Epstein frame measurements or provided by data-sheets of electrical steel manufacturers to develop an iron loss model and embed it into a finite element method (FEM) simulation. However, two factors decrease the accuracy of the iron loss prediction.

- First, the negative influences of manufacturing processes on electrical steels due to their variety and complexity are hard to model or incorporate into the developed iron loss model.
- Second, because the shape of laminations differ from that of samples used in a standard test method, the FEM simulation, which uses the standard measurements, can not reveal the performance of an actual electric machine.

4.1.2 Iron Loss Determination

A correct material selection is important for the electric machine design since the magnetic properties of electrical steel dominate the performance of an electric machine. Furthermore, in the FEM study of an electric machine, the accurate prediction of the iron loss in the electric machine depends on the data provided by the measurement of manufacturers or on the data obtained by the measurement of designers themselves. Hence, an accurate measurement of electrical steels is required and necessary for the design, optimization and manufacturing of an electric machine.

There are various methods to investigate and evaluate the magnetic properties and iron losses of electrical steel laminations. For grading electrical steels or comparing electrical steels produced by different manufacturers, two standardized methods, Epstein frame measurement [75–77] and Single Sheet Tester [78–83], are applied. The specimens used in the measurements of both methods are rectangle strips, and their dimensions are controlled by IEC standards. O-ring core measurements are also used for evaluating manufacturing influences [84–87]. The geometry of a toroidal core formed by O-ring laminations is similar to the geometry of motor stator cores, and each O-ring lamination, unlike the overlapped strips of an Epstein frame, provides a closed magnetic flux path without any air-gaps. A detailed comparison of these test methods above is beyond the scope of this thesis, and this report only presents the Epstein frame measurement shown in Appendix B.

4.1.3 Iron Loss Model Development Step

The non-linear magnetic behaviours of an electrical steel cause that the iron loss mechanism presents a complex phenomenon. The fundamental physical characteristics of the iron loss of an electrical steel are not well understand, and there is no standard physics based a practical computational model for the loss calculation. Because of this, an empirical model, a mathematical approximation, is recognized as the best practical method for an iron loss estimation. [88] presents an iron loss model can be achieved by the following three steps.
Chapter 4. Iron Loss Model Development for Three-phase Rotary Transformer

- First, the iron losses data of a particular electrical steel sheet are obtained from an Epstein frame experiment at various operating points, such as magnetizing frequencies and induction levels.

- Second, these data are fitted to an iron loss mathematical model; unknown parameters of the model are determined by a data fitting algorithm, but some of them, such as eddy current loss coefficient, can be identified by standard formulae.

- Last, this model can be integrated in a computational process, such as an FEM-based simulation, to investigate the iron loss of an electric machine.

4.2 Iron Loss Model of M235-35A

This thesis uses the first type, the model based on Steinmetz Equation, for computing the iron losses of the rotary transformer in the COMSOL Multiphysics because the limited information of electrical steel M235-35A is given by the data-sheet.

This section and Chapter 5 follow the three steps presented in Section 4.1.3 to build and use an iron loss model for the rotary transformer core loss prediction.

- The first step has been finished by the manufacturer, and the iron losses data are shown in Appendix A;
- The result of the second step is shown in Equation 4.4, Figure 4.1 and Table 4.1;
- The last step is executed in Chapter 5.

Equation 4.1 is the iron loss formula based on Steinmetz Equation in frequency domain [89].

\[
P_{\text{iron}} = P_{\text{Hysteresis}} + P_{\text{Eddy current}} = d_1 \hat{B}^\alpha f + F_{\text{skin}} d_2 \hat{B}^2 f^2 (1 + \frac{d_3 \hat{B}^4}{F_{\text{skin}}}) \quad [\text{W/kg}] 
\]

where

- \(\hat{B}\) is the peak magnetic flux density in T;
- \(f\) is the magnetization frequency in Hz;
- \(F_{\text{skin}}\) is used in the eddy current loss term, which is given by Equation 4.2,

\[
F_{\text{skin}} = \frac{3 \sinh(\lambda) - \sin(\lambda)}{\lambda \cosh(\lambda) - \cos(\lambda)} \\
\lambda = \frac{d_{\text{lam}}}{\delta_{\text{skin-depth}}} \\
\delta_{\text{skin-depth}} = \sqrt{\frac{1}{\pi f \sigma \mu}} \quad (4.2)
\]

where \(d_{\text{lam}}\) is the thickness of the electrical steel sheet, \(\sigma\) is the electrical conductivity, and \(\mu\) is the permeability;
• $\alpha$, $d_1$, $d_3$ and $d_4$ are identified by a mathematical fitting procedure done on the measured data sets of iron losses;

• $d_2$ is given by Equation 4.3.

$$d_2 = \frac{\pi^2 d_{\text{lam}}^2 \sigma}{6\rho}$$  \hspace{1cm} (4.3)

where $\rho$ is the density of the electrical steel sheet.

It should be noted that, this iron loss model does not have the item of excess loss. The excess loss can be included in the classical losses to define one global eddy-current loss term [74].

Equation 4.4 is the time domain form of Equation 4.1, which describes the relation among the instantaneous power loss $P_\phi$, the flux density $\phi$, and the flux density change rate $d\phi/dt$.

$$P_\phi = \frac{d_1}{C_\alpha} \left(\frac{1}{2\pi f}\right)^{\alpha-1} |\frac{d\phi}{dt}|^\alpha + \frac{d_2}{2\pi^2} (1 + d_3 |\phi|^{d_4}) \left(\frac{d\phi}{dt}\right)^2 \text{ [W/kg]}$$  \hspace{1cm} (4.4)

where $C_\alpha$ is expressed in Equation 4.5 [90].

$$C_\alpha = 4 \int_0^{\frac{\pi}{2}} \cos^\alpha \theta \, d\theta$$  \hspace{1cm} (4.5)

As shown in Appendix A, the power losses of the M235-35A electrical steel in the rolling direction of 0°, 90° and 0/90° are different (The loss of 0/90° is the average iron loss of 0° and 90°). Thus, Equation 4.4 with corresponding parameters in Table 4.1 is employed in the FEM simulation to compute iron losses in the direction of 0/90° and 90°, respectively.

Table 4.1: Parameters for the iron loss prediction model of M235-35A in the rolling direction of 0/90° and 90°

<table>
<thead>
<tr>
<th>M235-35A</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD</td>
<td>0/90</td>
<td>90</td>
</tr>
<tr>
<td>$d_{\text{lam}}$</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$17.18 \cdot 10^6$</td>
<td>$17.18 \cdot 10^6$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>7600</td>
<td>7600</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.545</td>
<td>1.500</td>
</tr>
<tr>
<td>$d_1$</td>
<td>$15.78 \cdot 10^{-3}$</td>
<td>$22.05 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$d_2$</td>
<td>$45.56 \cdot 10^{-6}$</td>
<td>$45.56 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$d_3$</td>
<td>$61.03 \cdot 10^{-2}$</td>
<td>$33.85 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$d_4$</td>
<td>2.653</td>
<td>2.783</td>
</tr>
<tr>
<td>$C_\alpha$</td>
<td>3.4592</td>
<td>3.4868</td>
</tr>
</tbody>
</table>
Figure 4.1: M235-35A iron loss model predication vs. the manufacturer data-sheet at 50 Hz. Upper: iron losses in the 0/90° rolling direction; lower: Iron losses in the 90° rolling direction.
Chapter 5

Two-dimensional Transient Finite Element Analysis

This chapter presents the necessary settings of the AC/DC Module in COMSOL Multiphysics for the rotary transformer modelling. Furthermore, the utilization of the iron loss model in the finite element analysis of COMSOL Multiphysics is presented in more detail. Last, this chapter shows the simulation results and a series of performance parameters of the rotary transformer.

5.1 Model Definition

Operation of a transformer is characterised by strong dynamic interactions between the electrical subsystems on the primary and secondary sides and the magnetic subsystem. Transient finite element analysis of a transformer together with SPICE-coupled external electrical sources and loads is a powerful tool for the analysis and design of transformers [91]. The interface of Magnetic Field (MF) and Electrical Circuit (CIR) in the AC/DC Module are used in the rotary transformer transient finite element analysis.

The MF physics interface solves Maxwell’s equations, which are formulated using the magnetic vector potential and, optionally for coils, the scalar electric potential as the dependent variables. It is used to compute magnetic field and induced current distributions in and around coils and transformer cores. Table 5.1 shows the model builders of every domain for modelling the rotary transformer in the MF.

CIR models electrical circuits with connections to the magnetic field model, solving for the voltages, currents, and charges associated with the circuit elements. As shown in Appendix C, the CIR builds a SPICE model for modelling the electrical circuit of the three-phase rotary transformer. This SPICE model achieves a Delta-wye (Δ-y) connection three-phase transformer and provides electrical sources and loads for the rotary transformer design and analysis. Additionally, the SPICE model uses extra resistors assigned with dynamic resistance respect to time to simulate a simple inrush current limiter. This thesis studies the transformer performance in the steady state rather than the inrush current phenomenon. Modelling the inrush current limiter enables the transformer to enter the steady state quickly, thereby shortening the simulation time.
5.1.1 Geometry Drawing and Material Assignment

The transformer geometric model is defined by parameters in the COMSOL Multiphysics. This simplifies the creation of the geometrical model and enables changes of the dimensions under the Parameters node, which can be used for parametric studies for the transformer design optimization.

Appendix D shows the rotary transformer geometry drawn in the 2D axisymmetric plane of COMSOL Multiphysics. The surrounding air, a round domain with the radius of 250 mm, holds the three-phase rotary transformer that has the overall size of 129.60 × 79.83 (height × radius (mm)). The rotary shaft is also drawn in this geometry to model the transformer and calculate the power loss because it is made of stainless steel, which has an inferior magnetic capability but can absorb the energy. Figure 5.1 zooms in the domain distribution of one single-phase. Every domain is modelled as a specific part of the rotary transformer, and Table 5.1 lists the selected materials, model builders and equations.

Figure 5.1: Zoom view of the geometrical and the domain distribution shown in the area close to one phase of the rotary transformer. The magnetic wire used in the secondary windings is a rectangle copper conductor, which has a high lay fill factor and can minimize the rotor volume. A 0.3 mm-thick air-gap, the major one, exists between the stator and the rotor. Considering the core manufacturing tolerance, allowing four 3 µm-thick air-gaps, the minor ones, to exist in the contact area between each two adjacent cores.

Table 5.2 presents the specification of the magnet wires used for modelling the transformer windings. The primary and secondary windings use the real enamelled magnets, but the insulation coatings of them are made of a special material, such as polyestereimide or polyurethane. Adding insulations to the transformer model will make the model more complex and increase the simulation time because modelling insulations needs large numbers of extra domains to assign material to them. Additionally, the insulation is a non-metal material of which permeability is similar to air. Therefore, these insulation coatings are modelled as many air-gaps that surround the bare copper conductors and connect to the surrounding air of the transformer. The size of air-gaps between two adjacent turns...
### Table 5.1: Summary of characteristics of domains that are defined in the COMSOL Multiphysics

<table>
<thead>
<tr>
<th>Major domain</th>
<th>Material</th>
<th>Model builder</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surrounding air</td>
<td>Air</td>
<td>Ampère’s Law</td>
<td>Equ. 8.7</td>
</tr>
<tr>
<td>Rotor rotary shaft</td>
<td>Stainless steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor/secondary winding</td>
<td>Copper</td>
<td>Single-Turn Coil in group</td>
<td>Equ. 8.8</td>
</tr>
<tr>
<td>Stator/primary winding</td>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor-axial core</td>
<td>M235-35A</td>
<td>Ampère’s Law and Single-Turn Coil in group</td>
<td>Equ. 8.7 and 8.8</td>
</tr>
<tr>
<td>Rotor-radial core</td>
<td>M235-35A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stator-axial core</td>
<td>M235-35A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stator-radial core</td>
<td>M235-35A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

of a winding is double of the insulation thickness. Similarly, the insulation coatings of transformer laminations are not drawn as any specific domains but replaced by many narrow air-gaps. It should be noted that except for the insulation coatings, the apparent area of the laminated core due to the stacking factor of 97% is considered and, thus, divided equally into narrow areas to add to these air-gaps. Figure 5.2 examples the stator cores to present the geometry drawing of laminated cores.

