



Addis Ababa University

Addis Ababa Institute of Technology

African Railway Centre of Excellence

***Design of Synchronous Reluctance Motor for Light Rail
Transit Traction.***

A Research Thesis Submitted to the School of Graduate Studies of Addis
Ababa University in Partial Fulfillment of the Requirements for the Degree of
Masters of Science in Railway Engineering
(Traction and Train Control)

By: Takunda Victor Gadza

Thesis Advisor: Dr Abebe Teklu

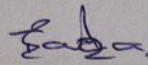
Date: 15 August 2023

APPROVAL

The undersigned has examined the thesis entitled "*Design of Synchronous Reluctance Motor for Light Rail Transit Traction.*" presented by Takunda Victor Gadza of registration number GSR/5231/14, in partial Fulfillment of the Requirements for the Degree of Master of Science in Railway Engineering (Traction and Train Control).

Submitted by:

Takunda Victor Gadza
Student



Signature

09/10/2023

Date

Approved by:

Dr. Abebe Teklu
Advisor

Abebe
Teklu

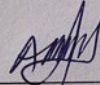
Digitally signed by Abebe Teklu,
DN: cn=Abebe Teklu, o=ETI, ou=KTH
Royal Institute of Technology,
ou=EMD, email=awolde@kth.se
Date: 2023.09.26 11:18:10 +0200

Signature

26/09/2023

Date

Mr. Alula Mebratu
Internal Examiner

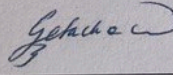


Signature

Oct-09, 2023

Date

Dr. Getachew Biru
External Examiner

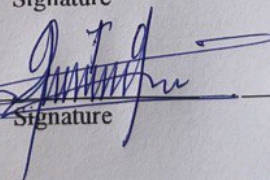


Signature

27/09/2023

Date

Mr. Zewdie Moges
Director of ARCE



Signature

Oct-10-2023

Date



Acknowledgment

This thesis would not have been possible without the assistance of many people I am grateful to. I want to thank my advisor Dr. Abebe Teklu for his guidance, support, and invaluable contribution throughout the preparations of this thesis. The support from the African Railway Center of Excellence grant through the World Bank Group is the main reason for my academic endeavor. Thus, special appreciation to all my lecturers at the African Railway Center of Excellence, who equipped me with knowledge and a better understanding of Railway Traction and Train control during my study. Also, my heartfelt gratitude goes to Addis Ababa Light Rail Transit Company and its entire staff. Finally, I want to thank my family, colleagues, and friends for their unwavering support and encouragement during my education journey.

Abstract

Trains play a crucial role in modern society transporting a significant portion of the freight and passengers transported worldwide. With increased urban populations, Light Rail Transit (LRT) systems have become one of the important means of transportation for large populations. Therefore, finding less expensive, reliable, and efficient ways of operating these trains is pivotal. In addition, there has also been a huge drive toward environmental conservation. This has resulted in standards and regulations that advocate for increased energy consumption efficiency and cleaner energy sources to reduce pollution-related environmental damage. Traction motors are one of the areas where these improvements may be introduced. Various types of traction motors have been used that include Direct Current (DC) motors, Alternating Current (AC) Induction Motors (IMs), and Permanent Magnet Synchronous Motors (PMSMs). However, these motors have shortcomings, such as inefficiencies in IMs due to rotor losses and expensive material costs in PMSMs due to rare earth permanent magnets. Therefore, finding alternatives with better efficiency and less cost is of paramount importance. One alternative is to replace the IM and PMSM with the Synchronous Reluctance Motor (SynRM). Therefore, this thesis designed a SynRM motor and drive system that can be used for the LRT application as an alternative. The design process includes investigating LRT traction requirements, investigating SynRM characteristics, design of a SynRM model for the LRT, optimizing the model's performance, and evaluating it using Finite Element Analysis (FEA). The motor was designed for the Addis Ababa Light Rail Transit. A control for the SynRM was also generated using SyR-e software and simulated. The SynRM performed comparably to the reference IM with a 4% higher torque output and 5% higher efficiency. It is also three times smaller in volume, weighs 50% less, and the material cost is 40% less than the reference IM. However, the designed SynRM has less power factor than the IM. This is due to the rotor needing a high level of magnetization, leading to an increase in reactive power. This increase in reactive power can then cause a decrease in the motor's power factor.

Keywords: FEM Analysis, FOC control, Light Rail Transit Application, Synchronous Reluctance Motor, Traction Motors

Acronyms and Abbreviations

AC: Alternating Current

ALA: Axially Laminated Anisotropic rotor

DC: Direct Current

DE: Differential Evolution

DTC: Direct Torque Control

ESS: Energy Storage System

EV: Electric Vehicle

FEA: Finite Element Analysis

FEAfix: Finite Element Analysis fix

FOC: Field-Oriented Control

GA: Genetic Algorithm

GUI: Graphic User Interface

HEV: Hybrid Electric Vehicle

HST: High-Speed Train

IM: Induction Motor

IPF: Internal Power Factor

IPM: Interior Permanent Magnet synchronous motor

LPF: Low Pass Filter

LRT: Light Rail Transit

LUT: Look UP Table

MFPCC: Model Free Predictive Current Control

MODE: Multi-Objective Differential Evolution

MOGA: Multi-Objective Genetic Algorithm

MOOA: Multi-Objective Optimization Algorithm

MOSA: Multi-Objective Simulated Annealing

MPC: Model-based Predictive Control

MTPA: Maximum Torque Per Ampere

MTPV: Maximum Torque Per Volt

OA: Optimization Algorithm

PC: Predictive Control

PI: Proportional Integral controller

PM: Permanent Magnet

PMSM: Permanent Magnet Synchronous Motor

PMSynRM: Permanent Magnet assisted Synchronous Motor

PWM: Pulse Width Modulation

SA: Simulated Annealing

SPM: Surface Permanent Magnet synchronous motor

SRM: Switched Reluctance Motor

SVPWM: Space Vector Pulse Width Modulation

SynRM: Synchronous Reluctance Motor

SYR-e: Synchronous Reluctance Motor evolution

TLA: Transversally Laminated Anisotropic rotor

VSD: Variable Speed Drive

Table of Contents

Table of Contents	VI
1. Introduction	1
1.1. Background	1
1.2. Problem Statement	3
1.3. Research Questions	4
1.4. Thesis Objectives	4
1.4.1. Main Objective.....	4
1.4.2. Specific Objectives	5
1.5. Research Methodology	5
1.6. Scope.....	6
1.7. Significance of the Research.....	6
1.8. Thesis Organization	6
2. Literature Review	7
2.1. Introduction.....	7
2.2. Types of Railway Systems.....	7
2.2.1. Light Rail Transit (LRT).....	7
2.2.2. High-Speed Trains (HSTs)	7
2.2.3. Locomotives.....	8
2.3. Traction Motors	8
2.3.1. DC Motors	9
2.3.2. AC Induction Motor (IM)	9
2.3.3. AC Permanent Magnet Synchronous Motor (PMSM).....	10
2.3.4. Switched Reluctance Motor (SRM).....	11
2.3.5. Synchronous Reluctance Motor (SynRM).....	12
2.4. Traction Motor Sizing.....	34
2.5. Design Optimization	34
2.5.1. Optimization Choices.....	35
2.6. Traction Control.....	36
2.6.1. Overview of Motor Control	36
2.6.2. SynRM Control	37
2.7. Software Tools	39

2.7.1.	SyR-e Software	39
2.7.2.	SyreDrive	40
2.8.	Related Works.....	40
3.	Design of the SynRM	43
3.1.	Traction Requirements for Target Railway System.....	43
3.1.1.	AALRT Traction Characteristic	44
3.2.	Traction Motor Investigation	46
3.3.	Traction Motor Sizing.....	47
3.3.1.	Analytical Design.....	49
3.3.2.	SyR-e Analytical Model	62
3.4.	Design Optimization	71
3.4.1.	Decision Variables	71
3.4.2.	Objective Function Evaluation	72
3.4.3.	The Optimization steps in SyR-e	73
3.4.4.	Simulation Set-Up.....	74
3.5.	Finite Element Analysis (FEA).....	78
3.5.1.	Proposed Method Validity and Evaluation	78
3.5.2.	SyR-e Simulation.....	78
3.6.	Traction Motor Drive Simulation	81
4.	Results Analysis and Discussion	83
4.1.	SynRM Motor Results Analysis and Discussion	83
4.2.	Flux, Inductance, and Saliency	83
4.2.1.	Torque, Power Factor, and Torque Ripple.....	87
4.2.2.	Power and Torque/Speed Envelop.....	92
4.2.3.	Structural Analysis.....	95
4.3.	Comparison of the Designed and Reference Machines	96
4.4.	Drive Simulation Results Analysis and Discussion.....	98
5.	Conclusion and Recommendations	101
5.1.	Conclusion	101
5.2.	Recommendations.....	101
	References.....	103

List of Tables

Table 3-1: Traction characteristics [57].	45
Table 3-2: Reference Motor Parameters [59].	46
Table 3-3:Initial Data.	49
Table 3-4: Assigned Data.	51
Table 3-5: M470-50A Characteristics.	56
Table 3-6: Analytical Design Parameters.	61
Table 3-7: Dimension of the motor.	65
Table 3-8: Parameters of the motor.	69
Table 3-9: Torque and power factor values for initial and FEAfix machine.	70
Table 3-10: Constraints of The Search Space for the Global Search.	71
Table 3-11: Parameters of Motor number 10.	77
Table 4-1: Comparison of the reference motor and designed motor parameters.	97
Table 4-2: Cost of the SynRM.	98
Table 4-3: Cost of the IM.	98

List of Figures

Figure 2-1: Performance comparison of traction motors used in different railway applications [3],[15], [16].	8
Figure 2-2: Synchronous Reluctance Motor [23].	12
Figure 2-3: Basic reluctance concept [7].	13
Figure 2-4: SynRM rotor nomenclature [26].	14
Figure 2-5: Rotation due to reluctance torque.	15
Figure 2-6. Different anisotropic structures of the SynRM's Rotor, (a) simple salient rotor, (b) axially laminated anisotropic rotor (ALA), (c) transversally laminated anisotropic rotor (TLA) [32].	16
Figure 2-7. SPM, IPM, PMSynRM, and SynRM respectively.	17
Figure 2-8: Vector diagram of the SynRM including iron losses [6].	21
Figure 2-9: The equivalent circuit of the SynRM including iron losses [6].	22
Figure 2-10: Typical configuration of a 4-pole, 36-slot SynRM with 4-layer TLA rotor[6].	29
Figure 2-11: Rotor barrier dimensions and angles [11].	31
Figure 2-12: Sinusoidal stator MMF averaged by the rotor iron carriers[11].	31
Figure 2-13: Block diagram of the field-oriented control scheme [52].	38
Figure 2-14: Process flow in SyR-e motor design software [52].	40
Figure 3-1: Research methodology flow diagram.	43
Figure 3-2: General block diagram of the traction load [56].	44
Figure 3-3: Traction requirements for the AALRT [57].	45
Figure 3-4: Design flow chart.	48
Figure 3-5: Dimensions of the stator slot (a) and wedge area (b) [39].	54
Figure 3-6: Machine rotor outer radius, stator inner radius, and stator outer radius.	55
Figure 3-7:M470-50A steel magnetization curve [62].	56
Figure 3-8: The SyR-e GUI for loading the analytical design values.	63
Figure 3-9: Torque/Power Factor parametric design plane from the analytical model.	64
Figure 3-10: FEMM rendering of the selected motor.	65
Figure 3-11: Maximum Torque characteristics of the chosen motor.	66
Figure 3-12 a) Additional iron section for the d-axis for saturation factor computation. b) equivalent magnetic circuit [11].	67

Figure 3-13: FEAfix Design Plane.	69
Figure 3-14: Torque and Power Factor characteristics of the chosen motor from FEAfix.	70
Figure 3-15: Rotor geometry with 3 circular barrier layers, $\Delta\alpha$ angles are layer positions, whilst h_{ci} are the layer heights.....	72
Figure 3-16: Pareto front of the optimization.	75
Figure 3-17: Torque values of the chosen machines after optimization.	75
Figure 3-18: Power Factor values of the chosen machines after optimization.	76
Figure 3-19: Torque ripple values of the chosen machines after optimization.....	76
Figure 3-20 : Motor number 10 rendered in FEMM.....	77
Figure 3-21: Single pole machine of the chosen machine in FEMM.	80
Figure 3-22: Flux density distribution in a single pole of the SynRM.	81
Figure 3-23: Setup for the complete SynRM drive simulation in Simulink.	82
Figure 3-24: Scopes to measure the signals.	82
Figure 4-1: 3 phase AC current and Flux vs electrical angle.....	84
Figure 4-2: a and b showing d and q axis flux nature.	85
Figure 4-3: a and b showing d and q axis inductance nature	85
Figure 4-4: Saliency ratio vs i_d , i_q currents.	86
Figure 4-5: Torque and Power Factor vs electrical angle.	87
Figure 4-6: Torque vs current angle.....	88
Figure 4-7: Current angle along the MTPA.	89
Figure 4-8: Torque ripple vs d-q currents	89
Figure 4-9: Torque ripple vs Torque along the MTPA.....	90
Figure 4-10: Power Factor vs Current Angle.....	90
Figure 4-11: Torque, Torque ripple, and Current together with MTPA and MTPV paths.....	91
Figure 4-12: MTPA LUT.....	92
Figure 4-13: Torque-Speed Graph of the SynRM motor.....	92
Figure 4-14: Power-Speed Graph of the SynRM motor.	93
Figure 4-15: Copper losses vs temperature and frequency map.	93
Figure 4-16: Rotor iron power losses at different speeds vs i_d and i_q	94
Figure 4-17: Stator iron power losses at different speeds vs i_d and i_q	94
Figure 4-18: Efficiency map of the SynRM machine.	95

Figure 4-19: Von Mises stresses on the rotor structure.	96
Figure 4-20: Structural displacement analysis.	96
Figure 4-22: Torque and Speed plots.	99
Figure 4-23: Currents and Flux plots.	99

1. Introduction

1.1. Background

Trains have become a vital workhorse of modern society carrying a significant portion of the freight and passengers transported worldwide. Therefore, finding less expensive, reliable, and more efficient ways of operating these trains is of paramount importance [1]. In addition, there has also been a huge drive toward environmental conservation. This has resulted in standards and regulations being implemented internationally that advocate for improving energy consumption efficiencies, and also the development and adoption of cleaner sources of energy to reduce damage to the environment due to pollution [2]. Therefore, increasing the traction efficiencies will also help contribute towards this drive. For many years, electric motors have been used as traction motors for railway traction in electric and diesel-electric locomotives [1]. Several types of motors such as Direct Current (DC) motors, Alternating Current (AC) Induction Motors (IMs), and Permanent Magnet Synchronous Motors (PMSMs) have been used [1]. DC series motors were initially used because it was easier to control their speed compared to AC motors and they also have a high starting torque [3]. However, the development of solid-state electronic control and converter technology helped improve the speed control of AC motors. Efficiency, reliability, maintainability, etc. became a priority; thus, IMs and PMSMs started replacing DC motors.

Three-phase AC motors are more rugged, reliable, efficient, require less maintenance, and have higher torque density, etc. than DC motors[1]. However, IMs and PMSMs have some shortcomings. IMs are less efficient due to power conduction losses in the rotor windings. PMSMs are more expensive and have unguaranteed availability due to the use of rare earth permanent magnets (PMs) in the rotor. The PMs (Neodymium and Dysprosium) have volatile and expensive prices [4]. One supplier produces 97% of the rare earth PMs used in the world [1]. In 2011 and 2012, there was reportedly a threat by the suppliers to cut off international supply. This threat resulted in a short-term price increase: dysprosium increased by up to 3000% [4], [5]. The supplier's percentage of the PMs used internally has also been growing over the years resulting in less availability for export [6]. In addition, sourcing and processing rare earth materials causes various types of pollution [7]. Therefore, the PMSM may not be economically, environmentally,

and technically favourable in the future [2], [6]. Therefore, a lot of research has recently been conducted to find possible alternatives that have high efficiencies and use little or no rare earth materials. This will reduce dependency on PMs and help replace IMs and PMSMs [2], [4], [6]. Manufacturers, and researchers, have been constantly investigating possible efficiency improvements using cost-effective solutions [2]. There is also a need to find alternatives that continue using the existing manufacturing systems and plants. This avoids costs due to building new plants: making the alternatives competitive against the technologies to be replaced [6].

One proposed alternative to such problems is the three-phase AC Synchronous Reluctance Motor (SynRM), and its derivative Permanent Magnet Assisted Synchronous Reluctance motor (PMSynRM) coupled with advanced controlling methods. The solution has been proposed in various industries for Electric vehicles (EV), Hybrid Electric Vehicles (HEV), pumping, handheld machines etc[4], [7]–[9]. Compared to IMs and PMSMs of the same power rating, SynRMs can perform similarly without requiring expensive windings (copper/aluminium), or rare earth PMs in the rotor [9]. SynRMs generate high reluctance torque which relies on the rotor structure and does not require PMs or windings in the rotor. This results in lower rotor losses than IMs, lower material costs than PMSMs, and a more rugged and robust structure [4], [9]–[11].

Based on efficiency trends, SynRMs can perform in the high IE4 Premium efficiency band [12]. This is the efficiency band recommended by the European Union [2], [4]. However, they currently do not have a standard design procedure due to the complexities that arise with the anisotropic structure. The lack of a PM magnetic field results in lower torque density and power factor with a higher torque ripple. Research has been going on to solve these problems, and several solutions have been proposed. The designs primarily focus on magnetic optimization of the rotor structure. This has resulted in an improved SynRM in the last two decades, that is comparable to IMs and PMSMs of the same rating when designed properly. In addition, the SynRM adds the advantage of removing rotor windings, conductor bars, or PMs [5], [8], [9]. Therefore, this thesis research aims to design a SynRM motor that can be applied to LRT applications. The motor is expected to increase the efficiency of the traction motor when replacing the IMs and simultaneously reduce costs compared to PMSMs. Thus, the research focuses on designing, optimizing, and simulating a SynRM motor and drive that can be used in an LRT system.