![Figure 5.2: Zoom view of the stator-radial core and stator-axial core. The each lamination with the thickness of 0.361 mm consists of the 0.35 mm-thick bare electrical steel and two 0.055 mm-thick air domains, and which therefore results 0.011 mm-thick air-gaps between every two adjacent laminations.](image-url)
Table 5.2: Specification of magnet wires used in the primary and secondary windings

<table>
<thead>
<tr>
<th>Item</th>
<th>Primary</th>
<th>Secondary</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation material</td>
<td>Air</td>
<td>Air</td>
<td>–</td>
</tr>
<tr>
<td>Insulation thickness (mm)</td>
<td>0.04</td>
<td>0.05</td>
<td>–</td>
</tr>
<tr>
<td>Conductor material</td>
<td>Copper</td>
<td>Copper</td>
<td>$\sigma = 5.96 \cdot 10^7$ S/m</td>
</tr>
<tr>
<td>Shape</td>
<td>Round</td>
<td>Rectangle</td>
<td>–</td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>0.9 (diameter)</td>
<td>10 × 1.50</td>
<td>Bare conductor</td>
</tr>
</tbody>
</table>

5.1.2 Analytic Function Definition for Using Iron Loss Model

The iron loss model, Equation 4.4, is defined as a series of analytic functions in the COMSOL Multiphysics. The following settings demonstrate the analytic function definition for the model that computes the iron loss in the 0/90° rolling direction.

\[
P(0/90) \text{[W/kg]} = M23535A_{090\text{hyst}} + M23535A_{090\text{eddy}} \tag{5.1}
\]

Equation 5.1, an analytic function, separates Equation 4.4 into two terms to calculate the hysteresis loss and eddy current loss, respectively. The definition of every term is expressed by Equation 5.2.

\[
M23535A_{090\text{hyst}} \text{[W/kg]} = 1.5097 \cdot |dB_t|^1.5451
\]
\[
M23535A_{090\text{eddy}} \text{[W/kg]} = 0.01754 \cdot (1 + 0.61027 \cdot |B_t|^2.6526) \cdot |dB_t|^2 \tag{5.2}
\]

where dB_t and B_t are two arguments represent the flux density in T and the flux density change rate in V/m², respectively, and the rest of the numerical values are calculated based on the parameters in Table 4.1.

The iron loss in the 0/90° rolling direction can be calculated as the power in watt (W) if the core volume and electrical steel density are known. To obtain the core volume in the 2D-axisymmetric form modelling, this model uses the function of Integration component coupling and enables the option of Compute integral in revolved geometry to integrate every domain in volume. The density is given by the electrical steel data-sheet. As expressed by Equation 5.3, hence, the core losses can be calculated in W.

\[
P(0/90) \text{[W]} = (M23535A_{090\text{hyst}} + M23535A_{090\text{eddy}}) \cdot \text{Vol}_{\text{core}} \cdot \rho
\]
\[
P(90) \text{[W]} = (M23535A_{090\text{hyst}} + M23535A_{090\text{eddy}}) \cdot \text{Vol}_{\text{core}} \cdot \rho \tag{5.3}
\]

where Vol_{\text{core}} is the core volume, and $\rho$ is the electrical steel density.

All laminations in an axial core use the electrical steel in the 90° rolling direction, and all laminations in a radial core use the electrical steel in the 0/90° rolling direction. It should be noted that, because of different flux densities between the upper and lower radial cores, the total core losses must take them into account individually, rather than having an item that simply represents a double core loss of one radial core. Hence, the total core losses of a single-phase transformer is expressed by Equation 5.4.

\[
P_{\text{single-phase}\text{, core}} \text{[W]} = P_{\text{us}rc} + P_{\text{ls}rc} + P_{\text{ac}} + P_{\text{ur}rc} + P_{\text{lr}rc} + P_{\text{ac}} = P(0/90us) + P(0/90ls) + P(90s) + P(0/90ur) + P(0/90lr) + P(90r) \tag{5.4}
\]
where

- **usrc or 0/90 us**: upper stator-radial core
- **lscr or 0/90 ls**: lower stator-radial core
- **sac**: stator-axial core
- **urrc or 0/90 ur**: upper rotor-radial core
- **lrrc or 0/90 lr**: lower rotor-radial core
- **rac**: rotor-axial core

### 5.1.3 Slitted O-ring Lamination Modelling

As presented in Section 7.2.1, O-ring laminations used in radial cores have WEDM-cut slits to reduce the eddy current loss. However, it is hard to draw geometry for them in the 2D axisymmetric plane of the COMSOL Multiphysics. The solution for modelling this issue is that the O-ring laminations, which are like many single-turn coils, allow using the Single-Turn Coil in the MF to define all laminations as normal single-turn coils and to set the current excitation with 0 A for them.

It should be noted that, in 2D and 2D axisymmetric of COMSOL Multiphysics modelling, the direction of the current flow in the coil is assumed to be in the out-of-plane or in-plane direction. Therefore, this single-turn coil configuration for modelling slitted laminations can only reduce the eddy current loss that circulates the axis of the laminated core, and the eddy currents in other directions remain in the core.

### 5.1.4 Meshing of FEM Model

During the meshing process, the geometry is subdivided into finite elements. A successive mesh generation can lead to a mesh of high quality and a relatively small number of elements. COMSOL Multiphysics provides an interactive meshing environment, which allows users to mesh domains with different element sizes and shapes by using the automatic mesh generation or the manually definition that is executed by building a multiple meshing sequence.

Figure 5.3 zooms in the mesh generation close to the major air-gap. First, to simulate the thin laminations and to ensure convergence of finite elements every core domain, a set of thin laminations, requires a manually restricted element size with the maximum of 0.15 mm. Second, the coil domains are allowed to have a bigger element size of 0.3 mm. Finally, the surrounding air, the remaining domain, is meshed with Fine size (the max. element size is 26.5 mm, and the min. element size is 0.15 mm). After the meshing, the complete mesh of the rotary transformer consists of 1 065 873 elements, which require the memory of 22 GB for solving the problem.
5.2 Transient Simulation

As presented in COMSOL Multiphysics User Guide [92], a frequency domain study assumes linear material properties, which can not simulate a non-linear magnetic behaviour, and therefore could produce inaccurate results. Thus, using the Time Dependent is the only option for computing the accurate iron loss. Additionally, the Time Dependent study can reveal the instantaneous characteristics of the transformer, such as the inrush current and instantaneous power loss.

In the case of the transformer modelling, the time range and time step are set to 0 – 0.10 sec and 0.1 ms, respectively, in the Time Dependent configuration. In other words, this simulation analyses the rotary transformer in five 50-Hz periods with 1000 steps. The time range can not be short because the inrush current is several times as the normal full-load current when first energized, and keeps a few cycles of the input current. However, a large time range directly increases the simulation time. Additionally, the transformer enters and keeps a steady state when the inrush current phenomenon disappears. Hence, setting a large time range will simulate the transformer in the steady state repeatedly, which makes no sense to the transformer analysis. The time step is one of the significant factors dominate the simulation accuracy. Setting a small time step results more study steps in the transient analysis, which can increase the simulation accuracy, but resulting a large number of study steps requires a longer simulation time.

The problem has been solved on a COMSOL Multiphysics 5.2 in a Windows 7 operation system operated by a computer that has a memory of 64 GB and an Intel i7-5960X processor with eight cores and a clock frequency of 3.00 GHz. Due to the laminated core modelling, the laminations create a large number of elements after the meshing, which
increase the simulation time to over seven days (169 h 6 min 30 s).

5.3 Result

<table>
<thead>
<tr>
<th>Table 5.3: Specification of the three-phase rotary transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Dimension</td>
</tr>
<tr>
<td>Volume power density</td>
</tr>
<tr>
<td>Winding configuration</td>
</tr>
<tr>
<td>Pri. winding inductance</td>
</tr>
<tr>
<td>Pri. winding resistance</td>
</tr>
<tr>
<td>Pri. voltage</td>
</tr>
<tr>
<td>Pri. no-load current</td>
</tr>
<tr>
<td>Pri. current</td>
</tr>
<tr>
<td>Sec. voltage</td>
</tr>
<tr>
<td>Sec. voltage</td>
</tr>
<tr>
<td>Sec. current</td>
</tr>
<tr>
<td>Power factor</td>
</tr>
<tr>
<td>Active power</td>
</tr>
<tr>
<td>Operating frequency</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Voltage regulation</td>
</tr>
<tr>
<td>Pri. winding utilization factor</td>
</tr>
<tr>
<td>Sec. winding utilization factor</td>
</tr>
<tr>
<td>Rotor copper + core</td>
</tr>
<tr>
<td>Stator copper + core</td>
</tr>
<tr>
<td>Power density</td>
</tr>
</tbody>
</table>

Figure 5.4 and 5.5 display the voltage and current of the primary and secondary windings. As a step-down transformer, it converts a high-voltage and low-current power into a low-voltage and high-current power. The input voltage and current in the primary side are 398.37 V (line RMS voltage) and 1.88 A, respectively, giving an output voltage of 14.65 V at 26.80 A in the secondary side (approximate average values of three phases), when the transformer supplies a resistive load of 1.17 kW with the efficiency of 95.43% (see Figure 5.8 and 5.9).

Figure 5.6 and 5.7 shows the voltage and current of the rotary transformer that is operating at the no-load test. The secondary circuit (rotor circuit) is an open circuit, and there is no load on the secondary side of the rotary transformer and, therefore, the current in the secondary circuit is 0 A. However, the primary circuit has the no-load current of 1.35 A/phase. The no-load current $I_n$ is divided into two components, magnetizing current $I_m$ and working power current $I_w$. The magnetizing current, which produces the magnetic flux in the transformer core, dominates the no-load current but does not consume any power; the working power current contributes to the stator and rotor core losses (see the no-load power loss of Figure 5.10).
Every parameter shown in Figure 5.9 and 5.8 has an average value that used for evaluating the transformer performance. However, when the transform is first energized, the inrush current mechanism and the inrush current limiter cause an unstable electrical and magnetic phenomenon in the transformer. All parameters, hence, take into account only the data in the time of 0.08-0.01 s to calculate accurate average values to present the transformer characteristics at the steady state.

Figure 5.10 shows the various losses of the rotary transformer. They are also average values taken from the steady state duration. The analysis of these losses is presented in the following list.
The secondary copper loss is 18.58 W, but the primary copper loss of 33.72 W in the stator side is higher than in the rotor side. In this rotary transformer, the air-gaps reduce the slope of the BH loop, reducing permeability and inductance, thereby increasing the magnetizing current in the primary windings.

The losses of rotor cores are higher than that of stator cores since the radial direction flux increases the magnetic flux density in the rotor (see Figure 5.11) and therefore results more core losses.

As expressed in Equation 2.10, the copper loss is proportional to square of the current, and current depends on the load. Hence, the copper loss in the rotary
transformer varies with the load. Compared with the no-load test, the copper loss of full-load test increases remarkably.

- In the SPICE model, using a resistor with the resistance of 1 MΩ causes a non-ideal open circuit for the rotary transformer modelling. Therefore, the rotary transformer has a small rotor copper loss of 0.1 W under the no-load test.

- The stator core losses or rotor core losses in both tests are similar. Hence, the summon of all core losses, approximately 12 W in both tests, are independent on the load of the rotary transformer.
Additionally, due to the rotary shaft, a small stray loss of 0.05 W (not shown in the figure) also contributes to the rotary transformer losses.

Figure 5.10: Three-phase rotary transformer losses under full-load and no-load tests

![Three-phase rotary transformer losses](image)

No-load total loss = 20.802 W

Full-load total loss = 64.387 W

Stator copper loss
8.403 W (40%)

Rotor core loss
6.484 W (31%)

Stator core loss
5.815 W (28%)

Figure 5.11: Magnetic flux density distribution at \( t = 0.1 \) s under full-load test

![Magnetic flux density distribution](image)
Chapter 6

Review of Influences of Manufacturing Processes on Electrical Steels

The iron loss prediction is essential to the design and analysis of an electric machine. Achieving the accurate prediction of iron loss for designing an electric machine not only uses an accurate iron loss model but also considers the effects of manufacturing processes because they deteriorate the magnetic properties of electrical steels.

This chapter, according to the literature, presents the influences of different manufacturing processes on electrical steels to study the iron loss of the rotary transformer in the view of manufacturing process, which helps the research to achieve an optimum utilization of electrical steels, to produce the rotary transformer design that can be manufactured, and to use proper manufacturing processes and methods to minimize the power loss and total owning cost of the transformer. It is to be observed that three manufacturing processes, wire electrical discharge machining (WEDM), milling and sticking, are presented in more detail because their inexpensive and easy operation are suitable for the rotary transformer prototype design.

6.1 Overview

As shown in Figure 6.1, the production of an electric machine consists of different manufacturing steps. The first step is that the mother coil is split in narrow coils by using a slitting machine to suit punching or other cutting methods. The next step is that the narrow coils are decoiled and then, depending on the purpose, they are cut by different cutting methods. Core laminations are produced by punching, laser cutting, water jet cutting or WEDM, and, commonly, samples are cut to strips by guillotine. After the cutting processes, the laminations are stacked together to form machine cores, and using annealing recovers the magnetic properties. Last, the machine core is inserted into frames to finish the final stator.

Except for the annealing process, all of these manufacturing steps above induce mechanical and thermal stresses to the magnetic materials and deteriorate their magnetic and electrical properties, thereby degrading the performance of electric machines.
6.2 Mother Coil and Slitting Process

An electrical steel wound in a roll of electrical steel called mother coil (MC) as produced may be too wide to suit punching or other lamination cutting processes. It is necessary that the electrical steel coil be mechanically slit in several narrow ones (appropriate width) by a slitting process in an electric machine core manufacturing. As shown in Figure 6.1, a slitting process is operated by the cooperation of four units, namely, de-coiling machine, slitting cutter, edge burr removing machine and recoiler, to produce narrow coils [93]. It is important to note that, in [94], for specific power losses of an electrical steel, the variation from MC to MC is much larger, which means that even same grade electrical steels from different MCs have a significant deviation of magnetic properties.

The slitting process causes the deterioration of magnetic properties, which can degrade the performance of electrical steels. The slitting cutter mechanically damages the edge of electrical steel strips, which causes plastic deformations in the area close to the cut edge and induces external iron losses to the electrical steel. Additionally, plastic deformations also occur during the bending and tension in the slitting process [93]. While most transformer manufacturers consider these losses to be negligible for large widths of electrical steel with 300 mm or greater, it is in fact appreciable for narrow widths of less than 200 mm and can not be neglected [95].

6.3 Losses Due to Cutting Techniques

The electrical steel laminations used to a machine core manufacturing are typically cut from coils or strips into proper shapes by punching, laser cutting, WEDM or water jet cutting. Punching is a high speed cutting method and used in large scale production like in the automotive industry, while laser, WEDM and water jet cutting are commonly used in prototype, trial manufacture or small-lot production. An Epstein frame, a single sheet tester or other standardised measurements use the guillotine-cut strips to perform the specific iron loss certification and the magnetic properties characterization for grading.
Chapter 6. Review of Influences of Manufacturing Processes on Electrical Steels

electrical steels.

It is known that every cutting method influences the magnetic properties of cut laminations, which would degrade electrical steel and decrease the efficiency and performance of electric machine. Additionally, the deterioration of magnetic properties depends on the amount of cutting per unit volume [75, 96], on the angle of cutting relative to the rolling direction [78, 97], on the silicon content of the steel [78, 79, 98], and also on cutting parameters [80, 99, 100].

As presented in [100, 101], the cutting process is commonly found to have the most significant degrading effect of all manufacturing steps. By punching and guillotine cutting, a mechanical deformation occurs in the zone near the cut edge. Laser cutting and WEDM introduce a thermal stress in the cut edge, and water jet cutting also has small negative influences on electrical steel. Thus, using different cutting methods and their effects on electrical steel have to be taken into account in electric machine design and loss calculation. As shown in Table 6.1, a number of papers compared influences of different cutting methods on electrical steels, but this section does not present them in detail and only summaries what they studied and compared.

Table 6.1: Summary of references that presents the comparison of different cutting methods

<table>
<thead>
<tr>
<th>Comparison</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punching vs Guillotine</td>
<td>[76, 82]</td>
</tr>
<tr>
<td>Mechanical(1) vs Laser</td>
<td>[76–78, 102–104]</td>
</tr>
<tr>
<td>Mechanical(1) vs WEDM</td>
<td>[76, 101, 105–107]</td>
</tr>
<tr>
<td>Mechanical(1) vs Water jet</td>
<td>[108]</td>
</tr>
<tr>
<td>Laser vs Laser(2)</td>
<td>[77, 102]</td>
</tr>
<tr>
<td>Laser vs WEDM</td>
<td>[101, 106, 107]</td>
</tr>
<tr>
<td>Laser vs Water jet</td>
<td>[83, 108]</td>
</tr>
<tr>
<td>Laser vs Milling</td>
<td>[87]</td>
</tr>
<tr>
<td>Water jet vs Milling</td>
<td>[87]</td>
</tr>
</tbody>
</table>

(1) It is punching or guillotine method.
(2) Comparison of different laser cutting methods

6.3.1 Wire Electrical Discharge Machining

The principles of a WEDM is presented in [109]: the electrical energy is converted into thermal energy in the plasma discharge channel during the spark discharge, and the thermal energy melts and vaporizes workpiece material during the process. The spark always takes place within deionised water that cools the workpiece and the electrode as well as flushing away the eroded metal particles.

The electrode used in the WEDM is not in contact with the cut material so no mechanical force is applied during cutting [76, 109], but it generates a heat zone up to the width of 0.1 mm from the cut edge [109], which can induce the magnetic properties deterioration in case of electrical steel. However, the following papers indicate that WEDM is the best method compared with punching and laser cutting.

[101] reports the characteristics (chemical composition, and hardness) of cut edges and the magnetic properties of an electrical steel sheet cut by punching, laser cutting and
WEDM. The electrical steel after the WEDM has two more chemical elements, Cu and Zn, that are derived from the brass wire. Because of this the hardness of the electrical steel after WEDM is lower than that of the electrical steel after punching. The iron loss of the specimen cut by WEDM is lower than that of specimens cut by punching and laser cutting, and the permeability of the specimen after WEDM is higher than that of specimens after punching and laser cutting.

Another study in [105] shows the similar result: two electric vehicle traction motors’ core are form by laminations that are cut by punching and WEDM, respectively. It is found that the iron loss of the core formed by punching is larger than that of the core of the same shape formed by WEDM cutting. [106, 107] exams and compares laser cutting, mechanical cuttings, and WEDM by micro-magnetic analysis, which also concludes that WEDM has the lowest impact on the magnetic quality of the material. However, WEDM is only suitable for small quantities due to its low cutting speed. An example in [76] shows that the speed of the WEDM for cutting an electrical steel sheet with a 0.3-mm thickness is 7.5 mm/min.

6.3.2 Milling

Although water jet cutting is the best method for cutting electrical steels [83, 108], because of its expensive and complex set-up, it may not be available for small manufacturers. [87, 110] presents a milling method for cutting electrical steel laminations by using a conventional lathe. It has the advantage of low cost and simple operation and, significantly, it can also minimize the cutting influence on the electrical steels (see Figure 6.2). Commonly, the milling method is used for the motor machining during an electric

![Figure 6.2: HB curves and specific hysteresis losses of a turned undivided ring specimen and a water jet cut specimen at 50 Hz [87].](image)

machine production. The outer surface of a stator core is milled by a turning process to ensure that the stator is fit into its frame. The turning process also smooths the surfaces of the stator core and rotor core for achieving a precise air gap and/or reducing the windage loss.

The thermal issues caused by the fraction due to a turning process degrades the magnetic properties of the cut electrical steel, but it can be minimized by using a fluid to cool the electrical steel during this process.
An O-ring shape lamination can be handled by using a lathe, but a more complex shape can be achieved by using a computer numerical control (CNC) router with appropriate cutting speeds, proper milling cutters and a coolant.

6.3.3 Summary of Different Cutting Methods

The mechanical punching is the common process to cut electric machine core laminations, and the guillotine cutting is always used for cutting test strips for the determination of magnetic properties and specific iron loss of electrical steels by using standardized test methods. Both mechanical methods induce shearing stresses at the cut edges. Because of their contact operation, the tool wear always occurs, and they require maintenance after finishing a certain number of products.

Although the laser cutting, WEDM and water jet cutting are low speed cutting methods, their flexibility is the significant advantage for the research and development of an electric machine. Additionally, because of the non-contact cutting effect, they do not have the problem of the tool wear and also can avoid the mechanical deformation and burr generation at the cutting edges.

The laser cutting and the WEDM have the thermal effects on cut materials due to the high temperature generation during the cutting process. Furthermore, both cutting methods also add extra chemical elements to the cut materials, which could change their mechanical and magnetic properties.

The water jet cutting is the best method for cutting electrical steel sheets, because it is a non-contact and cool operation. However, its high cost does not lead an economical research on the rotary transformer design.

All cutting methods mentioned above are two-dimensional cutting techniques, which are suit for cutting thin sheets. The rotary transformer has a special mechanical structure, which demands that its laminated cores have to be as solid workpieces to cut. Using a normal CNC milling machine can produce a workpiece that has different geometrical shapes. Furthermore, the milling method presented in Section 6.3.2 has low effects on electrical steel sheet. Additionally, the milling method due to its low cost, easy operation and feasibility can be considered for producing the rotary transformer cores.

In the aspect of the iron losses caused by cutting methods, the cutting methods increase the iron losses by two mechanisms:

- The induced mechanical and/or thermal stresses during a cutting process cause a deterioration of the magnetic properties. In another word, due to deteriorated magnetic properties the cut laminations lower the permeability of the fabricated core. Hence, the core requires more magnetizing filed in order to obtain the same induction level. Therefore, the cutting method increases the hysteresis loss.