1.2. Problem Statement

IMs and PMSMs are predominantly used in railway traction. However, IMs are inefficient due to rotor conductor power losses, whilst PMSMs are expensive due to their use of rare earth PMs. IMs have up to 40% more losses than other synchronous motors [2]. The rare earth material used in PMSM is expensive and can be up to 65% of the total material cost [13]. In addition, rare earth material prices and availability are volatile. 97% of the rare earth PMs are supplied by a single supplier whose internal use of the material has been growing over the years, lowering the amount available for export [6]. In 2011 and 2012, there was reportedly a threat by the suppliers to cut off international supply, which resulted in short-term price increases. The increase was up to 3000% in the case of dysprosium [4]. Rare earth material extraction and processing is also carbon intensive, negatively impacting the environment [2]. Therefore, using rare earth PMs may become economically, and environmentally unviable in the future. This has forced the industry to look for alternatives to PMSMs that use little or no rare earth PMs. Solutions that do not require new manufacturing systems are also preferred to reduce costs due to building new manufacturing systems [6]. There has been much research towards finding alternatives, and it has shown that SynRMs have characteristics that may make them a good alternative.

SynRMs have an anisotropic rotor structure that is optimized to produce high-reluctance torque. Thus, their rotor does not require PMs, conductor bars, or windings [5]. The absence of rotor windings in SynRMs results in no rotor windings power losses. This results in better efficiency compared to IMs. SynRM losses are almost 60% of the IM losses [2]. The absence of rotor losses results in cold rotor operation, significantly reducing operating temperatures. The reduced operating temperatures improve the lifetime of the insulation, bearings, and the maintainability of the motor [5], [9]. An increase in efficiency also reduces the sizes of cooling systems required [3]. In addition, due to the cold rotor operation, most of the heat is generated in the stator windings which are easily accessible for cooling. Thus, enclosed ventilation may be used. This is preferable for LRT motors, where air-forced ventilated cooling is less preferred because it requires ducts that can reduce the space available for passenger seats. Simultaneously, the low floor operation of the motors in urban areas exposes them to a dirty environment that affects open-air self-ventilated cooling [3]. The absence of PMs, rotor conductors, or brushes/ slip rings, results in 60% savings

in material costs. Its stator is similar to IM and PMSM stators. Hence, it can also be mass-produced conventionally [8]. Therefore, SynRMs have started to be adopted in the industry [4], [9], [10].

The choice of a traction motor usually depends on three major factors: weight, size, and cost. The SynRM can be considered a better alternative to IMs because it has a smaller size, lower costs, and higher efficiency. However, considering traction requirements, the major disadvantages of SynRMs are low torque production, low power factor, and high torque ripple. Research has been going on to solve some of these problems, and several design solutions have been proposed. The design solutions primarily focus on magnetic optimization of the rotor structure, and this has resulted in the improvement of the SynRM in the last two decades to be comparable with the IM when designed properly [8].

Therefore, this thesis aims to design a SynRM motor that can be applied to LRT. The major works that will be done will be the sizing of the traction motor, optimization of its torque, torque ripple, power factor, and efficiency, finite element analysis (FEA) of the optimized design to evaluate its performance characteristics, design of control to simulate a complete drive, and analysis of the performance results of the motor compared to other motors.

1.3. Research Questions

The study seeks to answer the following questions;

- a) What are the performance requirements for LRT applications?
- b) What characteristics of the SynRM affect its performance for LRT applications?
- c) How does the SynRM perform compared to other types of motors in LRT applications?
- d) How much is the performance improvement in terms of efficiency, starting torque, and other parameters?

1.4. Thesis Objectives

1.4.1. Main Objective

The main objective of this research is to design a SynRM drive system that can be applied to LRT applications with improved performance.

1.4.2. Specific Objectives

The specific objectives of this thesis are:

- To investigate traction requirements of the railway traction and use the requirements to come up with high-performance target parameters.
- To develop a design model and optimize its torque, torque ripple, efficiency, and power factor to develop the most appropriate SynRM design in light of LRT applications.
- To design a control system for the SynRM and simulate the drive system
- To propose recommendations for LRT traction motor manufacturers and future researchers based on the analysis of the result

1.5. Research Methodology

The process of researching the design of SynRM motor and drive for LRT applications involved a set of steps outlined in the research methodology. The methodology was structured to investigate LRT traction requirements, identify the parameters of the SynRM affecting its performance in relation to the traction requirements, and create a design model suitable for optimum performance in LRT traction application. Initially, an analytical model was obtained, and computer-aided analysis through automated optimization methods and FEA were utilized to modify the model until it was optimized for the LRT application. The model was then analyzed using FEA to assess its performance. A control was then designed for the motor and simulated. The following are the steps involved in the research methodology.

- Traction requirements investigation for the target railway system
- Traction motor investigation (mathematical modeling)
- Traction motor sizing
- Optimization
- FEA analysis
- Controller Design
- Drive Simulation
- Results Analysis

1.6. Scope

The structural integrity of the SynRM is an important factor, especially for railway traction applications. Structural integrity is stressed by centrifugal forces during service and overstress exerted on the structure during manufacturing [9]. Therefore, strategies may be adopted at the design stage to counter the stress during manufacturing. However, this research did not include a design strategy considering stresses during manufacture. Temperature insulation constraints and cooling methods are important factors when designing a traction drive system for railway traction [12]. However, the design in this research did not consider the thermal insulation and cooling methods.

1.7. Significance of the Research

The research provides a more efficient alternative to IMs in LRT traction applications. It also provides a less expensive alternative to PMSMs. This will increase diversity enabling flexibility in different economic conditions.

1.8. Thesis Organization

The thesis is organized as follows:

Chapter 1 provides an introduction to the research background, problem statement, research questions, objectives, methodology, scope, and significance. Chapter 2 delves into the relevant literature, presenting an overview of existing research and developments related to SynRM motor design and its application in transportation systems. Chapter 3 describes the methodology adopted for designing the SynRM motor, including the steps involved in optimizing its performance and simulating the drive system. Chapter 4 presents the results and analysis of the designed SynRM motor, comparing its performance with other motor types in LRT applications. Chapter 5 offers conclusions and recommendations based on the research findings, and provides guidance for future research in this domain.

2. Literature Review

2.1. Introduction

Railway systems come in various types, each with its own purpose. They use several traction systems that vary depending on performance needs and location. The traction systems consist of traction electric motors, power supplies, and control systems. This literature review examines research articles and literature on the types of railway systems and their traction requirements. It also surveys the traction motors and control systems employed in traction systems, including the SynRM.

2.2. Types of Railway Systems

2.2.1. Light Rail Transit (LRT)

The LRT is a type of passenger railway system that is commonly used for transportation in urban and suburban areas. It includes various types of trains, such as trams, trolleys, and metro systems. LRTs are lighter in weight compared to locomotives and high-speed trains, thus they require lower power and torque levels [3]. The electric motors typically used in LRTs have a power rating of 100 to 160 kW per axle. LRTs usually travel at low speeds, operate for short distances, and stop frequently at stations [14]. Induction motors are often used in LRTs, and the traction motors are usually located on the lower floor due to space constraints. This affects the type of cooling system used for the motors. Forced air ventilation is difficult to use because it takes up space, while open self-ventilation can cause problems due to the polluted air in cities. To cool the rotor, LRTs are forced to use either of these ventilation methods. Manufacturers prefer to use copper rotor conductors instead of aluminum conductors to reduce power losses incurred in the rotor windings of induction motors. However, this increases the motor costs because copper is more expensive. Therefore, solutions that allow for the use of aluminum conductors or the complete elimination of conductor bars are preferable [3].

2.2.2. High-Speed Trains (HSTs)

After locomotives, HSTs are considered the next most demanding railway application. HSTs are passenger trains that can travel above 200km/h. The propulsion system is equipped with gearboxes

at low gear ratios to maintain the motor's maximum speed within an acceptable range (5000-6000 rpm). Due to this, traction motors are required to operate at high torque levels to perform optimally [3]. HSTs are usually used for long-distance travel on a main line.

2.2.3. Locomotives

Locomotives are used to haul heavy goods for long distances usually. They are considered the most demanding because a high level of effort is needed both during acceleration and also at high speeds where some residual acceleration is required to be kept resulting in high torque and power requirements for the motors [3]. In earlier years, steam and diesel-hydraulic locomotives were used. However, nowadays, they are usually either diesel-electric or electric locomotives.

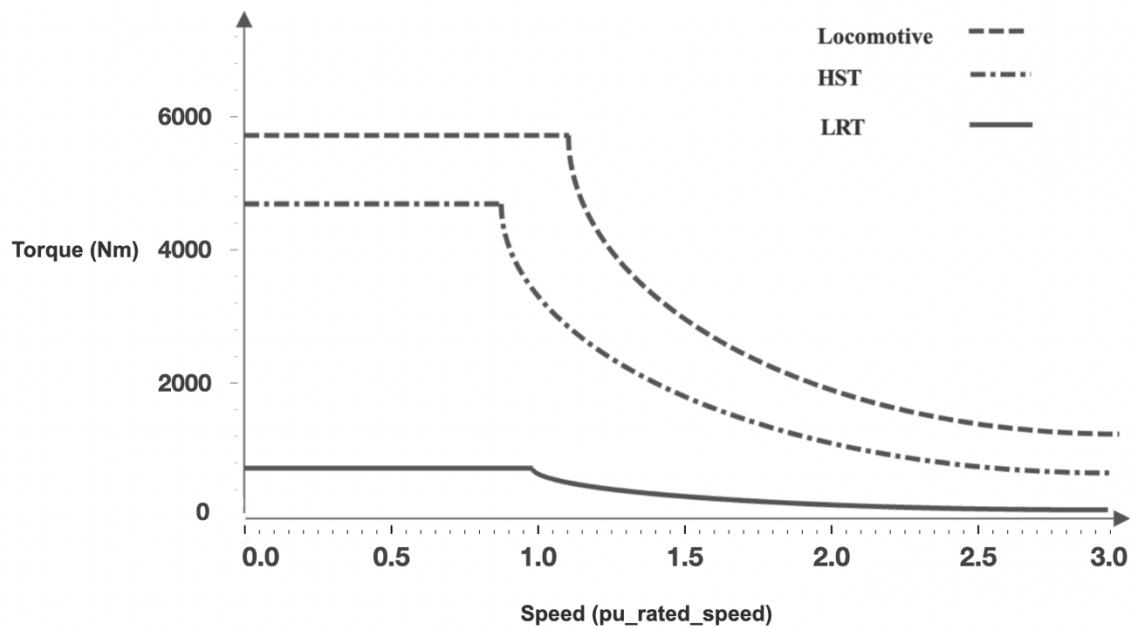


Figure 2-1: Performance comparison of traction motors used in different railway applications [3],[15], [16].

2.3. Traction Motors

For over a century, both DC and AC electric motors have been utilized as traction motors. Electric trains can obtain electrical power from an overhead line, third rail, or an energy storage system (ESS), while diesel-electric trains draw power from a diesel engine-powered electrical generator

[3]. Initially, DC series motors were commonly used for traction, but with the advancement of solid-state electronics control, three-phase AC motors became more prevalent [1], [17]. Nowadays, IMs are primarily used in railway systems, with PMSMs occasionally utilized as well [3]. Additionally, linear motors have been used for railway traction in limited instances, such as in the Shanghai Trans-rapid maglev and Linimo. Research in this field has been on the rise, with the Japanese L0 maglev still in the process of testing and development. Once launched, it will be the fastest train at over 600 km/h. Other projects, such as the hyperloop, are currently being explored [18].

2.3.1. DC Motors

DC series motors were initially used for many years because it was easier to control their speed and also because of their high starting torque [3]. The operating principle of DC series motors is that a voltage is connected across the armature and field, which are connected series. An armature flux is created by the armature current and back emf of the armature; this armature flux interacts with a field flux created by the field current to produce a torque which then rotates the armature [6]. Speed control was usually easily done using voltage control. Another advantage of series DC motors is that they have high starting torque which is required for railway traction [3]. However, DC series motors have some disadvantages that include high maintenance requirements due to sparking at commutator and brushes, low torque density, and bulkiness. DC motors have now been mostly replaced with AC motors [3], [6].

2.3.2. AC Induction Motor (IM)

A squirrel cage induction motor (IM) is a motor that has short-circuited copper/aluminium bars or windings in the rotor and three-phase AC windings in the stator. The three-phase AC currents in the stator result in a rotating flux. The rotating flux induces a current in the rotor windings. The induced current produces a flux in the rotor which follows the rotating stator flux to generate the required torque. IMs have been the workhorse of the industry being one of the most ubiquitous electric motors in the industry because they are cheap, rugged, and reliable [2]. However, IMs were initially difficult to use for traction applications because of the variation of speed required in traction and the difficulty in controlling IM's speed in earlier years. However, with the improvement of solid-state control methods which enabled better control of AC motors, IMs

started being employed for railway traction because of their higher efficiency, ruggedness, maintainability, and lower costs compared to DC motors [6]. The IMs have now been the most used electric motor for various railway traction purposes over the last four decades. [3], [19].

The torque profile of an IM operates over an extended speed range from base to maximum speed with constant power using the flux weakening control method. This is a major requirement for railway traction to enable a wide speed range [6]. IMs may also use multiple drive control where two or four motors can be connected in parallel to the same converter [3]. However, IMs come with some disadvantages that include rotor conductor losses, asynchronous speed, lower power factor, low torque density, low starting torque, etc [20]. Due to rotor losses, IMs usually operate optimally using open or forced air ventilation. This is a problem for most LRTs where the motors operate on the low floor level. Thus, they are exposed to the dirt in the environment. There is also not enough space in the train for forced air ventilation ducts. Therefore, where these factors matter, alternatives have been sought after, and PMSMs have been used in some of the instances [3].

2.3.3. AC Permanent Magnet Synchronous Motor (PMSM)

PMSMs are motors that have a dedicated PM field in the rotor and three-phase AC windings in the stator. The three-phase AC produces a rotating magnetic field which is followed by the rotor magnetic field at synchronous speed, producing the required torque. PMSMs may be interior permanent magnet (IPM) or surface permanent magnet (SPM) synchronous motors. PMSMs initially also had speed control difficulties and were only introduced later for traction applications with the development of better solid-state control. PMSMs have good torque density, power density, and power factor, and they rotate at synchronous speed [4]. However, despite their advantages, all synchronous motors are less common in railway traction compared to IMs. This is attributed to the use of rare earth PMs and their challenging electric rotor design. Some manufacturers have been opting for the PMSM, especially in HST applications, since the beginning of the 21st century, due to its high-performance advantages [3].

PMSMs come with the disadvantage of expensive rare PMs, which are also volatile in terms of availability [21]. Rare earth materials in PMSMs are approximately 70% of the motor's total material costs [13]. In addition, the availability of rare earth materials is volatile due to a monopoly of supply by one country. In 2011 and 2012, there was reportedly a threat by the suppliers of rare

earth materials to cut off international supply. This resulted in short-term price increases of up to 3000% in the case of dysprosium [2], [4]. Other PMSM disadvantages include possible loss of magnetism, speed limitations for SPMs, and inability to connect two motors to one inverter, as usually done in IM traction units. In faulty conditions, the magnets' induction can have braking effects on the train. There is also a need for overvoltage protection for converters [1], [3]. Due to some of the disadvantages of PMSMs, there has always been an effort to pursue better alternatives to counter these disadvantages.

2.3.4. Switched Reluctance Motor (SRM)

An SRM is an electromagnetic rotating machine that produces reluctance torque by switching the inductance in stator exciting windings causing a steel rotor core to follow this switched inductance in the direction of the switching to minimize the reluctance in the path of the flowing flux [22]. Its stator consists of salient poles where simple concentric windings are placed. The rotor has a simple steel structure with salient poles and no windings, magnets, commutators, or brushes. The motor generates reluctance torque whereby an energized stator pole causes an adjacent rotor to rotate towards it to minimize reluctance to flux flow. The SRM rotor has a low moment of inertia that causes a fast dynamic response, leading to fast acceleration. It also has high starting torque and high torque to inertia ratio. The SRM motor has several advantages like low cost, wide speed range, high efficiency, ruggedness, and reliability that make it a potential alternative motor for traction applications. However, it also has several disadvantages like high torque ripple, considerable DC bus current ripple, electromagnetic interference, complex design, and special converter topology that make it unsuitable for railway traction [6].

2.3.5. Synchronous Reluctance Motor (SynRM)

2.3.5.1. *Introduction to SynRM*



Figure 2-2: Synchronous Reluctance Motor [23].

The SynRM is an AC synchronous motor that generates its torque using the reluctance concept. The rotor has an anisotropic structure that produces the reluctance torque [2], [24]. The SynRM is similar to conventional synchronous motors. However, it does not have excitation windings or PMs in the rotor, thus it relies on the anisotropic structure to produce torque. The rotor is constructed with steel lamination layers that have flux barriers. SynRMs were invented in 1923 when Kostko calculated that if a SynRM is appropriately designed and manufactured, it may perform almost comparably to IMs of the same size (volume) [4], [9]. However, they were not widely used until the 1970s because of the complex power electronics they required [9]. In the early days, the motor lacked stability and start-up torque with a direct online start. However, Vagati showed in the 1990s that SynRMs could be controlled using a closed-loop technique, such as FOC and DTC control methods, to overcome these challenges. With this technique, SynRMs were capable of operating at significant power and torque density. [6], [25]. Direct online Line-Start SynRMs were also developed that were filled with aluminum in the flux barriers, enabling the motor to start direct online like IMs [2].