- Burr formation and insulation coating damage occur at the cut edges during a cutting process. The burrs and damaged insulation coating cause short circuits between adjacent laminations and increase the eddy current loss.
6.4 Losses Due to Stacking

This section presents the techniques that are used for stacking core laminations. Commonly, the pressing process is the first step for stacking the laminations after the cutting process, and then the laminations are permanently hold together by welding, interlocking, sticking or other stacking techniques. Each technique has the mechanical and/or thermal stresses on the electrical steel laminations, which degrades the magnetic properties and lower the performance of the electric machine.

Pressing  Pressing process stacks the cut laminations with pressure in the axial direction to prepare for welding, sticking or other methods to form the core. Applying force to laminations deteriorates their magnetic properties and thereby causes more hysteresis losses. In [111], measurements of two toroidal cores indicate that compared to the core without pressing process losses of the core with 1 MPa and 8 MPa pressing increase by 1% and 4% at \( B =1 \text{T} \), respectively.

Welding  After pressing, the stacked laminations are welded together at their external circumferences. This process can provide a reliable mechanical fixation for stacking laminations, but it causes mechanical and thermal stresses on electrical steel laminations, which degrades the magnetic properties and increases core losses [82, 100, 111–113].

Interlocking  As described in [114], the interlocking process of electrical steel stacking is that laminations are stamped and stacked manually or autonomously in a die system, which first makes protuberances on each lamination sheet and then rams them down into its adjacent lamination from the backside hole. The interlocking process mechanically compresses and expands laminations, which causes magnetic deteriorations and contributes to more core losses generation by narrowing the magnetic flux flows on individual lamination and increasing the eddy current through a set of laminations [114,115].

Fastening  Using riveting or bolt-fixing method forms an electric machine core, which needs extra fasteners to stack laminations. For large motors, the entire core is locked tightly in the axial direction by through bolts with plates at each end of the stacked core. Many E and I shape laminations of a transformer core have bolt holes in their corners, which allow insulated rivets or bolts to be inserted into to hold laminations together. Riveting and bolt-fixing methods can also induce more core losses, which is similar to losses caused by interlocking process. Bolt holes narrow the magnetic flux path on individual lamination; if a bolt has the damaged insulation coating, it will increase the eddy current through the stacked laminations.

6.4.1 Sticking

Simply, a sticking process is that applying glue on both sides of each lamination enable all laminations to be bonded to form a machine core through a heating process. The sticking has very low or even negligible effect on the magnetic properties of electrical steels, since the glue material has no magnetic contents. Therefore, the degradation due to the sticking could be caused by the thermal stress during the unavoidable heating process.
[111] reports that the sticking process is the best method for the lamination stacking. The experiments indicate that welding with 2 seams increases the iron losses by nearly 80% compared to a glued core, while the corresponding difference of a welding with 6 seams is 400% (see Figure 6.3).

![Figure 6.3: Increase of the specific magnetic core loss of a toroidal core after different manufacturing steps for a high Si-alloyed grade of non-oriented electrical steel [111].](image)

Figure 6.3: Increase of the specific magnetic core loss of a toroidal core after different manufacturing steps for a high Si-alloyed grade of non-oriented electrical steel [111].

However, [116] points two disadvantages of the sticking method: a) a glue can not meet any harsh requirements, and developing different kinds of glue will lead a high cost; b) the adhesive coating on laminations causes the low stacking factor for forming a core. Additionally, the sticking process requires the additional operation, applying glue, thereby increasing the manufacturing cost and production lead time.

### 6.5 Annealing

The annealing for electrical steels is designed to remove the carbon (decarburizing) from a bulk of laminations and enable the grain growth and stress relief [117]. The mechanical processes in the manufacturing of an electric machine heavily stress the machine’s cores, which degrade the magnetic properties of electrical steels. By an annealing process, the stress is removed, and the electromagnetic, thermal and mechanical properties are restored, which is critical to ensure that the electric machine will have the best performance and deliver minimum excitation losses [85, 118–121].

The effectiveness of annealing depends on temperature and time. Usually, the annealing temperature for the recrystallization is in the range of 700 - 800°C. In [120], two identical sets of rotor and stator of switched reluctance motors (SRM) are used in the same driver and test bench, while one set of SRM was annealed at 750°C for an hour after the punching process, and the other was not. It is found that the performance of the SRM can be enhanced when using the annealed electrical steel. In [122], the annealing is performed on a SiFe stator core at approximately 800°C for 8 minutes. It is shown that the iron losses of the sample decrease by 4.9% at the measurement of \( B = 1.5 \text{T} \).
[117] studies the annealing in the view of electrical steel grade. Figure 6.4 shows that the annealing reduces the specific iron loss, and therefore the electrical steels are improved by at least one grade.

Figure 6.4: Typical core loss values for conventional 0.35-mm thick fully processed electrical steel, as-received from the mill and compared with results after annealing. The typical data has been averaged across several supplies. [117]

The annealing process also has different influences on the magnetic properties of electrical steels before and after the cutting process. [118] investigated an annealing process on an electrical steel sheet (NO, 2%Si, 0.485-mm thickness) by a laser cutting method. The test sheets are characterized into four conditions:

- **JCUT**: a specimen is just cut
- **CUT+A**: a specimen is annealed after cut
- **A+CUT**: a specimen is annealed first and then cut
- **A+CUT+A**: a specimen is annealed, cut and annealed again

As shown in Figure 6.5, the hysteresis characteristic of specimens under the condition of CUT+A and A+CUT+A shows a lower value of the coercive field and a higher value of magnetization knee than other two specimens. CUT+A curve and A+CUT+A curve are very similar with almost the same remanence and coercive force values. Thus, in a practical electric machine production, choosing CUT+A can simplify the process of...
laminations to achieve an economical manufacturing and shorten the lead time for the final product.

6.6 Losses Due to Frame Assembly

In a frame assembly process, the stator of an electric machine is fitted with a cast iron or aluminium frame for protection from harsh environments. This assembly starts with the heating of the frame to ensure that it is expanded enough to be inserted into by the stator. When the frame turns cool, the stator is tightly embedded into the frame. However, the cooled frame induces radial compressive stresses to the stator, which deteriorates the magnetic properties of the electrical steel laminations.

Particularly, [123] compares the iron losses of a surface permanent magnet (SPM) motor before and after the frame assembly. The outer radius of the stator is bigger than that of the stator by 0.01 mm, which causes that the cooled frame applies the compressive stress with 4 Mpa on the stator core and increases the iron loss by 10% compared with the motor has no frame.

In [113], the frame does electrically contact the outer side of the inserted stator core, which causes an electrical connection area between the frame and laminations and creates a short circuit between insulated laminations. Thus, the frame assembly can also increase the eddy current loss.

Another option of the frame assembly is that normal press fitting and stator core fixation by glueing and screws introduce stress which has a negative impact on the iron losses [100, 124].

6.7 Summary

Through the literature review, this chapter gave the author a general understanding of the influences of manufacturing processes on electrical steels, and also covered different techniques of each manufacturing process, especially of the cutting process, and discussed their advantages and disadvantages.

This literature review also points out that cutting process has the most significant degrading effect on electrical steels in all manufacturing processes. There are many options for cutting electrical steels. In Section 6.3.3, different cutting techniques are presented and compared, and the relative papers that present the comparison of cutting techniques are summarized. Finally, it is found that the milling technique is a potential method for the rotary transformer core production.

It is known that the iron loss consists of two components, hysteresis loss and eddy current loss. The influences of manufacturing processes can be studied by analysing the hysteresis loss and the eddy current loss, respectively. In the view of individual lamination, the damaged zone due to mechanical and thermal stresses at the cutting edges has low magnetic permeability, which requires more magnetic field strength to obtain a certain induction level. Therefore, this mechanism increases the hysteresis loss. In the cross-sectional view of a laminated core, because of the burr formation, the insulation coating damage, the stacking process, and the frame assembly, the generated short-circuit currents between laminations increase the eddy current loss of the machine core.
Finally, Table 6.2 shows a summary of the references that are presented in this chapter, sorted by manufacturing process. Some papers focus on one of these manufacturing processes, but some of them concern more to present a comprehensive study. This chapter also starts a literature survey of transformer design for this Master by Research, but a complete transformer design involves numerous study fields. Additionally, with the development of new technologies and new research methods, a larger number of new papers spring up at an increasing rate. Hence, it is a great challenge to achieve a comprehensive literature survey in future works.

Table 6.2: Summary of references that study the influences of manufacturing processes on electrical steels

<table>
<thead>
<tr>
<th>Manufacturing Process</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slitting</td>
<td>[93, 95, 125, 126]</td>
</tr>
<tr>
<td>Cutting</td>
<td></td>
</tr>
<tr>
<td>Guillotine</td>
<td>[76, 78, 80, 96, 99, 118]</td>
</tr>
<tr>
<td>Laser</td>
<td>[77, 78, 82, 83, 96, 99, 101–104, 118]</td>
</tr>
<tr>
<td>WEDM</td>
<td>[76, 101, 105–107, 109]</td>
</tr>
<tr>
<td>Water jet</td>
<td>[83, 108]</td>
</tr>
<tr>
<td>Milling</td>
<td>[87, 110]</td>
</tr>
<tr>
<td>Stacking</td>
<td></td>
</tr>
<tr>
<td>Pressing</td>
<td>[100]</td>
</tr>
<tr>
<td>Welding</td>
<td>[82, 100, 111–113]</td>
</tr>
<tr>
<td>Sticking</td>
<td>[100, 111, 116]</td>
</tr>
<tr>
<td>Interlocking</td>
<td>[112, 114, 115]</td>
</tr>
<tr>
<td>Annealing</td>
<td>[85, 117–123]</td>
</tr>
<tr>
<td>Frame Assembly</td>
<td>[100, 113, 123, 124]</td>
</tr>
</tbody>
</table>
Chapter 7

Transformer Mechanical Design

A practical transformer design requires the knowledge of electrical principles, thermal analysis and material selection. Furthermore, to produce the transformer design that can be manufactured, to minimize transformer total owning cost and to prevent transformers from too-high temperatures, a designer has to deal with many engineering problems include mechanical design, cooling solution, mechanical assembly and cost control.

Chapter 5 designed and optimized the rotary transformer in the simulation stage and presented the final arrangement of copper windings and transformer cores. Chapter 6 presented a literature review to study the influences of manufacturing processes on electrical steels. According to the studies of both chapters above, this chapter presents a proposal of the mechanical design and assembly for realizing the three-phase rotary transformer.

7.1 Mechanical Design Overview

Figure 7.1 illustrates the major components of the three-phase rotary transformer. The core of the rotary transformer consists of three cylindrical stator cores that hold primary windings and three cylindrical rotor cores that hold secondary windings. Three separate cores, two radial cores and one axial core, construct a complete single-phase rotor core or stator core (see Figure 7.2). All rotor cores fit inside the stator cores with a slight air-gap separating it from the stator. Hence, there is no direct physical connection between the rotor and the stator.

The secondary windings use rectangle copper magnet wires that have a high fill factor to minimize the rotor volume. The primary windings use normal round copper magnet wires with the diameter of 0.98 mm rather than rectangle ones. A small size rectangle wire has relative large corner radius, which can not minimize the volume of the stator effectively. Additionally, the price of the small rectangle wire is much higher than the round one if purchasing a few wires for the transformer prototyping.

All terminals of the three secondary windings connect their inner turns of the corresponding coils and bend toward one end of the rotor. All rotor cores have slots to enable corresponding terminals to pass through them. Similarly, the stator cores also have slots to provide paths for all terminals of primary windings.