2.3.5.1. Basic Reluctance Concept

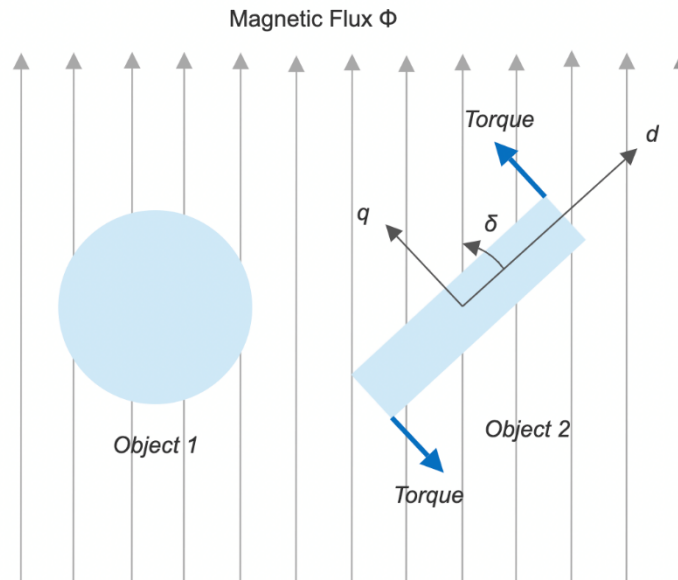


Figure 2-3: Basic reluctance concept [7].

In Figure 2-3 above, the basic concept of reluctance is illustrated. Two objects, labeled (1) and (2), are composed of isotropic magnetic material and are exposed to a magnetic field (Φ) in the air. Magnetic conductive material has less reluctance than air and tends to align with a magnetic field, reducing the total reluctance of the magnetic flux lines to a minimum [7]. Object (2) has different geometric dimensions in the direct (d-axis) and quadrature (q-axis), resulting in different reluctances in each axis. This is known as anisotropy. On the other hand, object (1) has similar geometric dimensions in all directions, resulting in the same reluctances in both the d-axis and q-axis. This is referred to as isotropy. If the d-axis of the object (2) misaligns with the magnetic field at an angle of (δ), it causes field distortion. This results in the development of electromagnetic potential energy that can generate an electromechanical torque to force the object to align with the field direction (d-axis) at minimum reluctance. This concept forms the foundation of how the SynRM works. By keeping the angle (δ) constant through the application of a constant mechanical load, the electromagnetic potential energy can be converted to mechanical energy on the shaft of the SynRM. The angle (δ) is known as the load angle [6], [7].

2.3.5.2. Working Principle

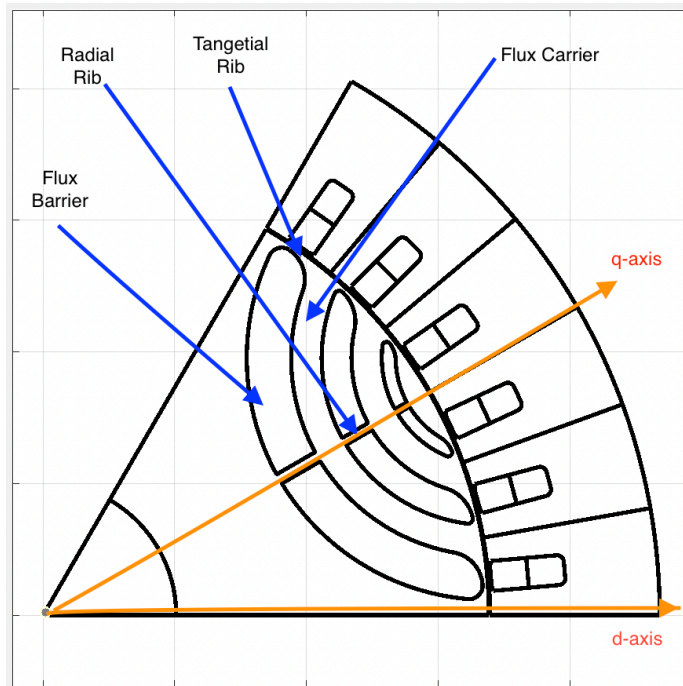


Figure 2-4: SynRM rotor nomenclature [26].

The SynRM generates reluctance torque using the reluctance concept. The reluctance torque is generated by creating an anisotropic structure in the rotor that is optimized for reluctance torque and then supplying a rotating magnetic field around the stator of the motor. An appropriate rotor anisotropic structure is created by introducing reluctance differences in its d-axis (longitudinal) and q-axis (transversal). This can be achieved by inserting non-magnetic material like air (flux barriers) that have high reluctance in the q-axis of the rotor whilst leaving low reluctance magnetic material like steel (flux carrier) in the d-axis [2]. The barriers create a high reluctance path for the flux along the q-axis resulting in a high saliency ratio. The saliency ratio is the ratio between the d and q axis magnetizing inductances L_d/L_q . It is an important parameter when designing and optimizing the motor because the reluctance torque produced is directly proportional to it.

When three-phase AC currents are then supplied to the stator windings, they produce a synchronous rotating magnetic field around the stator core and air gap of the motor. The rotor then follows the magnetic field, trying to align the magnetic field with its least reluctant d-axis path [6]. The rotor continuously follows the rotating magnetic field producing continuous reluctance torque, as illustrated in Figure 2-5.

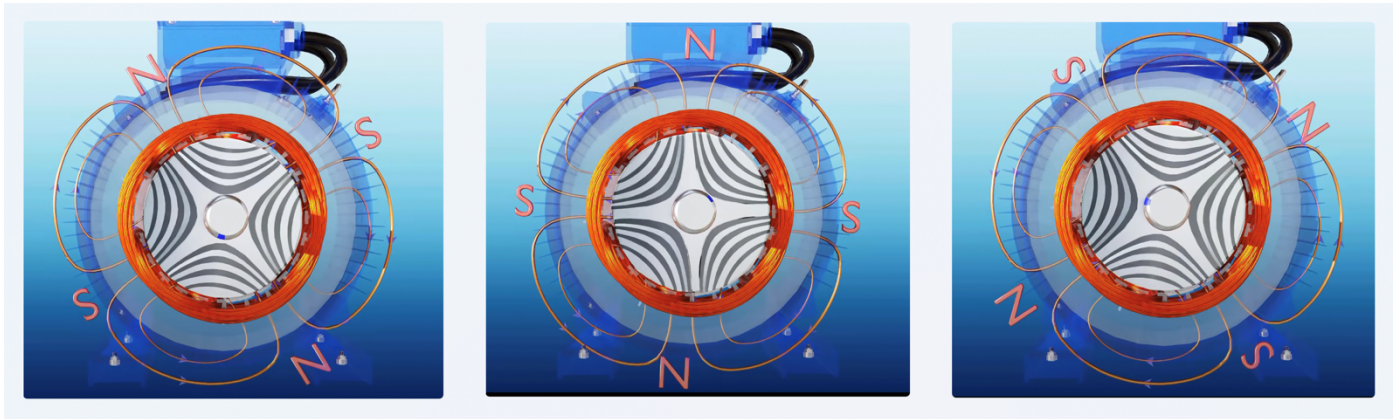


Figure 2-5: Rotation due to reluctance torque [27].

2.3.5.3. *SynRM Characteristics*

The SynRM motor has a simple and rugged structure that resembles that of the IM and PMSM. The rotor consists of a laminated iron core with an anisotropic structure and without windings or PMs [28]. The SynRM has many advantages, such as high torque per ampere, high efficiency, low cost, insensitivity to operating temperatures, simple control, field weakening, and short-time overload capability. It can be mass-produced like IMs and can meet several of the characteristics of IMs and PMSMs at an advantage. The SynRM has gained more interest for traction purposes due to its excellent features [9].

Compared to the IM, the SynRM has higher torque density, higher efficiency, and lower costs. The higher efficiency is because the absence of rotor windings eliminates rotor conductor losses. SynRMs can produce up to 82% of the torque produced by IMs with 50% less copper losses. Moreover, they can generate up to 42% higher torque with the same copper losses as IMs [29], [30]. The lower costs are also due to the absence of expensive windings and lower operating temperatures, leading to longer life and lower maintenance requirements. Additionally, most of the SynRM's losses are produced in the stator, which is more accessible for cooling than the rotor [1], [4], [31].

Compared to PMSMs, SynRMs are less expensive and more environmentally friendly due to the absence of rare earth PM [29]. They can produce lower but comparable output torque. However,

they have a low power factor, high torque ripple, a complicated design that is not yet standardized, and a low-speed range [6], [11], [32]. Researchers are working on magnetic optimization of the rotor structure to improve SynRMs' performance. Over the last two decades, the proposed strategies have resulted in motors' enhancement to performances comparable to other AC motors when designed properly.

2.3.5.4. *Types of SynRM Structures*

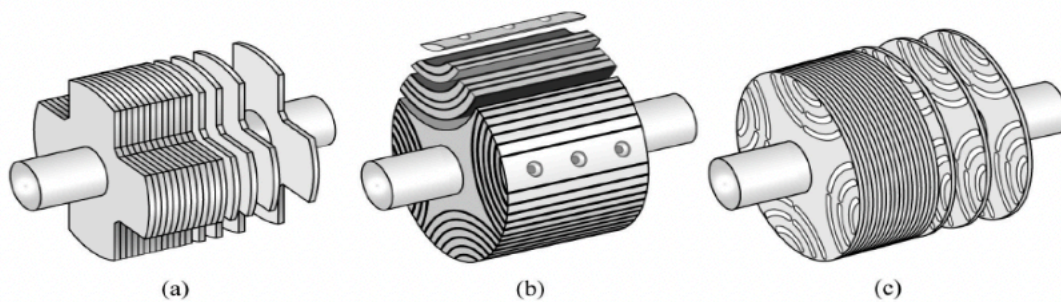


Figure 2-6. Different anisotropic structures of the SynRM's Rotor, (a) simple salient rotor, (b) axially laminated anisotropic rotor (ALA), (c) transversally laminated anisotropic rotor (TLA) [33].

Figure 2-6 displays three different types of SynRM anisotropic rotor structures. The first type is the simple salient pole rotor (a), where iron material is removed from each rotor in the transversal region. The resulting rotor structure has a low saliency ratio and high harmonics, making it an uncommon choice. The second type is the axially laminated rotor (ALA), where iron laminations are shaped at each pole and stacked with electric and magnetic insulation. The stacks are then connected to the shaft through pole holders. The ALA is slightly more efficient than the third type, the transversally laminated anisotropic rotor (TLA). The TLA's laminations are punched traditionally, and thin ribs and bridges are left to connect the various rotor segments. However, flux flows through these ribs, reducing the saliency ratio [4]. Thus when designing, it is essential to consider having a good saliency ratio and a sound rotor structure [3].

In general, TLA-SynRMs are preferred over ALA-SynRMs because of their stronger mechanical strength, ease of manufacture, ease of skewing, and cheaper production costs [1], [9] [29], [34].

This study primarily focuses on TLA-SynRMs due to these advantages. Another rotor structure is the Line Start SynRM, which has an additional conductor cage in the rotor. This structure enables asynchronous starting torque like IMs, which the SynRM does not naturally have [20]. However, with modern control technology, the machine can be started from a standstill using suitable field-oriented control and PWM techniques without inserting the cage into the rotor. The Line Start SynRM structure is mainly implemented in cases where Variable Speed Drives (VSDs) are not employed [30].

2.3.5.5. *SynRM vs other AC motors*

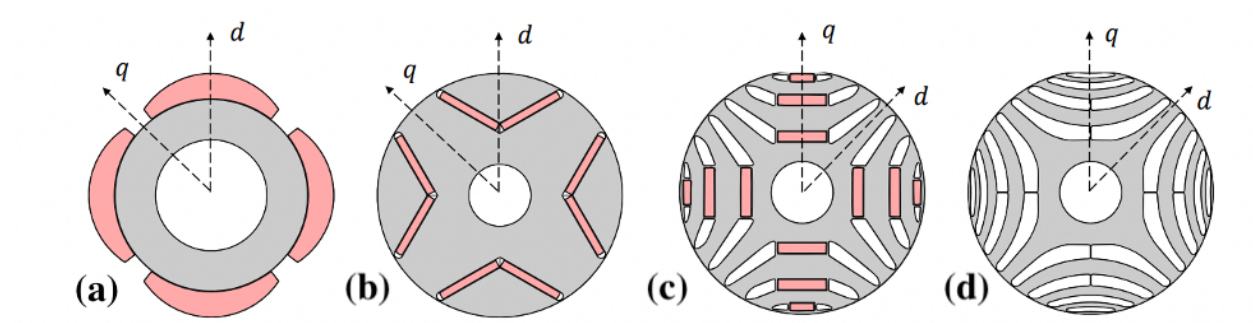


Figure 2-7. SPM, IPM, PMSynRM, and SynRM respectively.

The SynRM motor falls somewhere between an IM and a PMSM in terms of its design [8]. Its stator is similar to those found in both the IM and PMSM, but its rotor lacks the squirrel cage or windings found in an IM [1]. There are two types of torque produced by synchronous motors that can be used to differentiate them: reluctance torque, which occurs when magnetic material aligns with a magnetic field to reduce reluctance and create torque, and magnetic torque, which occurs when two magnetic fields interact. Anisotropy is required in the core magnetic material to produce reluctance torque. The SPM lacks this anisotropy as shown in Figure 2-7(a), resulting in a saliency ratio of 1 and only magnetic torque being produced [2], [10], [35]. The IPM has PMs inserted in its core to create anisotropy as shown in Figure 2-7(b), making it similar to the SynRM, but it is not optimized for high saliency and has a low saliency ratio, resulting in most of its torque being magnetic torque with only a minor component coming from reluctance torque. The SynRM, on the other hand, is optimized for high saliency and has no PMs in its structure, resulting in all of its torque being produced in the form of reluctance torque. The SynRM can be transformed into a

PMSynRM if PMs are inserted into its rotor barriers as shown in Figure 2-7(c), which helps saturate the barrier ribs and increase the torque and power factor [36]. The PMSynRM generates most of its torque in the form of reluctance torque due to its optimized anisotropic structure, but also has a smaller component of magnetic torque due to the inserted PMs, typically made of weak ferrite PM material [2], [4], [31], [37].

2.3.5.6. *Reluctance and Inductance*

Maximizing the reluctance differences in the d-axis and q-axis is a major goal in the design of the SynRM. The difference in reluctance is very important as it influences the difference in the inductances in the d and q axes. The difference in d and q axes inductances determines the electromagnetic torque produced by the motor. The relationship between reluctance and inductance is described by the following equation:

$$L = \frac{N^2}{R} \quad (2-1)$$

where L is inductance, N is the number of turns and R is the reluctance [7].

The generation of torque in a SynRM requires a difference in the inductance in d-axis (L_d) and the q-axis (L_q). In order to introduce a difference between L_d and L_q , the structures of the d and q axes of the rotor are made of material with different reluctances. As mentioned earlier, this is the core principle in the design of the SynRM rotor. L_d and L_q can be calculated from reluctance with the following relations:

$$L_d = \frac{N_d^2}{R_d} \times \frac{P}{N_{parallel}} \quad (2-2)$$

$$L_q = \frac{N_q^2}{R_q} \times \frac{P}{N_{parallel}} \quad (2-3)$$

where; N_d and N_q are the equivalent number of turns in the d and q axis, R_d and R_q are the reluctances in the d and q axis, P is the number of pole pairs, and $N_{parallel}$ is the number of parallel branches in the stator windings [7]. N_d and N_q can be calculated as,

$$N_d = N_q = N_{tc} K_w q n_{lay} \quad (2-4)$$

where N_{tc} is the number of turns per coil, q is the number of slots per pole per phase, K_w is the winding factor, and n_{lay} is the number of layers.

Mathematical expressions can be used to model the reluctance of the SynRM. However, the reluctance in both axes is affected by the saturation in the magnetic circuit field, making the expressions less accurate [7]. To improve the accuracy of the model, FEA analysis is employed to account for the saturation.

The d-q flux linkages may be written as

$$\lambda_d = L_d i_d = (L_{dm} + L_s) i_d \quad (2-5)$$

$$\lambda_q = L_q i_q = (L_{qm} + L_s) i_q \quad (2-6)$$

where i_d and i_q are the d-q current components and L_d, L_q are the inductances, equal to the sum of the magnetizing inductances L_{dm} and L_{qm} (different for each axis) and the leakage inductance L_s (identical for both axes). The inductances depend on geometric inputs and the number of turns [7].

2.3.5.7. *ABC/DQ Reference Frame Transformation*

In this section, we will discuss the process of transforming the 3-phase to a D-Q reference frame in SynRM. To simplify the analysis, the sinusoidally distributed stator of the three-phase system is converted to the reference frame of D and Q using Park's transformation. First, the system is transformed from 3-phase to $\alpha\beta$ coordinates and then to a D-Q frame [38]. The use of reference frame theory can help simplify the analysis of electric machines and provide a powerful tool for implementing sophisticated control schemes for SynRM drives. The most commonly used reference frames are the stationary and synchronous frames. The transformation of variables between these two frames is presented below. To transform the three-phase (abc-axis) variables of a SynRM to the equivalent two-phase (dq-axis) variables, we can perform the abc/dq frame transformation [39].

In Figure 2-8, x could represent current, voltage, or flux linkage, and θ is the angular displacement between the a-axis and d-axis of the three-phase and two-phase reference frames. The three-phase variables, x_a , x_b , and x_c , are in the stationary reference frame that does not rotate in space. Meanwhile, the two-phase variables, x_d , and x_q are in the synchronous reference frame whose direct (d) and quadrature (q) axes rotate in space at the synchronous speed ω_e . ω_e represents the angular electrical speed of the rotating magnetic field of the motor. The transformation equation of 2-7 is only valid for a balanced three-phase system [39].

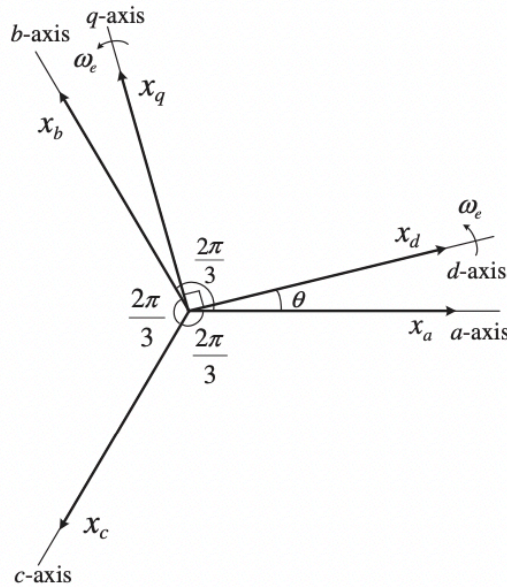


Figure 2-8: Variables in three-phase (abc) stationary reference frame and two-phase (dq) synchronous rotating reference frame [39].

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin \theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (2-7)$$

The variables in the synchronous frame can also be transformed into the stationary three-phase frame as shown below [39].

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} x_d \\ x_q \end{bmatrix} \quad (2-8)$$

2.3.5.8. Equivalent Circuit and Mathematical Model

Since the SynRM stator windings are similar to that of the IM in which the flux is distributed sinusoidally, the machine's equations defining the behavior of the SynRM can be derived based on the conventional wound field synchronous machine. The derivation is done taking into account two important properties; 1- there are no excitation windings: 2- the rotor does not have a cage or windings. The vector diagram and equivalent circuit of the SynRM are shown in Figure 2-9 and Figure 2-10 respectively, taking iron losses into account where; V is the terminal voltage vector, E_m is the stator electromotive voltage or internal voltage of the stator windings after the voltage drop due to losses, R_s is the stator windings resistance, i_s is the stator current vector, ω_e is the electrical base speed, L_s is the winding leakage inductance, λ_m is the magnetizing flux, L_m is the magnetizing current, ω is the mechanical base speed, i_{dm} , i_{qm} , L_{dm} , and L_{qm} represent the d-axis and q-axis magnetizing current and magnetizing inductance in the rotor reference frame respectively, V_d and V_q are the d-q voltages in the rotor reference frame, R_{cs} is the stator core resistance, R_{cr} is the rotor core resistance, i_{cs} is the stator core current, i_{cr} is the rotor core current [6], [7], [33], [38], [39].

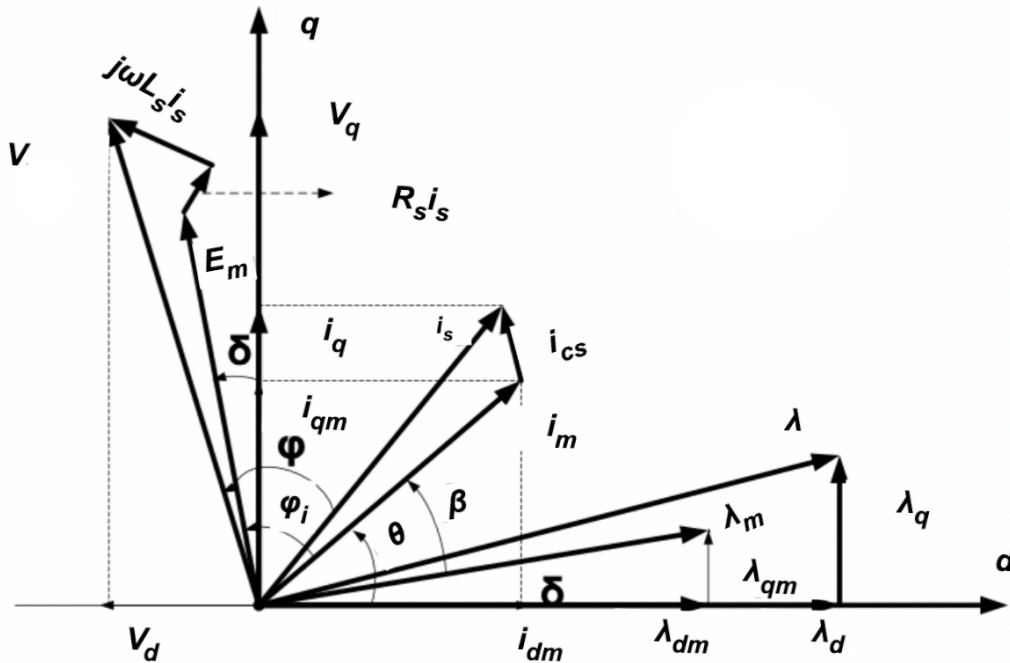


Figure 2-9: Space Vector diagram of the SynRM including iron losses [6].

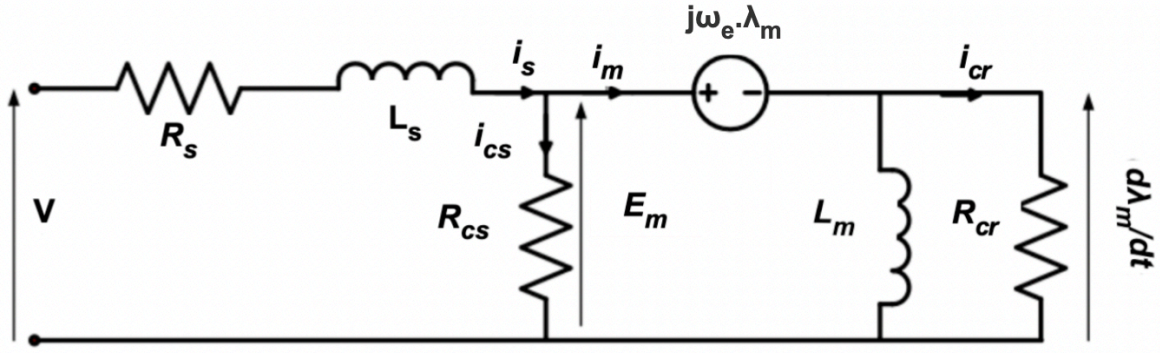


Figure 2-10: The equivalent circuit of the SynRM including iron losses [6].

From Figures 2-9 and 2-10 above, eliminating the rotor excitation due to windings or cage from the equations, the mathematical model of the SynRM in the rotating reference frame (d-q axis) at base speed can be expressed as follows:

$$V = E_m + R_s i_s + j\omega_{be} L_s i_s \quad (2-9)$$

$$E_m = \frac{d\lambda_m}{dt} + j\omega_e \lambda_m \quad (2-10)$$

$$\omega_e = \omega P \quad (2-11)$$

where; P is the number of pole pairs.

The SynRM dq -axis model can be derived by decomposing the space vectors in the space vector motor model into the d - and q -axis components as shown below [39].

$$\{V = v_d + jv_q; i_s = i_{dm} + ji_{qm}; \lambda_m = \lambda_{dm} + j\lambda_{qm}; L_s = L_{dm} + jL_{qm} \quad (2-12)$$

Magnetizing flux can be expressed as in (2-13) if the cross-coupling effect is neglected.

$$\lambda_m = L_{dm} i_{dm} + jL_{qm} i_{qm} \quad (2-13)$$

Therefore, in the steady state in which $\frac{d\lambda_m}{dt} \cong 0$, if (2-10) and (2-13) are substituted into (2-9) we can rearrange the machine's terminal voltage (2-9) and its d-q components as follows:

$$V = j\omega_e(L_{dm}i_{dm} + jL_{qm}i_{qm}) + R_s(i_{dm} + ji_{qm}) + j\omega_e(L_{dm} + jL_{qm})(i_{dm} + ji_{qm}) \quad (2-14)$$

$$V = (-\omega_e L_{qm} I_{qm} + R_s I_{dm}) + j(\omega_e L_{dm} I_{dm} + R_s I_{qm}) \quad (2-15)$$

$$V_d = -\omega_e L_{qm} I_{qm} + R_s I_{dm} \quad (2-16)$$

$$V_q = \omega_e L_{dm} I_{dm} + R_s I_{qm} \quad (2-17)$$

The vector equations (2-16) and (2-17) can be the machine mathematical model to characterize the magnetic and electric parameters of the proposed SynRM during the analytical designing [5]. This is discussed in more detail in the analytical design section.

2.3.5.9. Main Characteristics

It is crucial to verify the main SynRM parameters and characteristics when designing and evaluating the motor's performance. These parameters can be categorized into two types, target parameters, and design parameters. Target parameters refer to the performance parameters that fulfill the system's traction requirements. Conversely, design parameters are the motor's parameters that determine the target parameters [6]. The main parameters during the designing process are summarized below.

1) Target parameters

Target parameters are the traction performance requirements listed below, and a detailed description of each parameter follows [6], [41].

- Electromagnetic Torque
- Power Factor
- Efficiency
- Torque ripple
- Power factor
- Field weakening range
- Iron losses

- **Electromagnetic Torque:** The SynRM electromagnetic torque is generated by the interaction between the air gap flux and its corresponding magnetizing current. Hence, using Figure 2-9 together with (2-9), (2-10), and (2-22), several different expressions of the electromagnetic torque shown from (2-18) to (2-23) can be obtained [6].

$$T_e = \frac{3}{2} P (\lambda_d i_q - \lambda_q i_d) \quad (2-18)$$

$$T_e = \frac{3}{2} \frac{P}{2} \lambda_m i_m \sin \beta \quad (2-19)$$

$$T_e = \frac{3}{2} \frac{P}{2} (L_{dm} - L_{qm}) i_{dm} i_{qm} \quad (2-20)$$

$$T_e = \frac{3}{2} \frac{P}{2} (L_{dm} - L_{qm}) i_m^2 \sin 2\theta \quad (2-21)$$

$$\xi = \frac{L_{dm}}{L_{qm}} \quad (2-22)$$

$$T_e = \frac{3}{2} \frac{P}{2} (\xi - 1) \left(\frac{E_m}{\omega L_{dm}} \right)^2 \sin 2\delta \quad (2-23)$$

The saliency ratio, denoted by ξ in (2-22), is a crucial parameter in evaluating the performance of SynRM. The primary aim in designing SynRM with high performance is to maximize the saliency ratio by achieving a high L_d and a low L_q . The torque generated on the shaft, given a voltage and operating speed, is dependent on the saliency ratio (ξ) and reaches its maximum at a given load angle (δ) or current angle (θ), as shown in the equations above. It is not practical to control the load angle directly during operation. Therefore, the current angle is used to regulate the rotor position at appropriate values. Equations (2-12), (2-22), and the resultant (2-24), (2-25) from the vector diagram in Figure 2-9 depict the relationship between load and current angle as in (2-26) [6].

$$\tan \delta = \frac{\lambda_{qm}}{\lambda_{dm}} \quad (2-24)$$

$$\tan \theta = \frac{I_{qm}}{I_{dm}} \quad (2-25)$$

$$\theta = \tan^{-1}(\xi \tan \delta) \quad (2-26)$$

- **Power Factor:** Besides torque, the power factor is another key performance parameter of the SynRM motor. SynRMs tend to have a low power factor. This is attributed to the saliency characteristics of the rotor that result in needing a high level of magnetization,

leading to an increase in reactive power [42]. This increase in reactive power can then cause a decrease in the motor's power factor. The machine vector diagram (Figure 2-9) enables the identification of the air gap or apparent power factor, which is also referred to as the internal power factor (IPF). IPF can be expressed in different forms, as in (2-27), yielding the final expression of IPF as in (2-28) [6].

$$IPF = \cos\varphi \text{ or } IPF = \sin\beta \text{ or } IPF = \cos\left(\frac{\pi}{2} + \delta - \theta\right) \quad (2-27)$$

$$IPF = (\xi - 1) \sqrt{\frac{\sin 2\theta}{2(\tan\theta + \xi^2 \cot\theta)}} \quad (2-28)$$

From (2-28), it can be shown that IPF is a function of the current angle which is dependent on the saliency ratio and reaches its maximum at $\theta = \tan^{-1} \sqrt{\xi}$. Therefore, the maximum IPF can be expressed as shown in (2-29) [6], [43]. Again, this confirms the power factor's dependency on the saliency ratio in SynRM.

$$IPF(max) = \frac{\xi-1}{\xi+1} \quad (2-29)$$

The terminal power factor which is derived in (2-30) is not identical to the IPF at steady state. Hence, the vector diagram shows a slight difference between the two caused by the machine's losses [6].

$$\cos\varphi_i = \frac{V_d i_d + V_q i_q}{|V||i_s|} \quad (2-30)$$

- **Efficiency:** Efficiency is one of the most important characteristics to consider in the design of SynRM, especially for traction applications. Considering that iron losses are negligible compared to copper losses at low speed, efficiency can be expressed in (2-31) and rearranged in (2-32) [6].

$$\eta = \frac{\omega T_e}{\omega T_e + 3R_s i_s^2} \quad (2-31)$$

$$\eta = \left(1 + \frac{3R_s i_s^2}{\omega T_e}\right)^{-1} \quad (2-32)$$

Equation (2-32) shows that the (T_e/i_s) ratio has to be maximized to optimize the efficiency up to base speed. To maximize the ratio, it is required to maximize the saliency ratio. The assumption of negligible iron losses becomes invalid at high speeds because iron losses depend on torque ripple and flux fluctuations, which are higher at high speeds. However, a high saliency ratio is always dominant in attaining high efficiency.

- **Torque per kVA:** Torque per kVA refers to the motor's torque generation relative to the absorbed apparent power from the supply. A properly designed SynRM has a high torque per kVA ratio. This is attributed to the approximated effect of the saliency ratio on the torque per kVA shown in (2-33) [6].

$$\frac{T_e}{KVA} \cong \frac{P}{\omega} \left(1 - \frac{1}{\xi}\right) \sin \theta \quad (2-33)$$

- **Torque Ripple:** Torque ripple results in mechanical vibration, acoustic noise, and additional iron losses[44]. Suppose the torque harmonics of different rotor barrier slots in the air gap eliminate each other, and a pure sinusoidal current is applied to the stator winding. In that case, the torque harmonics amplitude is directly proportional to the flux harmonics. Taking into consideration the first harmonic of the torque ripple due to the stator slotting, the torque equation in (2-20) can be modified as shown below [6].

$$T_e(\vartheta) \cong \frac{3}{2} \frac{P}{2} (\lambda_d i_d - \lambda_q i_q) + \frac{1}{2} (i_d \frac{\partial \lambda_d}{\partial \delta} + i_q \frac{\partial \lambda_q}{\partial \delta}) \quad (2-34)$$

A term is added to the torque equation representing torque pulsations as shown in (2-34). However, the average value of the term is zero. Equation (2-35) shows the dependency of the inductances on the rotor position.

$$\begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} = \begin{bmatrix} L_d(\delta) & L_{dq}(\delta) \\ L_{dq}(\delta) & L_q(\delta) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2-35)$$

Taking into account how the inductances dependency, the torque equation (2-34) can be rearranged as (2-36) [6].

$$T_e(\delta) = \frac{3P}{2} \frac{3q}{2} \left(\frac{\pi}{\pi} \sin \frac{\pi}{3q} \right) ((L_d - L_q) i_d i_q + (\Delta L_d + \Delta L_q) i_d i_q \cos(3pq\delta) - \Delta L_{dq} (i_d^2 - i_q^2) \sin(3pq\delta)) \quad (2-36)$$

According to (2-36), torque ripple can be attributed to two components. The first component is linked to oscillations in the Carter factor and the circulating flux component (L_{cq}) and is proportional to the average torque ($i_d i_q$). These oscillations bring about variations in the d-q inductances ($\Delta L_d, \Delta L_q$), which can be eliminated using the distributed anisotropic structure of the rotor. The second component is caused by the stator slots effect, which results in ΔL_{dq} and consequently leads to torque ripple [6].

Torque ripple is generally calculated as follows

$$\%T_{ripple} = \frac{T_{max} - T_{min}}{T_{avg}} \times 100 \quad (2-37)$$

where T_{max} is maximum torque, T_{min} is minimum torque, and T_{avg} is average torque [38].

- **Iron Losses:** SynRM iron losses, like other synchronous ac drives, are composed of different components that can be divided into hysteresis losses, eddy current losses (Joule losses), and high-frequency hysteresis losses. For an area with constant flux density, the total iron losses per weight (W/kg) can be calculated for each flux harmonic as shown in (2-38).

$$\frac{P_{tot}}{kg} = K_h B_{om}^2 f_0 + \frac{\pi^2}{6} d^2 \sigma (B_m^h(h_{f1}))^2 + K_e (B_m^h(h_{f1}))^{\frac{3}{2}} \quad (2-38)$$

where $K_h B_{om}^2 f_0$ represents the hysteresis losses, $\frac{\pi^2}{6} d^2 \sigma (B_m^h(h_{f1}))^2$ represents eddy current losses and $K_e (B_m^h(h_{f1}))^{\frac{3}{2}}$ represents high-frequency hysteresis losses.

At high speeds, the iron losses in the rotor are somewhat comparable to the stator losses. This can change the design strategy from maximizing the average torque to maximizing the power factor or efficiency. The use of low-loss magnetic material, reducing the

lamination thickness, and filling the stator slots opening (wedge area) with semi-magnetic material, may reduce iron losses.

- **Field *Weakening Range*:** The field weakening range in constant power operation may be a requirement in traction applications, just like most of the specifications of the SynRM, the field weakening range also depends on the saliency ratio, which can be expressed as in (2-39) [6].

$$\frac{\omega_r}{\omega_b} = \left(\frac{v}{\omega_e}\right)^2 \frac{3P_o(L_d - L_q)}{3L_d L_q T_{em}} \quad (2-39)$$

The mathematical equations of the SynRM demonstrate the effect of the saliency ratio on the motor's performance, showing that this parameter can be considered key in the motor's design. The saliency ratio is directly dependent on the anisotropic nature of the rotor structure, thus the requirement of the identification and analysis of the rotor geometry.

2) *Design parameters*

To achieve a rotor design that meets performance requirements, it's important to consider the saliency ratio. This ratio can be increased by adjusting the rotor geometry through identifying the necessary design parameters. The objective of this section is to list and provide a brief explanation of the design parameters specific to SynRM rotor design methodology.