In addition to transformer cores and copper windings, this chapter also presents necessary mechanical components that are used for the transformer assembly, protection, cooling and mounting.
Figure 7.1: Cutaway view of the major components of the three-phase rotary transformer

Figure 7.2: Exploded view of the rotor assembly (left) and stator assembly (right) for each phase of the three-phase rotary transformer
Chapter 7. Transformer Mechanical Design

7.2 Winding and Core Design

7.2.1 Rotor-radial Core

Figure 7.3 presents the effect drawing and cross-sectional view of the final rotor-radial core. A bonding process is used for stacking 31 WEDM-cut O-ring shape laminations to fabricate the rotor-radial core. All laminations have same outer diameter but different inner diameters, which result the inner surface of the core is similar to a stair shape in cross-sectional view. Hence, the core requires a CNC milling method to smooth its inner surface.

![Figure 7.3: Effect drawing (left) and cross-sectional view (right) of the final rotor-radial core. Each lamination of the core has a WEDM-cut slit to reduce the eddy current loss. The rotor-radial core is stacked by 31 O-ring laminations with same outer diameter (OD) but with different inner diameters (IDs).](image)

The following two manufacturing processes of the rotor-radial core involve the magnetic anisotropy of the M235-35A.

**Slit Cutting** To reduce eddy currents circulating axially in the core each of laminations has a slit to break the eddy current path. Although the laminations are non-oriented electrical steels, their specific loss and permeability in the transverse direction (TD) are higher and lower than in the rolling direction (RD), respectively. Therefore, to minimize the core loss, the slit cut by the WEDM is parallel to the TD. Figure 7.4 examples three O-ring laminations with slits that are cut from an electrical steel strip by the WEDM.

**Lamination Placement** As shown in Appendix A, the M235-35A is an anisotropic material, and its magnetic properties are different in all directions, which is inevitably introduced during the electrical steel rolling process. To achieve the rotor core has a uniform performance in all directions, as shown in Figure 7.5, each of laminations is placed and rotated with an appropriate angle to ensure that an identical angular difference can be achieved between each two adjacent laminations. The angular difference depends on the number of laminations stacked in the core and is expressed by Equation 7.1.

$$\Delta r-\alpha = \frac{360^\circ}{N_{r-total}} = \frac{360^\circ}{31} = 11.61^\circ$$  (7.1)
A roll of electrical steel strip

Figure 7.4: O-ring laminations with slits cut from an electrical steel strip by the WEDM

Figure 7.5: Axial view of the angular displacement of 31 O-ring laminations in the rotor-radial core. The centre lines of these WEDM-cut slits are used as the reference lines. There is a constant angular difference $\Delta r-\alpha$ between two reference lines of two adjacent laminations.

Finally, a magnetic symmetry is present in the core after the lamination placement process, which enables the rotor to have a uniform performance in all directions.

Figure 7.6: Zoomed view of the red rectangle area of Figure 7.3

After the stacking process, the core is fixed in a CNC lathe to smooth the inner surface. Figure 7.6 zooms in the red rectangle area in Figure 7.3 and illustrates the first 5
laminations milled by the CNC lathe. It should be noted that, due to the thermal stress of the WEDM on the electrical steel sheet, every lamination has a magnetic damage zone \( t_{\text{WEDM}} \) from the cut edge. However, the CNC milling is similar to a water jet cutting process, which has little effect on electrical steels. Hence, in order to minimize the magnetic properties deterioration caused by the WEDM, each lamination has a smaller inner diameter to ensure that the entire deteriorated zone \( t_{\text{WEDM}} \) can be removed by the CNC milling.

### 7.2.2 Rotor-axial Core

Figure 7.7 shows the effect drawing of the rotor-axial core. The rotor-axial core, similar to a toroidal transformer core, is a strip-wound core with 42 layers, but its one end is cut by using a CNC milling method. Its contour is like a geometric shape that consists of an isosceles trapezoid and a rectangle in the cross-sectional view. The rotor-axial core has a slot on its side to enable both terminals of a secondary winding to pass through the core and go to the free O-ring space inside of the core (see Figure 7.9).

![Figure 7.7: Effect drawing (left) and cross-sectional view (right) of the rotor-axial core.](image)

The steel strip used for winding the rotor-axial core is cut from an electrical steel coil of M235-35A by a slitting process. After the core winding process, the CNC milling machine removes the milling part with the cutting angle of 36.43° from the top end to fit the inner surface of the rotor-radial core. Due to the tolerance of the core winding process, the bottom end may be not a flat surface. Therefore, the milling process is also required for smoothing the bottom end to ensure that the contact area between both rotor-axial cores does not have too much air gaps.

### 7.2.3 Secondary Winding

As shown in Figure 7.8, a copper magnetic wire that is used for producing a single-phase secondary winding is presented by 5 segments, namely, two coil groups (Coil Group 1 and Coil Group 2), two terminals (Terminal 1 and Terminal 2), and Joint turn. The cross-sectional view shows that the inner diameter and outer diameter of a secondary winding are 72.00 mm and 102.00 mm, respectively. However, unlike a normal coil or inductor, both terminals of the secondary winding in the inside, which require a special process to produce.
Coil Group 1 starts to wind the coil at Point A, but it ensures that an enough length should be remained for its terminal before the winding process. Then Coil Group 1 finishes its winding with 9 turns from the inside to the outside. Coil Group 2 is produced by the same winding process of Coil Group 1. The 10th turn of Coil Group 1 becomes Joint turn to connect the 9th turn of Coil Group 2. Finally, a complete secondary winding is achieved by the connection of Joint turn. It should be noted that Joint turn must have a precise length to ensure that all terminals of three single-phase windings are uniformly distributed and not overlapped in the free O-ring space between the rotor cores and the shaft (see Figure 7.9).

The length of the horizontal segment depends on the phase location in the rotary transformer. Hence, all secondary windings in the rotary transformer have different lengths, and therefore, the resistances and the inductances of the three single-phase windings are also different. More details are presented in Table 7.1.

Table 7.1: Characteristics of the secondary winding of each phase

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{Jt}$</td>
<td>286.43</td>
<td>286.43</td>
<td>286.43</td>
<td>mm</td>
<td>Joint turn length</td>
</tr>
<tr>
<td>$l_{s-Coil}$</td>
<td>2 434.95</td>
<td>2 434.95</td>
<td>2 434.95</td>
<td>mm</td>
<td>Single coil group length</td>
</tr>
<tr>
<td>$l_{s-t1}$</td>
<td>58.35</td>
<td>101.95</td>
<td>145.54</td>
<td>mm</td>
<td>Terminal 1 length</td>
</tr>
<tr>
<td>$l_{s-t2}$</td>
<td>68.03</td>
<td>111.63</td>
<td>155.22</td>
<td>mm</td>
<td>Terminal 2 length</td>
</tr>
<tr>
<td>$l_{s-Total}$</td>
<td>5 282.72</td>
<td>5 369.90</td>
<td>5 457.10</td>
<td>mm</td>
<td>$l_{Jt} + 2l_{Coil} + l_{s-t1} + l_{s-t2}$</td>
</tr>
<tr>
<td>$m_{s-Cu}$</td>
<td>658.23</td>
<td>669.09</td>
<td>679.95</td>
<td>g</td>
<td>Copper mass</td>
</tr>
<tr>
<td>$R_{s-DC}$</td>
<td>6.34</td>
<td>6.44</td>
<td>6.55</td>
<td>mΩ</td>
<td>DC resistance at 20 °C</td>
</tr>
<tr>
<td>$L_{s,f=50Hz}$</td>
<td>30.90</td>
<td>30.96</td>
<td>31.04</td>
<td>μH</td>
<td>air core at $f = 50$ Hz</td>
</tr>
</tbody>
</table>

Table 7.1 summarizes the characteristics of each secondary winding in the rotary...
Chapter 7. Transformer Mechanical Design

transformation. Considering the real manufacturing, the magnetic wire used for producing each secondary winding should have an enough length of 5.5 m. The large cross-sectional area of the magnetic wire results in a small DC resistance, approximately 6.44 mΩ on average, for every phase winding.

7.2.4 Primary Winding and Stator Core

Figure 7.10 illustrates that the stator of a single-phase rotary transformer consists of one primary winding, one stator-axial core, and two stator-radial cores (a non-slotted core and a slotted core). These cores are formed by the electrical steel of M235-35A, and the manufacturing of them is same as that of the rotor cores. However, the difference is that O-ring laminations used in the stator-radial core have the same inner diameter but different outer diameters. Appendix G shows their specific dimensions. Additionally, the stator cores also have milled slots to provide the paths for the terminal routing.

The winding process, using a hexagonal winding pattern, produces the primary coil to fill the inside of the stator core. The characteristics of the magnet wire and the primary winding are shown in Appendix H and Table 7.2, respectively. Considering the real winding process, every single-phase primary winding requires a magnet wire with the length of at least 200 meters.

7.3 Transformer Assembly

Figure 7.11 shows the rotary transformer assembly, which is divided into three assemblies, namely, the rotor assembly, the stator assembly, and the frame and terminal box assembly. The stator structure is similar to the rotor structure, hence this section only presents the rotor assembly. The assembly of the frame and terminal box is similar to that of a normal motor, details of which are presented in Appendix I.
Chapter 7. Transformer Mechanical Design

Figure 7.10: Cutaway view of primary winding arrangement, winding terminals, terminal slots, and stator cores

Table 7.2: Characteristics of the primary winding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall size (OD×H)</td>
<td>142.30 × 21.56</td>
<td>mm</td>
<td>Outer diameter × Height</td>
</tr>
<tr>
<td>ID</td>
<td>103</td>
<td>mm</td>
<td>Inner diameter</td>
</tr>
<tr>
<td>$l_{p-N}$</td>
<td>495</td>
<td>mm</td>
<td>Total turns</td>
</tr>
<tr>
<td>$l_{p-coil}$</td>
<td>190.73</td>
<td>m</td>
<td>Coil length</td>
</tr>
<tr>
<td>$l_{p-t1}$</td>
<td>23.22</td>
<td>mm</td>
<td>Terminal 1 length</td>
</tr>
<tr>
<td>$l_{p-t2}$</td>
<td>42.21</td>
<td>mm</td>
<td>Terminal 2 length</td>
</tr>
<tr>
<td>$l_{p-Total}$</td>
<td>190.80</td>
<td>m</td>
<td>$l_{p-coil} + l_{p-t1} + l_{p-t2}$</td>
</tr>
<tr>
<td>$m_{p-cu}$</td>
<td>1080.29</td>
<td>g</td>
<td>Copper mass</td>
</tr>
<tr>
<td>$R_{p-DC}$</td>
<td>5.03</td>
<td>Ω</td>
<td>DC resistance at 20 °C</td>
</tr>
<tr>
<td>$L_{p,f=50\text{Hz}}$</td>
<td>23.72</td>
<td>mH</td>
<td>at $f = 50$ Hz with air core</td>
</tr>
</tbody>
</table>
Figure 7.11: Exploded view of the rotary transformer assembly

Figure 7.12: Exploded view of the rotor assembly

Figure 7.12 shows the rotor assembly, all components of which are described as follows.

- **Phase A, Phase B and Phase C**: They are major parts in the rotor assembly, which are the secondary windings and rotor cores in the three-phase rotary transformer.
• **O-ring insulation**: The O-ring insulation, shown in Figure 7.13 (blue part), is used to fill the free space between each two phase cores. The O-ring insulation, a plastic CNC-milled workpiece, has many curved grooves on its both sides to enable the air to pass through the surface of the core and therefore cool the rotor cores.