- Rated Power and Maximum Torque
- Number of Poles
- Number of flux barriers segments (layers)
- Position and size of barriers and segments:
- Insulation Ratio
- Tangential and radial ribs
- ***Rated Power and Maximum Torque:*** SynRMs are currently manufactured in wide power range from 0.2kW to more than 300kW in different industrial applications. The rated power and maximum torque affect the machine's size and rotor outer diameter. This is discussed in further chapters.

- Number of Poles:** The q-axis is the maximum reluctance axis of the motor. In designing q-axis-related quantities, the aim is to minimize the flux flowing in this direction. This results in the maximization of the L_{dm}/L_{qm} ratio. The main design aspect in the q-axis is the rotor flux barriers. The q-axis magnetizing inductance L_{qm} is comprised of two main components, the circulating L_{qc} , and the flow-through L_{qf} inductances. The L_{qc} accounts for the stator flux paths crossing the airgap locally without crossing the barriers, while the L_{qf} term accounts for the flux paths crossing the rotor barriers from pole to pole [11]. Figure 2-11b shows the two components. The following equations show the relations of L_{qm} and its components [6], [11].

$$L_{qm} = L_{qc} + L_{qf} \quad (2-40)$$

$$\frac{L_{qc}}{L_{dm}} = \frac{\pi^2}{12n_{lay}} \quad (2-41)$$

$$\frac{L_{qf}}{L_{dm}} = KP \frac{g}{L_a} \quad (2-42)$$

L_{dm} is the d-axis magnetizing inductance, n_{lay} is the number of layers in each pole of the rotor structure, K is a constant, P is the number of poles pairs, g is the air gap length, and L_a is the total width of the segments (steel) in the q-axis direction (Figure 2-11 (a)). Equation (2-42) shows the dependency of L_{qm} on the number of poles. A SynRM with a lower number of poles has a smaller L_{qm} and a higher saliency ratio.

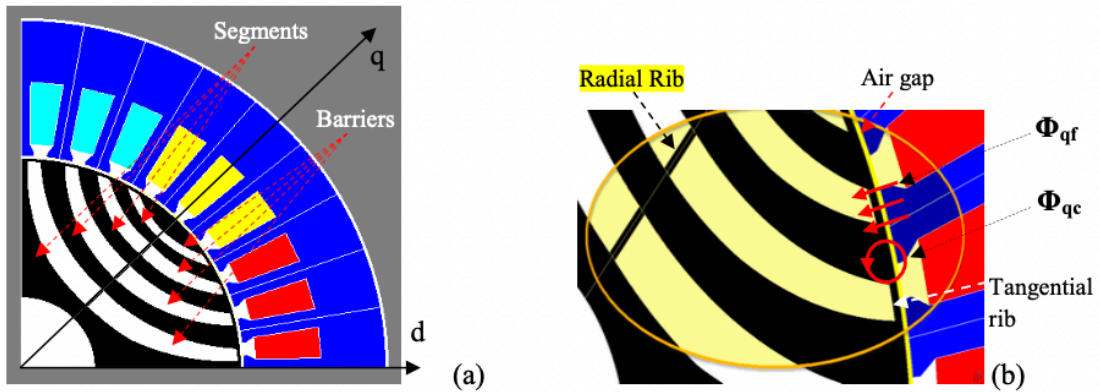


Figure 2-11: Typical configuration of a 4-pole, 36-slot SynRM with 4-layer TLA rotor [6].

- Number of flux barrier segments (layers):** The number of layers per pole (n_{lay}) is the total number of flux barriers or segments in a rotor anisotropic structure (Figure 2-11a). This parameter affects the motor's q-axis inductance. Thus, it has to be selected properly. The number of layers affects L_q because the higher the number of layers the lower the circulating flux (L_{qc}) in the q-axis (2-41). However, it does not affect L_d . Increasing n_{lay} is much more difficult and limited in TLA-type rotors than in ALA-type due to mechanical and manufacturing issues. This is the reason why the ALA type has a higher saliency ratio. To minimize the q-axis flux density in SynRM design, it is necessary to minimize the flowing flux L_{qr} (2-42). Therefore, the number of poles and the insulation ratio are the parameters used to adjust the saliency ratio in TLA type rotor [6].
- Position and size of barriers and segments:** In an ideal case where the rotor core losses and the stator slotting effects are negligible, the d-axis MMF_d has a sinusoidal shape with its peak value in the d-axis alignment. To achieve constant flux density in all segments, each segment's size may be made proportional to the corresponding average MMF_d. Therefore, each segment's width may be varied in the q-axis in a sinusoidal nature. The non-uniformed air gap caused by the interaction of rotor and stator slots creates torque pulsation when each barrier end tends to go into or out of the slot's opening area. Figure 2-12 and Figure 2-13 show the position of the k_{th} barrier and the q-axis flux distribution versus the end position of the barrier (α). The flux distribution in the q-axis is represented by f_k . Equations (2-43) to (2-46) show the contribution of the size and position of the barrier's end (α) to the value of L_q and the saliency ratio.

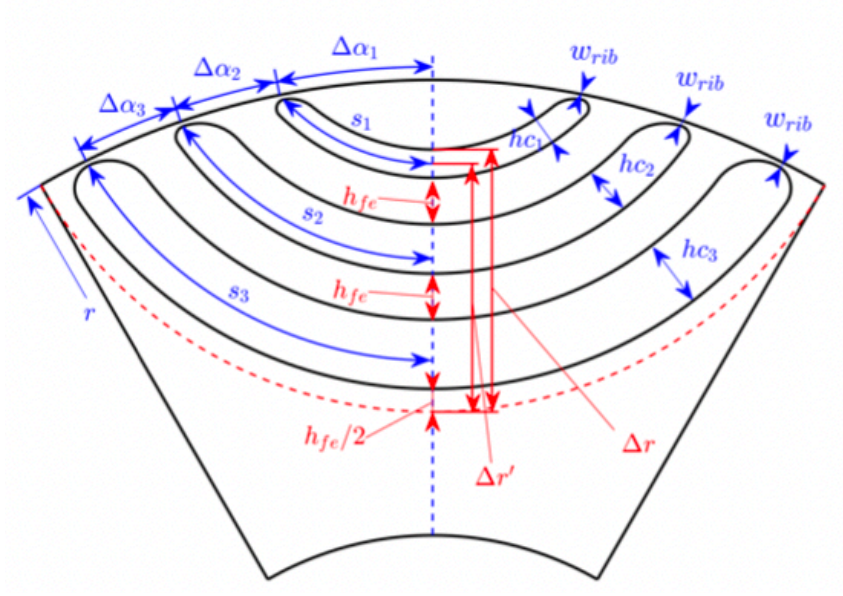


Figure 2-12: Rotor barrier dimensions and angles [11].

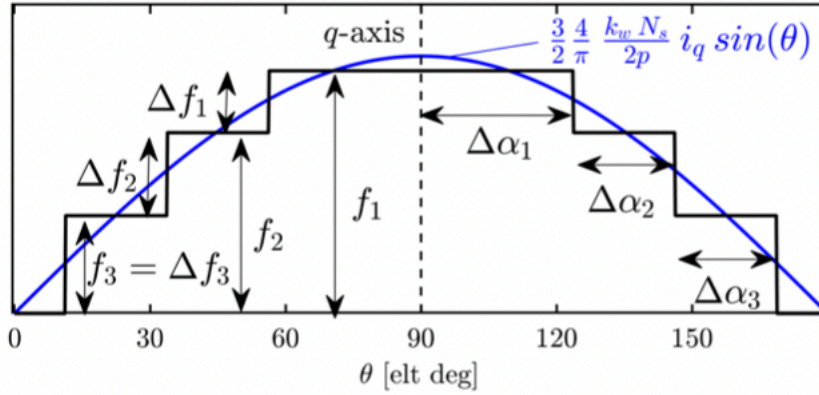


Figure 2-13: Sinusoidal stator MMF averaged by the rotor iron carriers [11].

$$f_k = \frac{1}{\Delta\alpha_k} \int_{\alpha}^{\alpha+1} \sin \alpha d\alpha = \frac{\cos \alpha_k - \cos \alpha_{k+1}}{\alpha_{k+1} - \alpha_k} \quad (2-43)$$

$$\frac{L_{qc}}{L_{dm}} = 1 - \frac{4}{\pi} \sum_1^{n_{lay}} f_k^2 \Delta\alpha_k \quad (2-44)$$

The flow-through inductance L_{qf} is computed as

$$\frac{L_{qf}}{L_{dm}} = \frac{4}{\pi} \sum_1^k f_k^2 (f_k - \Delta f_k) \Delta \alpha_k \quad (2-45)$$

$$\frac{L_{qf}}{L_{dm}} = \frac{4}{\pi} \frac{P k_c g}{R_{ro}} \sum_{k=1}^{n_{lay}} \Delta f_k^2 \frac{s_k}{h_{c,k}} \quad (2-46)$$

where; $h_{c,k}$ are the barrier widths, and s_k are the segment widths shown in Figure 2-12.

- **Insulation Ratio:** The insulation ratio can be used to adjust the width of the barrier. This affects the saliency ratio and strength of the rotor structure. Insulation ratio is defined as the ratio of the total width of the air to the total width of the steel through the q-axis (Figure 2-11a) which can be expressed as in (2-47) [6].

$$K_{wd} = \frac{W_{air}}{W_{st}} \quad (2-47)$$

If $K_{wd} = 0$ it means the rotor does not have any barriers and is only made of steel, whilst if $K_{wd} = 1$ it means that the total width of barriers (air) and segments (steel) are equal. For a proper design, the maximum saturation in the rotor segments has to be lower than the saturation in the stator back (yoke). This value of W_{air} can affect the flux density in the q-axis significantly. For a proper range of the insulation ratio, L_q will be minimized which consequently results in a maximum ($L_d - L_q$) and a higher torque production [6].

The “constant barrier permeance” law (2-48) is used in determining the widths of the carriers and segments[11].

$$\frac{h_{ck}}{s_k} = \frac{h_{c1}}{s_1} \quad (2-48)$$

Substituting (2-48) into (2-46):

$$\frac{L_{qf}}{L_{dm}} = \frac{4}{\pi} \frac{P k_c g}{R_x} \frac{\sum_{k=1}^{n_{lay}} s_k}{\sum_{k=1}^{n_{lay}} h_{ck}} \quad (2-49)$$

The total insulation must adhere to the iron carrier's width constraint, i.e., it should be equal to the available radial space Δr shown in Figure 2-12 less the stator back width h_{ss} [11].

$$\sum_{k=1}^{n_{lay}} h_{ck} = \Delta r - h_{ss} \quad (2-50)$$

The barrier widths are computed from the total insulation using the constant ratio principle.

$$h_{ck} = \sum_{k=1}^{n_{lay}} h_{ck} \cdot \frac{s_k}{\sum_{k=1}^{n_{lay}} s_k} \quad (2-51)$$

The method is independent of the number of rotor barriers.

- **Tangential and radial ribs:** The laminations in TLA-type rotors are identical; thin connections called ribs connect the middles and ends of the segments. These joints maintain mechanical integrity in the rotor structure to resist rotational and magnetic forces at high speed. The rotor ribs conduct an additional component of q-axis flux which causes an increase in the flux flowing in the q-axis resulting in a decrease in the saliency ratio. Thus, the additional q-axis flux path is not desired, however, it's inevitable. The related flux linkage is expressed as:

$$\lambda_{rib} = \frac{4}{\pi} k_w N_s w_{rib} L \cdot B_{rib} \quad (2-52)$$

where the w_{rib} is the width of the ribs. Where there are inner posts or additional ribs, their width is also added to w_{rib} s, to become the total ribs width. B_{rib} is the flux density in the ribs, and it corresponds to saturated iron. B_{rib} is assumed constant for all ribs [6]. The ribs reduce the machine-developed torque by ΔT_e as expressed in (2-53). The torque reduction caused by tangential ribs is dominant due to the greater number of tangential ribs.

$$\Delta T_e = \frac{4}{\mu_o} w_{rib} d B_{rib} P^2 B_{dm} \quad (2-53)$$

where; d is the thickness of the laminations, and (B_{dm}) is the d-axis flux density. Equation (2-53) shows that the torque reduction caused by ribs is proportional to P^2 and d . Therefore,

the torque reduction (ΔT_e) decreases for a given number of poles when the ribs' width is designed to be as thin as possible. The flux component is not proportional to i_q . However, its impact on torque and power factor is modeled by adding a q inductance component, $L_{qr} = \lambda_{rib} / i_q$ to L_{qm} [11].

2.4. Traction Motor Sizing

Traction motor sizing refers to the electric, magnetic, and geometric sizing of a particular SynRM motor to come with a model that meets the requirements of the railway traction application [41]. The design comes up with a particular model with specific design parameters. There is no standard yet for the design of SynRM motors. Literature reports various approaches to the design of SynRM motors [30]. However, some cases rely to some extent on analytical approaches. In some examples, iron saturation is evaluated iteratively using a magnetic model circuit with many nodes in order to accurately predict the shape of the airgap flux density. Sometimes, the analytical model is used at the machine sizing level and then FEA validated. The most popular design approaches include FEA and optimization algorithms [5]. The final precision in these latter cases is higher, but often at the cost of high computational time and little to no insight of the designer on the results. Nevertheless, most authors confirm that using FEA is mandatory when designing SynRM machines. This includes even those based on analytical modeling because linear magnetic models tend to be inaccurate due to the magnetic saturation of the iron core [28].

2.5. Design Optimization

The SynRMs rely on a good anisotropic structure to produce reluctance torque. They also usually have a low power factor and high torque ripple. Therefore, to produce adequate torque, acceptable power factor, low torque ripple, and high efficiency, there is a need to optimize the rotor geometry to achieve the best saliency. This optimization may be done by designing using optimization algorithms (OAs). Due to the magnetic characteristics of the SynRMs, the OA tools are coupled with FEA analysis to also account for magnetic saturation. Optimization tools are also used to determine the current phase angle that gives the MTPA for every new candidate machine. Due to the number of parameters that may require to be optimized; Multiple Objective Optimization Algorithms (MOOA) are usually employed. This enables the enhancement of the performance,

efficiency, and overall functionality of the motor. However, the challenge that comes with optimization is that it usually requires several FEA simulations. This may result in long computational times. Therefore effort has been put to simplify the optimization problem to enable faster FEA evaluation of candidate machines to minimize the amount of computational time required [45], [46]. This may be achieved by the proper selection of the optimization goals (e.g. torque and torque ripple) and the geometric variables to be optimized [45]. With the development in computation power, various OAs are now being implemented for the optimization of SynRMs. The favored ones are the MOOAs which enable the optimization of various objectives at once [31]

2.5.1. Optimization Choices

To effectively optimize using MOOA, it is pivotal to have a simplified rotor geometry, minimum FEA evaluation time of the candidate solutions, proper choice of the MOOA and its settings, and proper selection of the optimization goals. [47], [48] showed that an MOOA with a two-step application of Local Search and Global Search is capable of reducing computation time significantly. [28] continuing from [47], [48] compared three MOOAs i.e. Multiple Objective Differential Evolution (MODE), Multiple Objective Genetic Algorithm (MOGA), and Multiple Objective Simulated Annealing (MOSA), and showed that the MODE performed better than the other two in terms of the optimized values of the objectives and repeatability of the results. Other comparative analyses, also showed that MODE led to similar rotor designs to those of the other MOOAs but with a fewer number of FEA calls [45], [46]. [28] also showed that a 3-layer rotor performed almost similarly to a 5-layer rotor in terms of the objective functions but with lesser computation time due to the lesser number of geometric parameters. When it comes to objective selection, potential objectives include torque, torque ripple, efficiency, material cost, or the weight of the active part. However, torque maximization at a given current and stator geometry inherently maximizes the torque per joule loss ratio which immensely impacts the efficiency. The optimization will also be limited to varying the barrier parameters of the rotor which do not have a big impact on the weight and cost [28]. Therefore, only maximum torque, torque ripple, and power factor will be selected as the optimization objectives, MODE as the MOOA, and a three-barrier layer as the rotor type in this optimization.

2.6. Traction Control

2.6.1. Overview of Motor Control

The control unit is an important part of the drive that plays an important role in the performance of a system. A high-performance control system results in efficient and reliable energy conversion. It plays a pivotal role in the starting of non-Line Start SynRMs, which require control to start properly. Control methods can be classified as scalar and vector control methods. Scalar control methods are simple voltage/frequency (v/f) control methods applied in industrial variable speed drives (VSD)s. The application may be an open or closed loop with a current and speed sensor or sensorless control. The variations of scalar control are v/f , v/f^2 , or I/f . The v/f method maintains a constant v/f ratio over varying voltage and frequency. The scalar methods are useful for low-cost applications. However, it is challenging to track speed commands. Vector control methods are more precise control methods compared to scalar methods. These methods include field-oriented control, direct torque control, and model predictive control [12], [49].

Field-Oriented Control (FOC) is a precise and efficient method used in industries that require high efficiency and steady-state response. FOC separates the control of the motor's magnetic flux and torque components, allowing precise and independent control. FOC typically involves two control loops: the torque control loop and the flux control loop. There are two types of FOC schemes: Direct Field-Oriented Control (DFOC) and Indirect Field-Oriented Control (IFOC). DFOC measures or estimates the rotor position and flux components, while IFOC estimates them indirectly using mathematical models and control algorithms [50]. Both approaches have their advantages and disadvantages, and the choice between them depends on factors such as cost constraints and control performance requirements.

On the other hand, Direct Torque Control (DTC) is an advanced control strategy used for AC motors. It achieves direct control over the motor's torque and flux by selecting the optimal voltage vector from a pre-programmed switching table. DTC provides quick and direct control, allowing for rapid response to changes in torque and speed setpoints or load conditions. However, it may produce torque ripple and harmonic effects. It is suitable for applications requiring fast dynamic response and precise torque regulation [12], [49], [51].