![Figure 7.13: O-ring insulations between each two single-phase rotor cores. The black arrow denotes the possible airflow direction. The air comes from the grooves of the shaft-terminal insulation, passes through the curved grooves of the O-ring insulation and goes to the air-gap between the rotor and the stator.](image)

• **Shaft-terminal insulation**: The shaft-terminal insulation (see Figure 7.14), a plastic CNC-milled workpiece, fills the free O-ring space illustrated in Figure 7.9, having three functions presented as follows.

![Figure 7.14: Shaft-terminal insulation](image)

- **Copper terminal**
- **Major groove**
- **Minor groove**

a) It is inserted into the rotor cores to fasten them on the rotary shaft.
b) It has three major grooves, and every major one has two minor grooves. These grooves can avoid the copper terminal overlapping. Furthermore, because they are symmetrically distributed, all copper terminals can be held in their corresponding grooves to prevent the rotating unbalance.
c) Six holes provide a path for the airflow in the rotor, which helps to cool the transformer.

• **Circlips and end caps**: Figure 7.15 shows the assembly of the circlips and end caps. Both circlips are snapped into place, into the two machined grooves of the
rotary shaft and cooperate with their corresponding end caps to fasten the rotor cores in the axial direction.

- **PCB end cap**: The PCB end cap not only fastens the transformer cores but also acts as an internal cooling fan in the rotor. The PCB end cap has six blades to achieve that it becomes an axial fan that sucks in the air axially and blows it out axially again, which can help to cool the transformer cores and the PCB.

- **PCB**: The PCB, an O-ring circuit board that is held by the PCB end cap, connects to all copper terminals in a wye-topology connection for the secondary windings. Additionally, it also finishes for AC/DC conversion by a rectifier. Furthermore, as the development of power electronics for the PM DC motor, this PCB could have other necessary electrical units. Therefore, the diameter of the PCB is unknown, and even multiple PCBs are required rather than the single PCB illustrated in the figure. This will be discussed in the future works.

- **Rotary shaft**: The rotary shaft has the diameter of 20 mm, which is inserted into the shaft-terminal insulation. The two machined grooves close to its both ends are used for locking the circlips.

- **Bearing**: It is mounted on the shaft, supports the rotor and allows it to turn.

- **Fan**: This rotary transformer and the permanent magnet DC motor build up a totally enclosed fan cooled motor. The fan is mounted on at the end of the rotary shaft, which rotates at the same speed as the rotor and delivers the cool air for cooling the motor. Motor cooling fans, made of metal or plastic, have many standard sizes that are available in electric motor spare parts markets.

### 7.4 Summary of Mechanical Design

Figure 7.16 shows the rotary transformer production flowchart. This production does not need an annealing process. Each of laminations will be cut to a larger size to ensure that the magnetic deterioration zone caused by the slitting or WEDM can be removed by milling process. After the rotor assembly, the rotor balancing must be finished, which
is important to the performance of the entire rotary machine [132]. The frame assembly
uses a normal press fitting process to fasten the stator part in the frame.

![Diagram of three-phase rotary transformer production flowchart]

Table 7.3 lists the bill of material for the transformer prototype. In addition to transformer cores, copper windings, and other mechanical parts, the necessary electrical insulation materials and varnish are needed in this rotary transformer assembly for protecting the windings or other electrical conductors.
### Table 7.3: Rotary transformer prototype bill of material

<table>
<thead>
<tr>
<th>Component</th>
<th>Qty</th>
<th>Material</th>
<th>Mass (kg)</th>
<th>Produce</th>
<th>Price (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor-radial core</td>
<td>6</td>
<td>M235-35A</td>
<td>0.43×6</td>
<td>1</td>
<td>500×6</td>
</tr>
<tr>
<td>Rotor-axial core</td>
<td>6</td>
<td>M235-35A</td>
<td>0.30×6</td>
<td>1</td>
<td>300×6</td>
</tr>
<tr>
<td>Stator-radial core</td>
<td>6</td>
<td>M235-35A</td>
<td>0.71×6</td>
<td>1</td>
<td>500×6</td>
</tr>
<tr>
<td>Stator-axial core</td>
<td>3</td>
<td>M235-35A</td>
<td>0.91×3</td>
<td>1</td>
<td>300×3</td>
</tr>
<tr>
<td>Secondary winding</td>
<td>3</td>
<td>Copper(2)</td>
<td>0.68×3</td>
<td>Hand made</td>
<td>200×3</td>
</tr>
<tr>
<td>Primary winding</td>
<td>3</td>
<td>Copper(2)</td>
<td>1.68×3</td>
<td>Hand made</td>
<td>180×3</td>
</tr>
<tr>
<td>Shaft</td>
<td></td>
<td>AISI 304</td>
<td>0.50</td>
<td>CNC milling</td>
<td>100</td>
</tr>
<tr>
<td>Insulation (3) and varnish</td>
<td>–</td>
<td></td>
<td>0.10</td>
<td>BIVE.se</td>
<td>500</td>
</tr>
<tr>
<td>Stator O-ring insulations (4)</td>
<td>–</td>
<td>POM</td>
<td>0.11</td>
<td>CNC milling</td>
<td>300</td>
</tr>
<tr>
<td>Rotor O-ring insulations (4)</td>
<td>–</td>
<td>POM</td>
<td>0.03</td>
<td>CNC milling</td>
<td>250</td>
</tr>
<tr>
<td>Shaft-terminal insulation</td>
<td>–</td>
<td>POM</td>
<td>0.13</td>
<td>CNC milling</td>
<td>250</td>
</tr>
<tr>
<td>Bearing end cap</td>
<td>–</td>
<td>POM</td>
<td>0.07</td>
<td>CNC milling</td>
<td>150</td>
</tr>
<tr>
<td>PCB end cap</td>
<td>–</td>
<td>POM</td>
<td>0.01</td>
<td>CNC milling</td>
<td>300</td>
</tr>
<tr>
<td>Circlip (SGA 20)</td>
<td>2</td>
<td>Carbon spring steel</td>
<td>0.02×2</td>
<td>liljenbergs.com</td>
<td>15×2</td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td>Al 6063-T5</td>
<td>2.50</td>
<td>Profile and Milling</td>
<td>3000</td>
</tr>
<tr>
<td>Frame mount foot</td>
<td>2</td>
<td>Al 6063-T5</td>
<td>0.33×2</td>
<td>Profile and Milling</td>
<td>100</td>
</tr>
<tr>
<td>Terminal box</td>
<td>–</td>
<td>ADC-12 Al alloy</td>
<td>0.15</td>
<td>Digikey</td>
<td>250</td>
</tr>
<tr>
<td>Cable gland</td>
<td>–</td>
<td>Brass with nickel</td>
<td>0.09</td>
<td>Digikey</td>
<td>80</td>
</tr>
<tr>
<td>Fan</td>
<td>–</td>
<td>Reinforced PP</td>
<td>0.06</td>
<td>electricmotormarket.co.uk</td>
<td>100</td>
</tr>
<tr>
<td>Fan axial cover</td>
<td>–</td>
<td>PLA</td>
<td>0.07</td>
<td>3D printing</td>
<td>100</td>
</tr>
<tr>
<td>Fan end cover</td>
<td>–</td>
<td>PLA</td>
<td>0.11</td>
<td>3D printing</td>
<td>150</td>
</tr>
<tr>
<td>Non-drive end endshield</td>
<td>–</td>
<td>6061 Al alloy</td>
<td>0.62</td>
<td>CNC milling</td>
<td>300</td>
</tr>
<tr>
<td>Bearing (6204-2Z SKF)</td>
<td>–</td>
<td>Stainless steel</td>
<td>0.10</td>
<td>Elfa.se</td>
<td>60</td>
</tr>
<tr>
<td>Screws/Nuts/Washers</td>
<td>–</td>
<td></td>
<td>0.1</td>
<td>Elfa.se</td>
<td>140</td>
</tr>
</tbody>
</table>

Total: 21.92 – 16 200

(1): Transformer core manufacturing includes slitting, cutting, bonding and milling process.
(2): Appendix H
(3): Motor and transformer insulation materials, such as sleeving, Kapton film and insulation paper.
(4): All O-ring insulations in the stator or the rotor.
Chapter 8

Conclusions and Future Work

This chapter summarizes the work previously described in this thesis, discusses its results and achievements, points out limitations of the current work, and also outlines ideas and directions for future work.

8.1 Conclusions

In this thesis, a kilowatt three-phase rotary transformer design was presented, which proposes a contactless power transfer solution for a new PMDC motor without using the technique of inductive resonant frequency. The rotary transformer can deliver enough power (1.17 kW) to the PMDC motor with a high power efficiency (over 90%). Furthermore, it achieves a simple power supply and has manufacturable and low-cost components and structure.

Compared with inductive resonant frequency wireless power transfer, due to the low frequency (50 Hz), this rotary transformer has a large size and low power density, which causes the new PMDC motor to occupy a large space on mounting and have a heavy weight. However, the rotary transformer simplified the power process and control of the PMDC motor, thereby reducing the troubleshooting time, maintenance cost and manufacturing cost for the entire system.

An iron loss model was developed and a finite element analysis was performed in COMSOL Multiphysics for predicting the power losses of the three-phase rotary transformer in Chapter 4 and 5, respectively. Both chapters showed that the development and utilization of the iron loss model based on Steinmetz Equation is a simple and fast implementation. In the development stage, the model can be achieved by using a data curve fitting on the given loss data, which does not require any extensive experimental measurements. In the utilization stage, if the magnetic flux density is obtained as well as its change rate, the model can be easily integrated into the post-processing of COMSOL Multiphysics to compute the iron loss. However, three issues should be pointed out from this transformer model. First, it is based on Steinmetz equation development and does not consider the flux density in history because it also influences on the transformer power losses. Hence, this model is not suited for an exact iron loss determination. Second, electrical steel manufacturing process also influences on electrical steels, and this model does not take them into account. Third, the temperature rising is caused by power losses is another factor that influences on electrical steels and copper windings, but this model
ignores it.

In Chapter 6, a literature review presents influences of various manufacturing processes on electrical steels as well as different techniques of each manufacturing process. For realizing the rotary transformer, manufacturing processes are unavoidable steps, and therefore, they caused the iron losses can not be avoided. However, though the review, three manufacturing processes, WEDM, sticking, and milling, were found and can be used for the rotary transformer production because of their relative low effect on magnetic properties, easy operation and low cost.

According to the study in Chapter 6, Chapter 7 proposed the manufacturing process for the transformer cores and copper windings and summarized their electrical and mechanical characteristics. Necessary mechanical components used for the transformer cooling and assembly were also presented. This manufacturing proposal could cause the lowest negative effect on electrical steels and also lead a low cost for the transformer prototyping. All components are easily produced by a normal milling CNC technique, printed by a 3D printing method, cut from aluminium profiles, or available in electronic component markets. Some components are used for cooling the three-phase rotary transformer, but this thesis did not deeply study them or present their specific shapes and dimensions. The cooling solution study, which involves thermal analysis and fluid mechanics, is a great challenge for a transformer design, especially for the special structure of the rotary transformer. Hence, it is an interesting study in the rotary transformer design and will be implemented in future work.

8.2 Recommendations for Further Work

First of all, to further investigate the mechanism of iron losses, considerable work for iron loss modelling in COMSOL Multiphysics needs to be developed and improved in a number of ways presented in the following list. Furthermore, to finish the transformer design and realize the rotary transformer, several tasks for future work are also proposed in the list.