Lastly, Model Predictive Control (MPC) is commonly used in industries to control complex systems with multiple inputs and outputs. It predicts future behavior and makes optimal control decisions to achieve desired performance objectives. MPC involves a mathematical model, a prediction horizon, a cost function, and a control algorithm. MPC is versatile, adaptable, and can optimize multiple control objectives for superior performance. However, it can be computationally complex and requires accurate modeling and real-time computation [12], [49], [52].

The SynRM control in this research was designed using syreDrive which is a control design feature in SyR-e software. This section provides a brief overview of how syreDrive was created and set up by [53]. SyR-e is software used for designing the SynRM in this study. More information about the software is found in section 2.7. Once a motor is designed in SyR-e software, the syreDrive feature can automatically generate a Simulink model that includes the electric motor, inverter, and vector control. This makes the transition from motor design to control design fast and seamless. The overview presents the mathematical model elements of the SynRM used in achieving the control as well as the control strategy.

Figure 2-14: Block diagram of the field-oriented control scheme [53].

2.6.2.1. Motor Model and Control Strategy

The voltage equations for the SynRM machine are expressed as follows:

$$s\lambda_{dq} = v_{dq} - R_s i_{dq} - \omega J \lambda_{dq} \quad (2-54)$$

Here, s represents the differential operator d/dt , R_s is the stator resistance, $\lambda_{dq} = [\lambda_d \ \lambda_q]^T$ represents the stator flux linkage space vector, ω represents the electrical angular speed, and J is an orthogonal rotational matrix given by (2-55) [53].

$$J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \quad (2-55)$$

The electromagnetic torque is calculated using the following equation:

$$T = \frac{3}{2} P (\lambda_{dq} \times i_{dq}) \quad (2-56)$$

The flux linkage and its derivative are calculated using incremental inductance L_∂ and apparent inductance L , as shown below:

$$\lambda_{dq} = L i_{dq} \quad (2-57)$$

$$s\lambda_{dq} = L_\partial s i_{dq} \quad (2-58)$$

Matrix L_∂ and L are reported in (2-59). Matrix L_∂ consists of incremental inductances l_d and l_q , the incremental inductance along the d and q axis, and the cross-saturation term l_{dq} . Apparent inductances are defined similarly [53].

$$L_\partial(i_{dq}) = \begin{bmatrix} l_d & l_{dq} \\ l_{dq} & l_q \end{bmatrix} \quad L(i_{dq}) = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \quad (2-59)$$

To accurately describe saturation and cross-saturation effects and achieve precise torque estimation at zero speed, current-to-flux linkage maps (denoted with λ) are stored in the form of Look Up Tables (LUTs) [53], [54]. These maps can be automatically determined by FEA.

Field-Oriented Control: FOC is the adopted control strategy. It is a universally accepted control strategy chosen for closed-loop control due to its simplicity[53], [55]. Torque reference T^* is

derived from the speed Proportional-Integral (PI) controller. The Maximum Torque Per Ampere (MTPA) strategy is then employed to ascertain the appropriate current reference values (i_{dq}^*) using the reference torque. The MTPA trajectory effectively maximizes the torque output for any given inverter current, approximating peak efficiency when disregarding iron losses at low speeds. The implementation of current control within the MTPA strategy necessitates knowledge of the MTPA locus, meaning the precise correlation between the reference torque T^* and the reference d and q currents i_d^* and i_q^* [53]. This correlation is stored as LUTs. The reference current values are then cascaded to the current controllers. The current controllers operate by directly regulating the d and q current values to align with the reference current values through PI current regulators, resulting in the determination of the reference voltages (v_{dq}^*) [56]. The reference d and q voltages are compensated by back-EMF feedforward compensation, calculated using the observed flux from the flux observer [53] to come up with the voltage values v_{abc} for the PWM. This FOC scheme is visually represented in Figure 2-14.

2.7. Software Tools

2.7.1. SyR-e Software

The SyR-e software is used in a number of stages in this thesis research including the analytical design, optimization, FEA analysis, and drive design stages. Therefore, a brief introduction to the software is given in this section. SyR-e stands for Synchronous Reluctance – evolution. It is an open-source code developed in MATLAB/Octave. SyR-e is used to design SynRMs automatically using analytical models, FEA, and MOOAs [5]. It can be downloaded on SourceForge and GitHub. Figure 2-15 shows the process flow in the operation of SyR-e. A MATLAB script generates a parameterized drawing of a synchronous machine in .fem file format. The file is analyzed by FEMM quickly. The main results are sent back to MATLAB for performance evaluation, further post-processing, and elaborations. This flow may be used to automatically design or analyze existing machines. A simple Graphical User Interface (GUI) is used, making the design and simulation workflow simple and the tool usable [54]. GNU Octave may be used instead of MATLAB for all mentioned purposes. SyR-e was first released in 2014 for the design of SynRM machines through MOOA. It evolved over the years to include new geometries (including PM motors), preliminary design models, the ability to migrate to other FEA tools, and a comprehensive

FEA analysis and validation environment. The FEA analysis and validation include several kinds of analysis, e.g. simple evaluation of the motor outputs for a single operating point, to the analysis of characteristic current and flux maps evaluation [10].

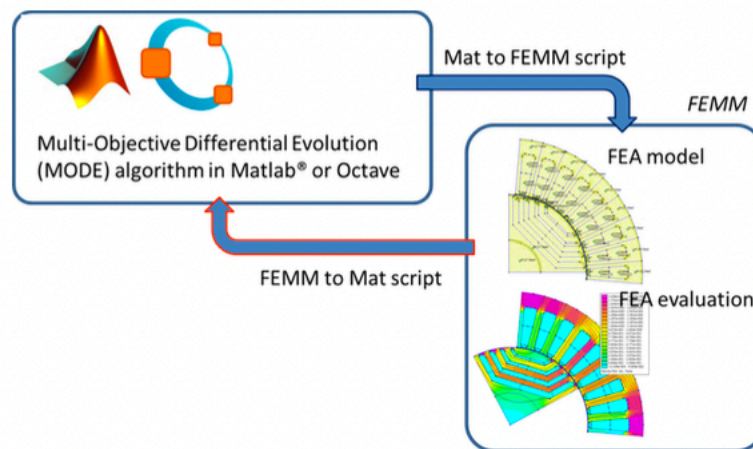


Figure 2-15: Process flow in SyR-e motor design software [53].

2.7.2. SyreDrive

SyreDrive is a feature in SyR-e software that is used to automatically build a Simulink model comprising the electric motor, inverter, and control blocks. This enables a fast and seamless transition from motor design to control environments. An overview of how the FOC control technique is implemented is given in section 2.4 [53], [54].

2.8. Related Works

[6] designed a SynRM for automotive applications. In the first step [6] identified electrical, magnetic, and geometrical parameters that are dominant in the machine's performance. The second step was to come up with an analytical design method that enabled to sizing of a high-performance machine. The sizing method was used to come up with a SynRM that meets a specific torque speed envelope. The sizing method criteria were based on the machine's mathematical model, equivalent circuit, some initial data, and assigned parameters. The electric and magnetic parameters of the proposed machine in conjunction with the core dimensions were calculated. Finally, the proposed method's evaluation and validity were investigated using FEA analysis and experimental tests.

[38] utilized FEA software to simulate the SynRM and ensure the accuracy of the analytical models, while also enhancing machine performance. Initially, basic rotor structures were created to enable automatic variation during parameterization and optimization. Four flux barrier shapes were analyzed to determine the most effective shape for optimal performance by examining the natural path of flux. The findings resulted in the study of a multi-barrier arrangement with an advanced algorithm for three and four-layer designs, leading to the proposition of an ideal rotor based on the simulations. Additionally, [38] employed both single-objective and multi-objective optimization techniques to enhance the SynRM design. An advanced topology was developed for automated optimization, providing flexibility in the variation of optimization variables in research. The performance of the optimized design was analyzed in detail and compared with analytical models in terms of torque, torque ripple, and power factor, with the multi-objective design yielding better results.

In [7] a SynRM was developed for handheld machines to replace IPMs and IMs. The stator remained the same while the focus was on the rotor design. An analytical procedure followed by FEM analysis was used to design two types of rotor structures: circular and straight flux barriers. The circular structure showed better performance than the straight one. Additionally, a drive was designed to simulate a complete drive.

[20] conducted an investigation into the design and performance of a SynRM that can start similarly to an induction motor. A three-phase induction motor with a 20kW power output was used as a benchmark. The goal was to create SynRM designs that have the same starting capability as the induction motor being studied. To achieve this, the proposed SynRM designs had the same stator design as the IM but differ in the rotor. As SynRMs are not self-starting, proposed rotor designs were equipped with cages, resulting in improved performance. Two different hyperbolic-line and hyperbolic curve shapes of flux barriers were introduced in the proposed models, with the performance of these models further improved by adding permanent magnets to the rotor flux barriers. All proposed motor designs were simulated and tested for different loading conditions in FEM software. The designed motors demonstrated satisfactory performance in both steady-state and starting conditions, with up to a 10% increase in efficiency and power factor compared to the induction motor.

[4] conducted research aimed at improving the SynRM optimization process by simplifying the rotor radial cross-section parameters and developing a software framework to validate the feasibility of rotor geometry. The research focused on a new method of defining rotor geometry by using shape objects instead of traditional geometrical primitives like points, lines, and arcs. This approach allows for a more straightforward and reliable feasibility validation and calculation of at least one point within each object, which is crucial for assigning material to different regions in the finite element analysis tool. This new solution can be applied to all types of electric machines. Additionally, the study determined a group of feasible SynRM rotor geometries that require only a minimal set of parameters to reduce design complexity and overall optimization time. Once the geometry is selected and optimization commences, the optimization system must identify unfeasible designs, such as those with overlapping rotor barriers. The proposed solution is a new concept of forced feasibility, where unfeasible designs are forced to change parameters until they become feasible. If a design remains unfeasible, it is rejected, which can impact optimization convergence. The results indicated that forced feasibility leads to faster optimization convergence compared to the alternative approach.

[29] analyzed the performance of a 22kW TLA-SynRM machine with distributed winding using FEA in ANSYS Electronics. The study focused on various rotor parameters such as the phase angle of current, number of flux barriers, starting diameter of flux barriers, and ribs. A novel rotor design was created based on these parameters, where the same stator and size as the 22kW IM were used. The machine's performance was evaluated based on torque, torque ripple, efficiency, saliency, and power factor. Additionally, the study compared the performance of the 22kW SynRM with the same sized and powered IM and a different SynRM while taking into account the phase angle of the current. The results showed that the novel SynRM had higher torque ripple values than the IM, but it was still better due to the lack of copper losses in the rotor and efficiency classes. The efficiency class of the novel SynRM was IE4, whereas that for the previously utilized SynRM and IM are IE3 and IE1, respectively.

.

3. Design of the SynRM

The research aims to investigate the railway traction requirements, identify electrical, magnetic, and geometric parameters of the SynRM motor that determine its performance relative to traction requirements, and develop an appropriate design model that can perform well in LRT railway traction application. Using computer-aided analysis through automated optimization methods and FEA assists in the design performance and modification until it is optimized for the given railway application [6]. Thus, this section provides a detailed design approach to the required SynRM. The following are addressed in this section to achieve the thesis objectives.

- Traction requirements investigation for the target railway system
- Traction motor investigation (mathematical modeling)
- Traction motor sizing
- Optimization
- FEA analysis
- Controller Design
- Drive Simulation
- Results Analysis



Figure 3-1: Research methodology flow diagram.

3.1. Traction Requirements for Target Railway System

A study of the traction requirements of the target railway system is performed. The study is necessary to establish the target parameters required by the system for satisfactory performance.

The investigation is performed through a literature review of research articles, books, data sheets, and other relevant literature. The Addis Ababa LRT is used as a reference model in this study. Therefore, investigations are also performed to establish its traction requirements and characteristics for reference. Some of the major factors that are also considered by railway manufacturers and operators that are investigated include performance requirements like the torque-speed envelope and constraints like size, weight, and cost. The constraints are important given that there are limitations in terms of funds, space in the vehicle, and the weight the vehicle may carry. Some of the target parameters that are obtained include the following:

- Electromagnetic torque
- Power factor
- Efficiency
- Speed range

3.1.1. AALRT Traction Characteristic

The AALRT vehicle is made up of three coaches. Only two of the coaches are motor-driven. Each driven coach has two motors. The system uses YJ128C squirrel cage three-phase asynchronous traction motors. DC is collected from the overhead contact system via a pantograph mounted on the intermediate wagon. The DC power is converted to AC by an inverter and then fed to the traction motors. The general block diagram of the traction load is given in Figure 3-2 [57].

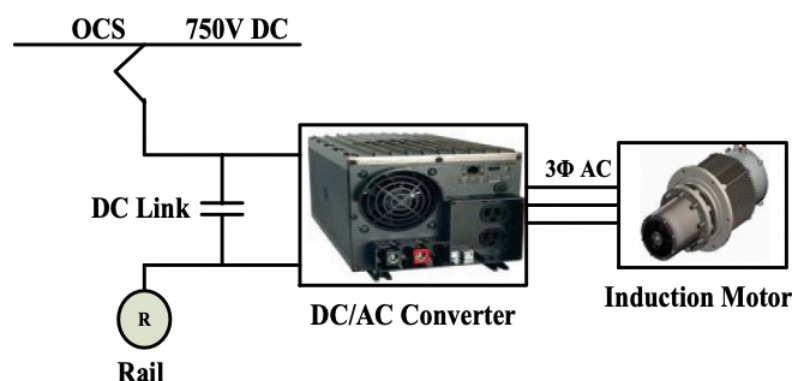


Figure 3-2: General block diagram of the traction load [57].

The combined traction requirements for the two sets of motors for the system are shown in Figure 3-3.

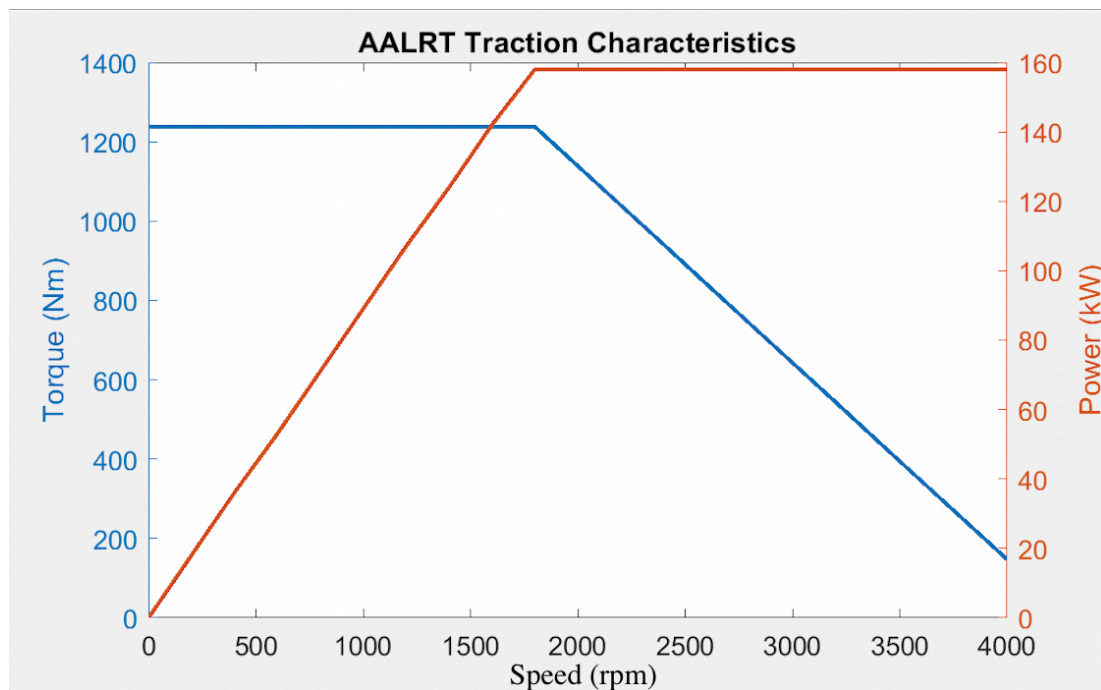


Figure 3-3: AALRT Traction Characteristics [58].

Table 3-1: AALRT Traction characteristics [58].

Torque/Nm	Speed/rpm	Power/kW	Relative speed/kmh ⁻¹ (half wear wheel)	Relative speed/kmh ⁻¹ (new wheel)	Relative speed/kmh ⁻¹ (full wear wheel)
1240	0	0			
1240	1240	161	23.9	25.5	22.4
527.3	2917	161	56.3	60	52.6
296.6	3890	120	75	80	70.3

The design traction requirements shown in Table 3-1 are important to help understand the torque and power demand by the vehicle and traction motors during traction mode. Figure 3-3 shows the system's required torque-speed envelope and the electric motors' power/speed relationship. High

torque is required during starting and lower speeds until the rated speed is reached; after the rated speed, the torque starts to decline. Inversely, power rises with speed until the rated speed is reached. It is then maintained at maximum from rated speed upwards. Calculating from the traction characteristics, each motor requires about half the torque and power shown in Table 1 i.e., 620 Nm and 80 kW respectively. Therefore, almost the same values are used in technical parameters [59], [60]. The technical parameters of each asynchronous motor are shown in Table 3-2.

Table 3-2: Reference Motor Parameters [60].

Parameter	Value	Parameter	Value
Rated Power	130 kW	Rated Efficiency	92.4%
Rated Voltage	500V	Weight	440±0.3 kg
Rated Current	215A	Stator Coil Resistance (R_s)	0.1968 ohms
Rated Frequency	91Hz	Stator Coil Inductance (L_s)	0.00182 henry
Number of Poles	6	Stator Coil Reactance (X_s)	0.10400936 ohms
Rated Speed	1800 rpm	Rotor Coil Resistance (R_r)	0.164 ohms
Rated Speed	188.4 rad/s	Rotor Coil Inductance (L_r)	0.00152 ohms
Synchronous Speed	1820 rpm	Rotor Coil Reactance (X_r)	0.08686496 ohms
Synchronous Speed	190.5 rad/s	Core Inductance (L_m)	0.00159 henry
Rated Torque	689N/m	(Stator Mutual Leakage Inductance) L_{im}	0.00159 henry
DC Voltage	750 VDC	Moment of Inertia	0.089 kg.m ²
Volume	0.092 m ³		

3.2. Traction Motor Investigation

The characteristics of the SynRM motor are investigated, and most of the results are presented in Chapter 2. The investigation identifies the design parameters that determine the performance of the SynRM in delivering the traction requirements, which are the target parameters in this research. The motor equivalent circuit, and mathematical models (analytical and numerical) that describe the motor's electrical, magnetic, and geometric characteristics and link the design parameters and

target parameters, are investigated, described, and discussed. Other factors like material and their effects on performance, cost, weight, and size are also investigated. The investigations are performed through a literature review of research articles, published books and data sheets, and other relevant literature resources. Some of the design parameters that were investigated and established are listed below [6], [41].

Design Parameters:

- Rated power
- Maximum torque
- Number of poles
- Number of flux barriers and segments (layers)
- Insulation ratio
- Position and size of barriers and segments
- Tangential and radial ribs
- Air gap length

3.3. Traction Motor Sizing

This research uses an analytical equation-based design approach done in stages. In the first stage, an initial analytic/linear model is generated. From then onwards, progressive improvements of the initial linear model are generated and tested using SyR-e software. As explained in Chapter 2, the SyR-e platform is a software that was designed to enable fast automatic design of motors using various analytical, FEA, and optimization tools. It takes some analytical design parameters as input and it can then be manipulated to perform various design computations to come up with a final design. Therefore, the analytical model is loaded on the SyR-e platform. A torque/ power factor model of the motor is selected on a design plane. FEA is used to fix the residual saturation errors of the analytical design equations using a method called FEAfix. FEAfix relies on simulating a few relevant machines to correct the torque and power factor estimation of a large family of designs. The generality and computational speed of the analytical model are preserved, together with the precision of the FEA approach [11].

Automatic design optimization of the motor is then performed using Multi-Objective Optimization Algorithms (MOOAs) and FEA analysis. The Multi-Objective Differential Evolution (MODE) is

used as it gives the best results according to [28] in terms of convergence time and repeatability of the results. FEA software is then used to analyze the motor's performance regarding the output functions such as developed torque, torque ripple, and output power as well as magnetic characteristics e.g., flux density and saliency ratio. The process is finished if the FEA results satisfy the design requirements. Otherwise, the process will be carried out again by updating the assigned parameters such as magnetic and current loading, stack aspect ratio, and pole pitch-to-air gap ratio to obtain the proper size

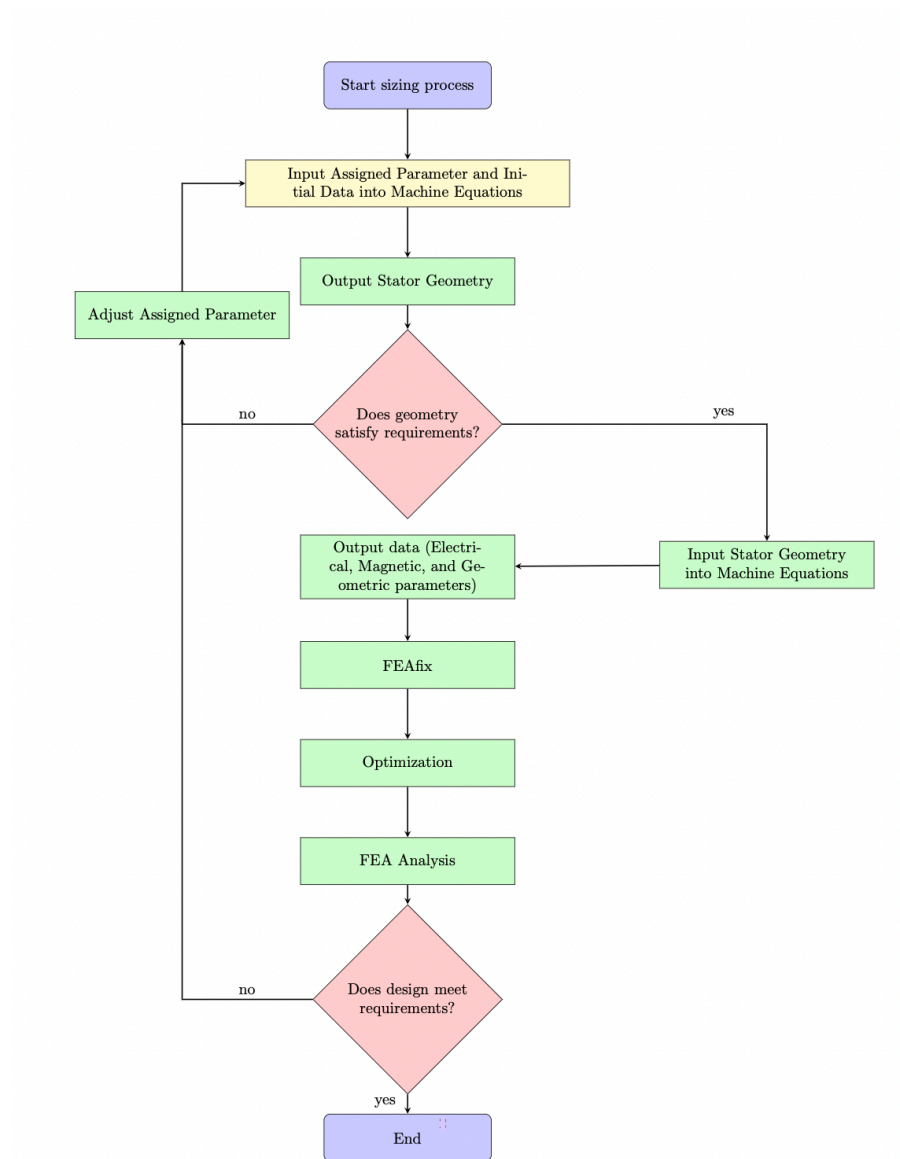


Figure 3-4: Design flow chart.

3.3.1. Analytical Design

The analytical design of the SynRM refers to the determination of the electric, magnetic, geometric, and thermal model parameters using the machine's mathematical equations and equivalent circuits. The design strongly depends on the application. To develop the torque required in traction applications in critical times such as start-up and maximum power demand at maximum speed, the motor has to be designed for high current density and high-frequency operations. Therefore, it is necessary to perform the whole procedure of sizing taking into account the power, torque-speed profile, some initial data, and assigned parameters. The sizing process of the proposed motor begins with the preparation of the initial data obtained from the traction requirements and the assignment of some key parameters that determine the performance of the motor. These are used together with the mathematical model of the motor to calculate geometric, magnetic, and electric parameters. The pre-design output parameters are the stator geometry and rotor outer diameter. New iterations with updated assigned parameters are performed if the geometries are not satisfying the design requirements. After this step, the electrical, magnetic, and geometrical parameters i.e., stator geometry, windings specifications, inductances, saliency ratio, maximum torque, etc. are characterized for further steps [41].

3.3.1.1. Initial Data

The initial data whose key parameters are used for further analysis is shown in Table 3-3. This data is extracted from design requirements like the AALRT torque characteristics in Figure 3-3 and the AALRT technical parameters in Table 3-2.

Table 3-3:Initial Data.

Symbol	Parameter	Quantity
P_{rated}	Rated Power	130kW
T_{em}	Rated Torque	689Nm
N_b	Rated Speed	1800 rpm
V_o	DC-Bus voltage	750 V
f	Rated Frequency	91 Hz

3.3.1.2. Assigned Parameters

Some parameters which are required during calculations have to be assigned. Some of them may be modified during the design process;

- 1) Air gap magnetic loading (B_{gm}): B_{gm} is selected relative to the core type to provide enough flux density without resulting in unwanted saturation. This study's core type is M470-50A steel and $B_{gm}=1$ Tesla, which gives enough boundary before core saturation.
- 2) Pole pitch to air-gap ratio (τ/g): This ratio affects the d and q-axis magnetizing coefficients (K_{dm} , K_{qm}) respectively. In this study, $\xi=10$. The saliency ratio of 10 is assigned because this value is at the boundary of the two rotor types (ALA, TLA) [38], [41]. The value of τ/g is 345 as chosen in [6].

Equations (3-1), (3-2), and (3-3) show the relations as follows:

$$L_{dm} = L_m K_{dm} \quad (3-1)$$

$$L_{qm} = L_m K_{qm} \quad (3-2)$$

$$\xi = \frac{L_d}{L_q} \text{ Then; } \xi = \frac{L_{dm}+L_s}{L_{qm}+L_s} \quad (3-3)$$

where L_{dm} and L_{qm} are the d-axis and q-axis magnetizing inductances respectively and L_s is the leakage inductance.

4. Stack aspect ratio ($\lambda = L/\tau$, $0.6 < \lambda < 3$): This ratio gives to the motor's stack length. A higher ratio refers to a longer stack length and shorter pole pitch suitable for higher-speed applications whilst a lower ratio refers to a shorter stack length and longer pole pitch suitable for lower-speed applications [61]. Given that the machine in this study has a low-rated speed, it is selected to be $\lambda = 0.9$ which gives a shorter stack length which is suitable for lower-speed applications.
5. Current density (J): It can be selected from 3.5 A/mm² to 8 A/mm² for axial or axial-radial air-cooled machines. In this study, $J=5$ A/mm² is assigned because the machine uses an open-air self-ventilated cooling system [17].

Table 3-4 shows the summary of the assigned data.

Table 3-4: Assigned Data.

Symbol	Parameter	Quantity
B_{gm}	Air gap magnetic loading	1 T
τ/g	Pole pitch to air gap ratio	345
λ	Stack aspect ratio	0.9
ξ	Saliency ratio	10
J	Current density	5A/mm ²
K_{fill}	Fill factor	0.7

3.3.1.3. Rotor Core Diameter

The motor's pole pitch (τ) is one of the required parameters to obtain the rotor outer diameter (D_{ro}). Equations (3-4) to (3-7) show how to obtain the rotor diameter.

$$B_{dm} = \frac{B_{gm}}{\sqrt{1 + \left(\frac{K_{qm}}{K_{dm}}\right)^2 \frac{L_d}{L_q}}} \quad (3-4)$$

Where B_{dm} is the flux density in the d-axis,

Using the rated frequency f , number of pole pairs is:

$$P = \frac{60f}{N_b} \quad (3-5)$$

$$\tau = \sqrt[3]{T_{em} \frac{K_{dm} \mu_0 \left(\frac{\tau}{g}\right) \left(\frac{\tau}{L}\right)}{B_{dm}^2 P^2 \left(1 - \frac{K_{dm}}{K_{qm}}\right) K_c \sqrt{\frac{L_d}{L_q}}}} \quad (3-6)$$

Where μ_0 is the permeability of free space, K_c is the Carter factor

$$D_{ro} = 2P \frac{\tau}{\pi} \quad (3-7)$$

The above equations illustrate that there are two key parameters K_{dm} and K_{qm} . Since the flux leakage is unknown, to simplify the solution it is assumed that L_σ is approximately equal to the q-axis L_{qm} . Even if the actual L_{qm} is higher than the calculated one, the torque and motor performance will remain approximately the same thus the design will still be fine. Taking into consideration this assumption along with substituting the assigned saliency ratio ($\xi=10$) in (3-3) gives $\frac{K_{dm}}{K_{qm}} = 19$ and then $K_{dm} = 0.95$. These two key parameters can be substituted again into (3-4), (3-5), and (3-6) to give the pole pitch and the rotor outer diameter. On the other hand, the machine's pole pitch, pole pitch to air gap ratio, and stack aspect ratio give the air gap and stack length respectively. The saliency ratio of 10 is assigned because this value is at the boundary of the two rotor types (ALA, TLA). Previous investigations in the literature showed that a saliency ratio higher than 10 may be achieved by the ALA rotor, whereas for the TLA rotor, it is usually $\xi \leq 10$. However, the TLA type is preferable in many applications and is the most widely used structure therefore it will also be used in this design [41].

3.3.1.4. Stator Geometry

1) Ampere-turns per Slot

The flux in the motor's magnetic circuit is proportional to the resultant MMF (resultant ampere-turns). This means the magnetic loading is assigned such that the motor operates in the linear portion of the magnetization characteristic. Therefore, exciting ampere-turns are required to maintain the proper flux density across the air gap. Equations (3-8) to (3-10) show how to obtain the d-q components and total value of the ampere-turns per slot, respectively.

$$n_s i_{dm} = \frac{B_{dm} \pi g K_c}{3\sqrt{2} \mu_0 q K_w K_{dm}} \quad (3-8)$$

$$n_s i_{qm} = n_s i_{dm} \sqrt{\frac{L_d}{L_q}} \quad (3-9)$$

$$n_s i_{qm} = \sqrt{(n_s i_{dm})^2 + (n_s i_{qm})^2} \quad (3-10)$$

Where n_s is the number of turns per slot, q is the number of turns per phase per pole, i_{dm} and i_{qm} are the magnetizing currents in the d and q axes respectively, K_w is the winding factor and K_c is the Carter factor.

2) Winding Factor

The winding factor is the ratio between the MMF generated by a stator that has short-pitched, distributed, or skewed windings, and the MMF generated by a stator that has full-pitched, concentrated, and non-skewed windings. It is a product of three factors i.e., distribution (K_d), pitch (K_p) and skew (K_{skew}) factors, as shown in (3-11). Electromotive forces for the coils which are distributed along pole pitch are not the same. The torque includes torque ripple which is caused by odd harmonics. Therefore, chording pitch winding may be employed to reduce the harmonics and improve the torque quality. However, round rotors with uniform flux barriers attenuate low-order MMF harmonics. Hence it is not necessary to employ chording on their stator windings as a means to reduce low-order harmonics. In addition, chording reduces the machine power rating by 5 to 10%. Therefore, when calculating the motor's winding factor in (3-11) below, chording winding is neglected. Thus, the pitch factor, K_p is equal to 1. The skewing of the rotor also helps to reduce the harmonics. However, in this design, skewing is neglected. This reduces the manufacturing cost of the machine and allows to evaluate the impact of torque ripple before skewing [31]. Therefore $k_{skew}=1$. Therefore, the only factor affecting the winding factor is the distribution factor because the stator uses distributed windings. The winding factor is given below:

$$K_w = K_d K_p K_{skew} \quad (3-11)$$

$$\text{where} \quad K_d = \frac{\sin(\frac{\pi}{6})}{q \sin \frac{\pi}{6q}}, \quad K_p = 1, \quad K_{skew} = 1, \quad q = \frac{N_s}{3(2P)} \quad (3-12)$$

Using the guidelines for selecting number of stator slots per pole phase (q) for a salient pole machine from [61] where q should be less than or equal to 4, $q = 2$ is selected.

3) Stator Slots Dimensions and Core Size

To design the stator core geometry, all the stator slots' dimensions must be obtained. The stator geometry from [41] is adopted in this design because it was also used for a traction application. Figure 3-5 shows the details of the slot parameters.

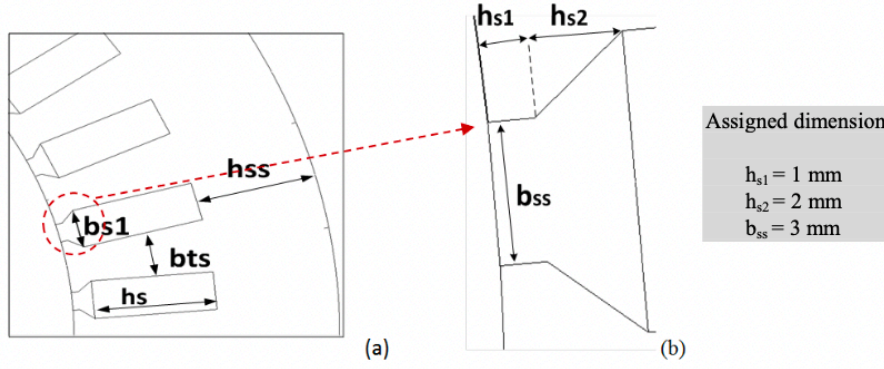


Figure 3-5: Dimensions of the stator slot (a) and wedge area (b) [41].

The ampere-turns per slot and pole pitch enable the calculation of the useful area (A_s) and slot pitch (τ_s) using (3-13) and (3-14).

$$A_s = \frac{n_s i_m}{JK_{fill}} \quad (3-13)$$

$$\tau_s = \frac{\tau}{3q} \quad (3-14)$$

Equations (3-15) to (3-17) yield the dimensions of each slot, where h_{s1} and h_{s2} are the stator slot opening depths, b_{s1} is the slot width, b_{ts} is the tooth width, h_s is the tooth length and h_{ss} is the stator yoke length. B_{ts} is the tooth flux density which is approximately twice the d-axis magnetizing flux density.

$$b_{s1} = \pi \frac{D_{ro} + 2(h_{s1} + h_{s2})}{3 \times 2Pq} - b_{ts} \quad (3-15)$$

$$h_s = \frac{A_s}{b_{s1}} \quad (3-16)$$

$$b_{ts} = \frac{B_{gm}}{B_{ts}} \tau_s \cong \frac{B_{gm}}{2B_{dm}} \tau_s \quad (3-17)$$

In order to be able to reduce the air gap flux pulsations, it is necessary to choose the minimum possible dimensions for slots opening. Therefore, the following dimensions are chosen, $b_{ss} = 3\text{mm}$, $h_{s1} = 1\text{mm}$, and $h_{s2} = 2\text{mm}$. b_{s1} and b_{s2} will be identical for rectangular wires, thus, rectangular wire is used. According to the wire gauge standards, if the calculated gauge of the flat wire is unavailable, some modifications might be applied to the slot's dimensions, and the closest gauge

may be selected. In such conditions, the new slot's area must be close to the calculated useful area to maintain the assigned current density [6], [41], [62].