- Transformer modelling in COMSOL Multiphysics
  - Iron loss model development: In an electric machine design, because of the magnetic properties of core materials are non-linearity, the iron loss prediction is always a complex and challenging work. However, for the development and electromagnetic design of a high-efficiency rotary transformer, there is a strong need for improved and more accurate iron loss models. Hence, the iron loss model development is still a significant task in the future work.
  - Iron loss model utilization in COMSOL Multiphysics: As presented in Chapter 4, the hysteresis model is the part of the solving process in an FEM software, which takes into account the history of magnetic flux density waveform, thereby performing a high accurate iron loss calculation. Furthermore, as presented in Chapter 6, the accuracy of an iron loss model is influenced by the manufacturing processes. Hence, developing and implementing a hysteresis model with concerning the influence factors of electrical steel manufacturing
processes to study the rotary transformer will be an extremely challenge in the future work.

- Temperature influences: Because the magnetic characteristics of electrical steels are temperature sensitive, the temperature influences on the magnetic characteristics should be considered in the rotary transformer FEM simulation. Hence, developing a thermal model, such as a temperature correction function, which takes temperature changes at different operating points into account, can improve the accuracy of the iron loss prediction.

- SPICE model: In the primary circuit of the rotary transformer, an actual inrush current limiter should be modelled rather than using simple resistors with dynamic value respect to time. For example, developing a logically controlled circuit to simulate a microcontroller based inrush current limiter can be considered in future. In the secondary circuit, using a purely resistive performs a relative ideal test, but which can not reveal the actual transformer performance. Hence, adding more complex loads, such as rectifier and filter circuits, to enable the SPICE model to close to a real circuit should be one of the tasks in future work.

- Mechanical loss study and other electrical losses investigation: This thesis only studied the iron and copper losses of the rotary transformer. However, as a rotating machine, its mechanical loss is the other main component that constitutes the total power loss to the permanent magnet DC motor, and, as a static electrical device, its stray losses and effects of magnetostriction also influence the DC motor performance and even the surrounding environment. Therefore, a study of them should be implemented in future to present a more comprehensive power loss for the motor design.

- The transformer realization, the parameter measurement and performance test should be implemented in the future work to verify the simulation in COMSOL Multiphysics and evaluate the accuracy of the developed iron model. A building factor should be carried out for determining the losses caused by manufacturing processes, and it can also give feedback on the literature review study of the manufacturing processes to discuss the chosen methods (WEDM, sticking and milling) are whether or not suitable for the rotary transformer manufacturing.

- Mechanical design for the cooling solution: Because of the air-gap, the copper loss increased by the magnetizing current dominates the transformer power loss, which is the main source of the heat generation in the rotary transformer. If the heat is not dissipated properly, the temperature will rise continually and may damage the insulations and even cores and windings, which causes the transformer or motor faults. Hence, to prevent the rotary transformer from too-high temperatures and to ensure the long life, an efficient cooling system in the mechanical design should be achieved in the future work.

- Literature review study: To develop a more accurate iron loss model, to deeply study the influences of manufacturing process on electrical steels and to understand other ferromagnetic materials rather than only silicon steels, the literature review
study for all of them should be continued in the future work. Furthermore, the mechanical design and thermal study of the rotary transformer should be given a literature review in future as well.
Appendix

A HB-curve and specific iron loss of M235-35A given by ThyssenKrupp Steel
B Epstein Frame Measurement

The Epstein frame measurements are performed to investigate electrical steels according to IEC 404-2 for frequencies of up to 400 Hz and IEC 404-10 for frequencies above 400 Hz. The following figure illustrates a 25-cm Epstein frame, of which more details are presented as follows.

- Each Epstein strip has the width of 30 mm and the length of 280 mm.
- The set of specimens under test is composed of multiple of four strips creating the square with mean length of side 250 mm.
- The longitudinally and the transversely cut strips are inserted into two opposite coils of the Epstein frame respectively.
- \( I_m = 940 \text{ mm} \) is the effective magnetic path of the Epstein frame.
- The characteristics of the primary winding and the secondary winding are:
  - Both windings are fixed in the Epstein Frame and are composed of the two sets of four coils connected in series. Each coil is 190 mm long and has 175 turns. Therefore, both windings have the identical total turns of 700.
  - The primary winding is magnetizing coils that are wound by using a copper wire with the cross-sectional area of 1.8 mm\(^2\). Hence, due to the large cross section area of the copper wire, each coil of the primary winding is arranged by three layers.
  - The secondary winding is the measuring winding, and its coils are by using a copper wire with the cross-sectional area of 0.8 mm\(^2\).
The internal cross-sectional area of the coils is a rectangle with the demonstration of $10 \times 32$ mm.

The total loss of the test specimen $P_c$ is derived from the measurement of the input power $P_m$, which is expressed by

$$ P_c = \frac{N_p}{N_s} P_m - \frac{(1.111 \bar{V}_s)^2}{R_i} \quad (8.1) $$

where,

- $P_c$ - the total losses of the specimens in watt (W).
- $N_p$ - the total number of the turns of the primary winding.
- $N_s$ - the total number of the turns of the secondary winding.
- $P_m$ - the measured power.
- $\bar{V}_s$ - the rectified voltage induced in the secondary winding.
- $R_i$ - the total resistance of the instruments connected to the secondary winding.

The measured specific total loss density ($P_s$ in W/kg) is the ratio of the total losses of the specimens $P_c$ to the effective mass of the specimens $m_e$, as given in Equation 8.2.

$$ P_s = \frac{P_c}{m_e} \quad [\text{W/kg}] \quad (8.2) $$

The effective mass of all stripes $m_e$ is defined as shown in Equation 8.3.

$$ m_e = \frac{m_t l_m}{4l} \quad (8.3) $$

Where $m_t$ is the total mass of the test specimens and $l$ is the length of one Epstein strip. The instance magnetic field strange $H(t)$ is obtained through the current in the primary winding $I_p(t)$ and is given by Equation 8.4.

$$ H(t) = \frac{N_p}{l_m} I_p(t) \quad [\text{A/m}] \quad (8.4) $$

The induced magnetic flux density $B(t)$ can be obtained by integrating the voltage of the secondary winding $V_s(t)$.

$$ B(t) = -\frac{1}{N_s A} \int V_s(t) dt \quad [\text{T}] \quad (8.5) $$

Where $A$ is the cross-sectional area of the test specimen, as shown in Equation 8.6, which takes into account the total mass of strips $m_t$, the length of strips $l$, and the density of test materials $\rho_m$.

$$ A = \frac{m_t}{4l \rho_m} \quad [\text{m}^2] \quad (8.6) $$
C  SPICE Model Coupled to the Magnetic Field Model of the Transformer

The CIR uses six External I vs. Us (No.1, 2, 3, 11, 21 and 31) to connect the three single-phase windings (Phase A, B and C), the voltage sources (AC1, AC2 and AC3) and resistive loads (R4, R5 and R6).

AC1, AC2 and AC3 represent a three-phase power system with 230 V, 50 Hz, and each voltage phase is separated by 120 degree from the other.

The resistance of loads are assigned different values loadR(t) to used for the transformer no-load and full-load tests. R2 and R3 with the value of LlimR(t) are modelled as inrush current limiters.

To simplify the simulation, the AC1 starts with its peck voltage (at the phase shift of 90 degree), which lowers the inrush current to approximate 0 A. Hence, the resistance of R1 is assigned as 0 Ω rather than LlimR(t), which means that it no longer acts as an inrush current limiter.

To avoid the differential algebraic equation (DAE) issues of the CIR during the simulation, the rest of the resistors have to be added in the circuit and assigned as 0 Ω.
D Geometry of the Three-phase Rotary Transformer Drawn in COMSOL Multiphysics

- Rotary shaft
- Air boundary (Magnetic insulation)
- Phase A
- Phase B
- Phase C
- Axial symmetry
Equations Used in COMSOL Multiphysics for Modelling the Three-phase Rotary Transformer

\[ \nabla \times \mathbf{H} = \mathbf{J} \]
\[ \mathbf{B} = \nabla \times \mathbf{A} \]
\[ \mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \]
\[ \mathbf{J} = \sigma \mathbf{E} \]

\[ I_{\text{coil}} = \int \mathbf{J} \cdot e_{\text{coil}} \]
\[ \mathbf{J}_e = \sigma \frac{V_{\text{coil}}}{2\pi r} e_{\text{coil}} \]
\[ e_{\text{coil}} = \text{Out-of-plane unit vector} \]  

where

- \( \mathbf{H} \) - Magnetic field intensity
- \( \mathbf{B} \) - Magnetic flux density
- \( \mathbf{A} \) - Magnetic vector potential
- \( \mathbf{J} \) - Current density
- \( \mathbf{E} \) - Electric field intensity
- \( I_{\text{coil}} \) - Total coil current
- \( V_{\text{coil}} \) - Total coil voltage
- \( \mathbf{J}_e \) - Externally generated current density
- \( \sigma \) - Electrical conductivity
- \( e_{\text{coil}} \) - Coil current flow
F  Dimension of O-ring laminations in the rotor-radial core

\[ N_{r\text{-total}} = 31 \quad t_{\text{apparent}} = 0.3610 \text{ mm} \quad t_{\text{WEDM}} = 0.1000 \text{ mm} \]
\[ h_{\text{r-core}} = 11.1910 \text{ mm} \]
\[ ID_{r\text{-a-core}} = 71.60 \text{ mm} \quad ID_{r\text{-b-core}} = 41.27 \text{ mm} \quad OD_{r\text{-core}} = 102.00 \text{ mm} \]
\[ \tan \alpha_r = 0.7381 \]
\[ l_{r\text{-allowance}} = 0.5891 \text{ mm} \]

<table>
<thead>
<tr>
<th>N</th>
<th>ID (mm)</th>
<th>OD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.4218</td>
<td>102.200</td>
</tr>
<tr>
<td>2</td>
<td>69.4436</td>
<td>102.200</td>
</tr>
<tr>
<td>3</td>
<td>68.4654</td>
<td>102.200</td>
</tr>
<tr>
<td>4</td>
<td>67.4872</td>
<td>102.200</td>
</tr>
<tr>
<td>5</td>
<td>66.5090</td>
<td>102.200</td>
</tr>
<tr>
<td>6</td>
<td>65.5308</td>
<td>102.200</td>
</tr>
<tr>
<td>7</td>
<td>64.5526</td>
<td>102.200</td>
</tr>
<tr>
<td>8</td>
<td>63.5745</td>
<td>102.200</td>
</tr>
<tr>
<td>9</td>
<td>62.5963</td>
<td>102.200</td>
</tr>
<tr>
<td>10</td>
<td>61.6181</td>
<td>102.200</td>
</tr>
<tr>
<td>11</td>
<td>60.6399</td>
<td>102.200</td>
</tr>
<tr>
<td>12</td>
<td>59.6617</td>
<td>102.200</td>
</tr>
<tr>
<td>13</td>
<td>58.6835</td>
<td>102.200</td>
</tr>
<tr>
<td>14</td>
<td>57.7053</td>
<td>102.200</td>
</tr>
<tr>
<td>15</td>
<td>56.7271</td>
<td>102.200</td>
</tr>
<tr>
<td>16</td>
<td>55.7489</td>
<td>102.200</td>
</tr>
<tr>
<td>17</td>
<td>54.7707</td>
<td>102.200</td>
</tr>
<tr>
<td>18</td>
<td>53.7925</td>
<td>102.200</td>
</tr>
<tr>
<td>19</td>
<td>52.8143</td>
<td>102.200</td>
</tr>
<tr>
<td>20</td>
<td>51.8361</td>
<td>102.200</td>
</tr>
<tr>
<td>21</td>
<td>50.8579</td>
<td>102.200</td>
</tr>
<tr>
<td>22</td>
<td>49.8797</td>
<td>102.200</td>
</tr>
<tr>
<td>23</td>
<td>48.9015</td>
<td>102.200</td>
</tr>
<tr>
<td>24</td>
<td>47.9234</td>
<td>102.200</td>
</tr>
<tr>
<td>25</td>
<td>46.9452</td>
<td>102.200</td>
</tr>
<tr>
<td>26</td>
<td>45.9670</td>
<td>102.200</td>
</tr>
<tr>
<td>27</td>
<td>44.9888</td>
<td>102.200</td>
</tr>
<tr>
<td>28</td>
<td>44.0106</td>
<td>102.200</td>
</tr>
<tr>
<td>29</td>
<td>43.0324</td>
<td>102.200</td>
</tr>
<tr>
<td>30</td>
<td>42.0542</td>
<td>102.200</td>
</tr>
<tr>
<td>31</td>
<td>41.0760</td>
<td>102.200</td>
</tr>
</tbody>
</table>
G  Dimension of O-ring laminations in the stator-radial core

\[ N_{s-total} = 28 \quad t_{apparent} = 0.3610 \text{ mm} \quad t_{\text{WEDM}} = 0.1000 \text{ mm} \]
\[ h_{s-core} = 10.1080 \text{ mm} \]
\[ OD_{s-a-core} = 158.5870 \text{ mm} \quad OD_{s-b-core} = 142.7030 \text{ mm} \quad ID_{s-core} = 102.60 \text{ mm} \]
\[ \tan \alpha_s = 1.2727 \]
\[ l_s\_allowance = 0.3836 \text{ mm} \]

<table>
<thead>
<tr>
<th>N</th>
<th>OD (mm)</th>
<th>ID (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>143.4703</td>
<td>102.4000</td>
</tr>
<tr>
<td>2</td>
<td>144.0376</td>
<td>102.4000</td>
</tr>
<tr>
<td>3</td>
<td>144.6049</td>
<td>102.4000</td>
</tr>
<tr>
<td>4</td>
<td>145.1721</td>
<td>102.4000</td>
</tr>
<tr>
<td>5</td>
<td>145.7394</td>
<td>102.4000</td>
</tr>
<tr>
<td>6</td>
<td>146.3067</td>
<td>102.4000</td>
</tr>
<tr>
<td>7</td>
<td>146.8740</td>
<td>102.4000</td>
</tr>
<tr>
<td>8</td>
<td>147.4413</td>
<td>102.4000</td>
</tr>
<tr>
<td>9</td>
<td>148.0086</td>
<td>102.4000</td>
</tr>
<tr>
<td>10</td>
<td>148.5759</td>
<td>102.4000</td>
</tr>
<tr>
<td>11</td>
<td>149.1431</td>
<td>102.4000</td>
</tr>
<tr>
<td>12</td>
<td>149.7104</td>
<td>102.4000</td>
</tr>
<tr>
<td>13</td>
<td>150.2777</td>
<td>102.4000</td>
</tr>
<tr>
<td>14</td>
<td>150.8450</td>
<td>102.4000</td>
</tr>
<tr>
<td>15</td>
<td>151.4123</td>
<td>102.4000</td>
</tr>
<tr>
<td>16</td>
<td>151.9796</td>
<td>102.4000</td>
</tr>
<tr>
<td>17</td>
<td>152.5469</td>
<td>102.4000</td>
</tr>
<tr>
<td>18</td>
<td>153.1141</td>
<td>102.4000</td>
</tr>
<tr>
<td>19</td>
<td>153.6814</td>
<td>102.4000</td>
</tr>
<tr>
<td>20</td>
<td>154.2487</td>
<td>102.4000</td>
</tr>
<tr>
<td>21</td>
<td>154.8160</td>
<td>102.4000</td>
</tr>
<tr>
<td>22</td>
<td>155.3833</td>
<td>102.4000</td>
</tr>
<tr>
<td>23</td>
<td>155.9506</td>
<td>102.4000</td>
</tr>
<tr>
<td>24</td>
<td>156.5179</td>
<td>102.4000</td>
</tr>
<tr>
<td>25</td>
<td>157.0851</td>
<td>102.4000</td>
</tr>
<tr>
<td>26</td>
<td>157.6524</td>
<td>102.4000</td>
</tr>
<tr>
<td>27</td>
<td>158.2197</td>
<td>102.4000</td>
</tr>
<tr>
<td>28</td>
<td>158.7870</td>
<td>102.4000</td>
</tr>
</tbody>
</table>
H Magnet wire

The magnetic wire is a custom enamelled copper conductor controlled by the standard of IEC 60317-0-1, and its characteristics are shown in Table H.1 and H.2.

**Table H.1:** Characteristics of the magnetic wire used for the secondary winding

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare wire (W × L)</td>
<td>(1.35 ± 0.081) × (10.00 ± 0.081)</td>
</tr>
<tr>
<td>Max. overall dimension of film-coated wire (W × L)</td>
<td>1.50 × 10.10</td>
</tr>
<tr>
<td><strong>Electrical Resistance at 20 °C (Ω/m)</strong></td>
<td>1.20 × 10⁻³</td>
</tr>
<tr>
<td><strong>Insulation characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Polyesterimide</td>
</tr>
<tr>
<td>Thermal class (°C)</td>
<td>180</td>
</tr>
<tr>
<td>Max. Thickness (mm)</td>
<td>0.0455</td>
</tr>
<tr>
<td><strong>Price (USD/kg)</strong></td>
<td>12.8(1)</td>
</tr>
</tbody>
</table>

(1) ZhengZhou LP Industry Co., LTD. Minimum order: 1000 kg

**Table H.2:** Characteristics of the magnetic wire used for the primary winding

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare wire (diameter)</td>
<td>0.9</td>
</tr>
<tr>
<td>Max. overall dimension of film-coated wire (diameter)</td>
<td>0.989</td>
</tr>
<tr>
<td><strong>Electrical Resistance at 20 °C (Ω/m)</strong></td>
<td>1.20 × 10⁻³</td>
</tr>
<tr>
<td><strong>Insulation characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Polyesterimide</td>
</tr>
<tr>
<td>Thermal class (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Max. Thickness (mm)</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Price (SEK/kg)</strong></td>
<td>49(1)</td>
</tr>
</tbody>
</table>

(1) BEVI AB
I Frame and Terminal Box Assembly

The frame of the rotary transformer holds all the parts in place and provides a means of mounting the motor to machinery. A die-cast aluminium frame, due to its high cost, is not suit for this rotary transformer prototyping. A custom aluminium profile design for producing the frame, however, is less expensive than the die casting method. The profile geometry is similar to a tube that has many fins are on its outer surface. To mount the terminal box and fix the two frame mount feet on the frame, remaining three flat surfaces on the tube’s outer surface during the profile extrusion. The tube could be a long profile after the extrusion, and it will be cut to an appropriate length to fit the entire machine that is constructed by the rotary transformer and the permanent magnet DC motor. Two frame mount feet are also cut from an aluminium profile. Both have drilled 8 mm diameter holes for the M8 fixing screws that are used for the transformer mounting.

The non-drive end endshield, a CNC-milled aluminium workpiece, is fastened on the frame by eight M4 screws. The fan shown in Figure 7.11 is fixed on the shaft and placed between the non-drive end endshield and the fan end cover. Both fan covers, the fan axial cover and the fan end cover, are fastened on both sides of the non-drive end endshield, respectively, by four sets of M4 screws, washers and nuts.

Both fan covers are produced by a 3D printing technology, because their large size and complex geometry will lead a high cost if using a CNC milling method. Both fan covers can achieve the cooling airflow to blow the frame and cool the transformer. Figure I.1 shows that the possible cooling airflow direction passes through the frame. (The design of the cooling and the fan covers learns from [133–135].)
Figure 1.1: Cross-sectional view of the rotary transformer and the possible cool airflow direction denoted by blue arrows
References


T. Rahman, J. C. Akiror, P. Pillay, and D. A. Lowther, “Comparison of iron loss prediction formulae,” 

D. Eggers, S. Steentjes, and K. Hameyer, “Advanced iron-loss estimation for nonlinear material 

D. Lin, P. Zhou, W. Fu, Z. Badics, and Z. Cendes, “A dynamic core loss model for soft ferromagnetic 
and power ferrite materials in transient finite element analysis,” Magnetics, IEEE Transactions on, 

spice-coupled transformer including eddy currents with comsol multiphysics 4.2,” in 2011 COMSOL 


Z. Godec, “Influence of slitting on core losses and magnetization curve of grain-oriented electrical 

A. J. Clerc and A. Muetze, “Measurement of stator core magnetic degradation during the manufac-

R. Girgis et al., “Effect of slitting electrical core steel on measured iron loss,” Journal of magnetism 

R. Siebert, J. Schneider, and E. Beyer, “Laser cutting and mechanical cutting of electrical steels and 
its effect on the magnetic properties,” Magnetics, IEEE Transactions on, vol. 50, no. 4, pp. 1–4, 
2014.

A. Schoppa, J. Schneider, and J.-O. Roth, “Influence of the cutting process on the magnetic properties 
of non-oriented electrical steels,” Journal of magnetism and magnetic materials, vol. 215, pp. 100– 
102, 2000.

R. Rygal, A. Moses, N. Derebasi, J. Schneider, and A. Schoppa, “Influence of cutting stress on 
magnetic field and flux density distribution in non-oriented electrical steels,” Journal of magnetism 

magnetic properties of fe–si steels due to laser and mechanical cutting,” Magnetics, IEEE Transac-

A. Schoppa, J. Schneider, and C.-D. Wuppermann, “Influence of the manufacturing process on the 
magnetic properties of non-oriented electrical steels,” Journal of Magnetism and Magnetic Materials, 

Y. Kurosaki, H. Mogi, H. Fujii, T. Kubota, and M. Shiozaki, “Importance of punching and workabil-
ity in non-oriented electrical steel sheets,” Journal of Magnetism and Magnetic Materials, vol. 320, 

G. Loisos and A. J. Moses, “Effect of mechanical and nd: Yag laser cutting on magnetic flux distribu-
tion near the cut edge of non-oriented steels,” Journal of materials processing technology, vol. 161, 

V. Manescu, G. Paltanea, H. Gavrita, and I. Peter, “The influence of punching and laser cutting 
technologies on the magnetic properties of non-oriented silicon iron steels,” in Fundamentals of 

P. Baudouin, A. Belhadj, F. Breban, A. Deffontaine, and Y. Houbaert, “Effects of laser and mechan-
ic cutting modes on the magnetic properties of low and medium si content nonoriented electrical 


sheets in respect of cutting: Micromagnetic analysis and macromagnetic modeling,” IEEE Transac-

H. Naumoski, B. Riedmüller, A. Minkow, and U. Herr, “Investigation of the influence of differ-
cent cutting procedures on the global and local magnetic properties of non-oriented electrical steel,” 

A. Schoppa, H. Louis, F. Pude, and C. von Rad, “Influence of abrasive waterjet cutting on the mag-
etic properties of non-oriented electrical steels,” Journal of magnetism and magnetic materials, 

S. F. Miller, C.-C. Kao, A. J. Shih, and J. Qu, “Investigation of wire electrical discharge machining 
of thin cross-sections and compliant mechanisms,” International Journal of Machine Tools and 