Stator back yoke width (h_{ss}) is obtained using (3-18), where the yoke flux density, B_{Fe} , is considered to be 50% higher than the air gap flux density.

$$h_{ss} = \frac{B_{gm} \tau}{B_{Fe} \pi} \quad (3-18)$$

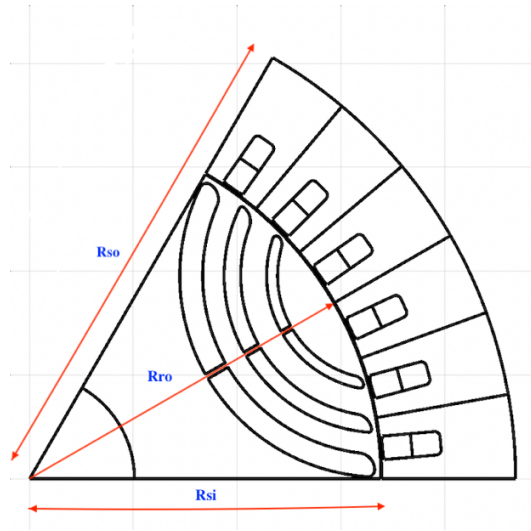


Figure 3-6: Machine rotor outer radius, stator inner radius, and stator outer radius.

All parameters required for the calculation of the stator geometry have been obtained. The stator's inner (D_{si}) and outer diameter (D_{so}) can be calculated using (3-19) and (3-20).

$$D_{si} = D_{ro} + 2g \quad (3-19)$$

$$D_{so} = D_{si} + 2(h_{s1} + h_{s2} + h_{ss}) \quad (3-20)$$

R_{ro} , R_{si} and R_{so} are the machine rotor outer radius, stator inner radius, and stator outer radius respectively.

$$R_{ro} = \frac{D_{ro}}{2}, \quad R_{si} = \frac{D_{si}}{2}, \quad R_{so} = \frac{D_{so}}{2} \quad (3-21)$$

3.3.1.5. Stator and Rotor material

One of the problems with SynRMs is the mechanical stress due to a lot of space in the rotor, resulting in less structural support. Suppose segments and ribs are made thicker to help with the mechanical stresses. This will inevitably result in lower torque and power factor due to leakage flux through the ribs and a small insulation ratio between steel and air in the q-axis of the rotor. Simultaneously, magnetic steel with good magnetic properties is required. In this study, the rotor and stator steel were chosen as M470-50A steel because of its high yield strength at $\sigma_v = 295\text{MPa}$, and its magnetic characteristics shown in Figure 3-7. M470-50A steel was selected because the higher the yield strength, the less the ribs and segments would yield to stress. This enables the use of thinner ribs and segments [7].

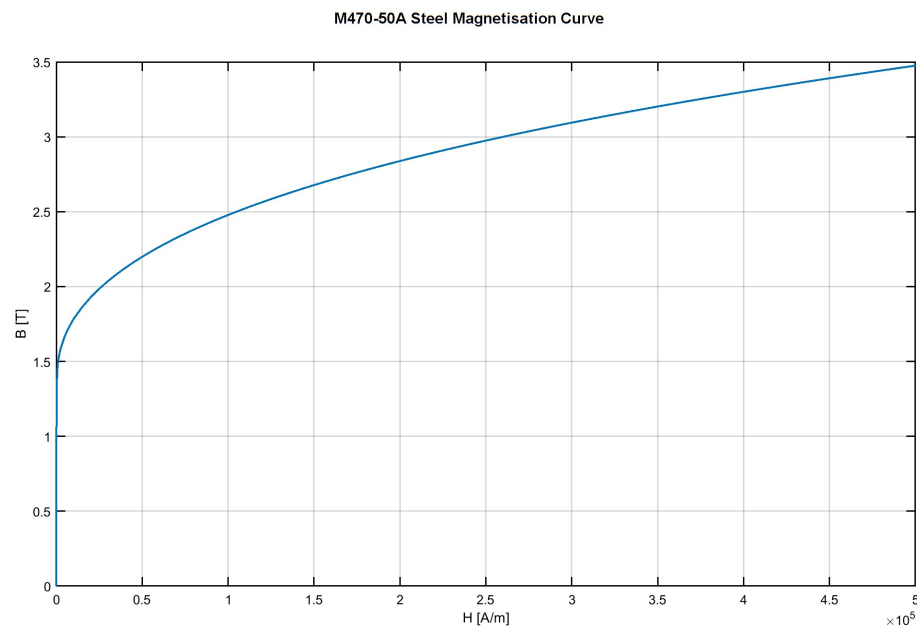


Figure 3-7:M470-50A steel magnetization curve [63].

Table 3-5: M470-50A Characteristics.

Category	Iron
Mass Density	7700 kg/m ³
Yield Strength	295 MPa
Alpha (Loss coefficient)	1.2625

Kh (loss coefficient)	0.0089837
Ke (loss coefficient)	0.00011618
beta (loss coefficient)	2.335
Young Modulus	200

3.3.1.6. Machine Parameters

To be able to analyze the performance of the proposed motor by FEA, its electric and magnetic parameters need to be identified. Using the approaches below, the motor's dimensions, initial data, and assigned parameters enable the characterization of all the required parameters as a function of the number of conductor-turns per slot (n_s). Therefore, n_s is a key parameter in the design [41].

1) Phase Resistance and Inductances

The leakage inductance can be expressed as in (3-22) [41].

$$L_s = 2\mu_0 n_s^2 qP (\lambda_s + \lambda_z + \lambda_f) \quad (3-22)$$

where;

$$\lambda_s \cong \frac{2h_s}{3(b_{s1}+b_{s2})} + \frac{2h_{s2}}{b_{s1}+b_{ss}} + \frac{h_{s1}}{b_{ss}} \quad (\text{slot permeance}) \quad (3-23)$$

$$\lambda_z = \frac{5g}{5b_{ss}+4g} \quad (3-24)$$

$$\lambda_f = \frac{0.34q}{L} (l_{end} - 0.64\tau) \quad (3-25)$$

$$l_{end} = \pi \frac{\tau}{2} \quad (\text{stator end winding length}) \quad (3-26)$$

Substituting all data into (3-25) and then the result into (3-22) gives the leakage inductance in (3-27) [41].

$$L_s = 2.90642 \times 10^{-5} (n_s)^2 \quad (3-27)$$

Equation (3-28) shows the phase resistance as a function of n_s , $\rho = 2.3 \times 10^{-8} \Omega m$ is copper resistivity [41].

$$R_s = \rho l_c P_o q (n_s)^2 \frac{J}{n_s i_m} \quad \text{where; } l_c = 2(L + l_{\text{end}}) \quad (3-28)$$

Therefore, we can express the phase resistance as in (3-29).

$$R_s = 4.8 \times 10^{-4} (n_s)^2 (\Omega) \quad (3-29)$$

For uniform air gap assuming ideal iron with infinite permeability the magnetizing inductance L_m is inversely proportional to the airgap length g , and it can be expressed as shown in (3-30) [41].

$$L_m = 6\mu_0 \frac{(P_o q K_w 1 n_s)^2}{\pi^2 P_o g K_c (1 + K_s)} \quad (3-30)$$

We can then define the magnetizing inductance and its d-q components as a function of n_s as follows:

$$L_m = 2.01787 \times 10^{-4} (n_s)^2 (H) \quad (3-31)$$

$$L_{qm} = 1.0089 \times 10^{-5} (n_s)^2 (H) \quad (3-32)$$

$$L_{dm} = 1.91697 \times 10^{-4} (n_s)^2 (H) \quad (3-33)$$

As was mentioned earlier, to simplify the solution, the q-axis magnetizing inductance is considered equal to the leakage inductance although it is always bigger. Therefore, the d-q axis inductance of the motor can be expressed as shown in (3-34) to (3-37)

$$L_d = L_{dm} + L_\sigma \cong L_{dm} + L_{qm} \quad (3-34)$$

$$L_q = L_{qm} + L_\sigma \cong 2L_{qm} \quad (3-35)$$

$$L_d = 2.01787 \times 10^{-4} (n_s)^2 (H) \quad (3-36)$$

$$L_q = 2.01787 \times 10^{-5} (n_s)^2 \quad (H) \quad (3-37)$$

2) *Number of Turns per Slot*

The number of turns per slot depends on the voltage across the stator phases. It is changed based on the stator connection and also the converter type. For a delta connection supplied by an SVPWM power converter, the supply voltage (V) can be obtained as in (3-38) where V_o is the DC-bus voltage [41].

$$V = \frac{\sqrt{6}}{\pi} V_o \quad (3-38)$$

To get n_s , the motor's equivalent circuit and its relevant vector diagram at base speed are used to define the motor's mathematical model through voltage equations. Using the motor's vector diagram, Figure 2-8 and (2-9) to (2-17) the voltage equations may be expressed as follows [41].

$$V = (-\omega_e L_{qm} I_{qm} + R_s I_{dm}) + j(\omega_e L_{dm} I_{dm} + R_s I_{qm}) \quad (3-39)$$

$$V_d = -\omega_e L_{qm} I_{qm} + R_s I_{dm} \quad (3-40)$$

$$V_q = \omega_e L_{dm} I_{dm} + R_s I_{qm} \quad (3-41)$$

$$\omega_e = N_b P \frac{2\pi}{60} \quad (3-42)$$

$$V = \sqrt{V_d^2 + V_q^2} \quad (3-43)$$

The values of d-q components of the ampere-turns from (3-8) and (3-9) are then substituted into (3-39) to (3-43) to yield the number of turns per stator slot of the conductor. This is the key in obtaining all the motor's required parameters. Therefore, $n_s = 12 \text{ turns}$.

3) Thermal loading factor

The thermal loading factor (k_j) is a design input that determines the current loading [11]. It is defined as the allowed copper loss by the stator's outer surface as shown in (3-44).

$$k_j = \frac{\frac{3}{2}R_s i_s^2}{2\pi R_{ro} L} \quad (3-44)$$

Typical values of k_j (verified on several prototypes and commercial motors) are $k_j = 1.5 \sim 3 \text{ kW/m}^2$ for non-ventilated machines, $k_j = 5 \sim 12 \text{ kW/m}^2$ for machines with ventilation, and $k_j = 12 \sim 20 \text{ kW/m}^2$ for water-cooled machines [11]. The rated current i_s relates to thermal loading according to the following equation:

$$N_{sp} i_s = \sqrt{k_j \cdot \frac{K_{fill}}{\rho} \cdot \frac{L}{L+l_{end}} \cdot \frac{\pi R_{so} A_{slots}(x,b)}{9}} \quad (3-45)$$

where N_{sp} is the number of turns in series per phase, K_{fill} is the slot filling factor, ρ is the copper resistivity, l_{end} is the end-winding length, the stator outer radius R_{so} , stack length L and A_{slots} is the total cross-section of the slots [11].

4) Speed Range

The maximum speed range, the corresponding phase current, and its d-q components can be expressed as follows:

$$\frac{\omega_r}{\omega_b} = \left(\frac{V}{\omega_e}\right)^2 \frac{3P(L_d - L_q)}{2L_d L_q T_{em}} \quad (3-46)$$

$$i_d = \sqrt{\frac{T_{em} L_q \omega_b}{3P(L_d - L_q) L_d \omega_r}} \quad (3-47)$$

$$i_q = i_d \frac{L_d}{L_q} \quad (3-48)$$

$$i_s = \sqrt{i_d^2 + i_q^2} \quad (3-49)$$

The product of power factor and efficiency over speed range is a parameter of the SynRM used to justify the motor's performance relative to speed variations.

$$\eta \cos \varphi = \frac{T_e \omega_i}{3PV_{im}} \quad (3-50)$$

As shown in (3-50), efficiency and power factor depend on each other. Their product is constant at any operating speed (ω_i) over the speed range and the corresponding electromagnetic torque (T_e). Therefore, the improvement of one can lead to the decline of the other. Therefore, proper values for both are required to improve the motor performance with regards to output power and losses. This can lead designers to choose the motor control strategy of maximum power factor or maximum efficiency techniques depending on requirements [41].

Excel is used to set all the equations and calculate the key input data reported in Table 3-6 automatically. The table shows the design specifications of the proposed motor after the analytical sizing.

Table 3-6: Analytical Design Parameters.

Parameter	Quantity	Parameter	Quantity
τ	171.31mm	R_s	0.081ohms
L	201 mm	L_d	0.0341 H
g	0.5 mm	L_q	0.00341 H
D_{ro}	345 mm	i_{dm}	29 A
b_{ts}	14.47 mm	i_{qm}	91 A
b_{sl}	14.6 mm	i_m	29A
h_s	24.29 mm	$i_d(w_r)$	12 A
h_{ss}	32.08 mm	$i_q(w_r)$	122 A
D_{si}	328 mm	$i_s(w_r)$	123 A
D_{so}	468mm	$n_s i_m$	1242
$Volume$	0.0315 m ³	L_s	0.00491 H
$\eta \cos \phi$	0.48	W_r/w_b	2.4
n_s	12	V	590 V
k_j	10	n_{lay}	3

N_{sp}	72		
----------	----	--	--

3.3.1.1. Rotor Geometric Parameters

The analytical design procedure is used to obtain stator parameters. The next step is to obtain the rotor geometric parameters. These include the number of layers, their angular position, barrier widths, and the carrier segments widths etc. From (3-44) the circulating inductance L_{qc} is affected by the number of barriers (n_{lay}) and their positions at the airgap $\Delta\alpha_k$ where $k = 1, 2, \dots, n_{lay}$. To cater for L_{qc} the number of layers and their positions are chosen using the following methods. According to the golden rule by [64], $n_{rotor} = n_{stator} \pm 4$, where n_{rotor} is the number of slots per pole pair in the rotor and n_{stator} is the number of slots per pole pair in the stator [40]. Therefore, for this motor $n_{stator} = 12$ slots per pole pair, therefore $n_{rotor} = 16$ is chosen. This translates to the number of layers per pole being 4. However, in such instances the fourth layer is normally omitted for ease of manufacturing hence $n_{lay} = 3$. The angular positions are also chosen relative to the regular pitch, following the golden rule for torque ripple minimization[64]. Therefore $\Delta\alpha_2 = \Delta\alpha_3 = \frac{2\pi}{16P}$ and $\Delta\alpha_1 = 1.5\Delta\alpha_2$ because of the omitted fourth layer on top of the q-axis [11]. The rotor flux carriers must carry the airgap flux of half pole just like the stator back iron therefore a design constraint is set that makes sure that the total size of the rotor carriers equals the yoke size h_{ss} . The widths of the flux carriers are shown in Figure 2-12 in red. The top segment of the pole is not considered a proper flux carrier thus it is neglected. As previously mentioned, the total insulation must be per the iron carriers' width constraint shown in (3-46), i.e., it has to be equal to the radial space available $\Delta r - h_{ss}$, (46). The width of each barrier is calculated according to (3-49). Therefore, from here the barrier widths (hc_{ks}) and angles are determined using this criterion in the SyR-e software.

3.3.2. SyR-e Analytical Model

A set of some of the analytical design parameters is fed into SyR-e. These include geometric quantities like R_{so} , L , p , q , n_{lay} as well as target loading factors ($B_{Fe} [T]$ and $k_j [W/m^2]$). SyR-e generates an x , b parametric design plane from the inputs. The plane represents various maximum torque and power factor combinations as functions of x and b , with each point on the plane representing a different motor design that has a unique rotor diameter (x) and core dimensions (b). All machines on the design plane share the set of input design parameters. The user then selects the motor with the desired maximum torque /power factor combination.

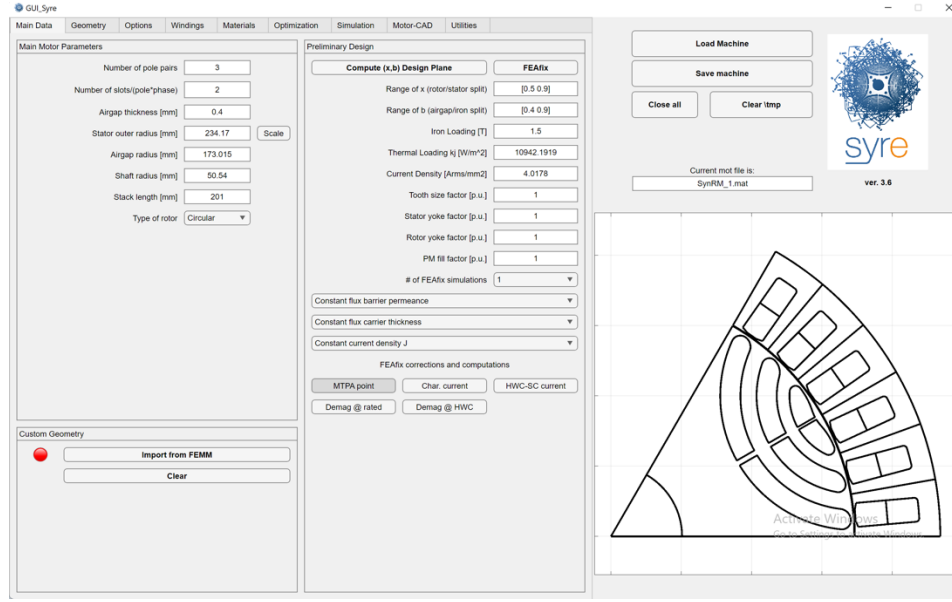


Figure 3-8: The SyR-e GUI for loading the analytical design values.

3.3.2.1. Per-unit design factors x and b

$$x = \frac{R_{ro}}{R_{so}} \quad (3-51)$$

$$b = \frac{B_g}{B_{Fe}} \quad (3-52)$$

The two factors, x and b , to represent the rotor/stator split ratio and the airgap/iron flux density ratio shown in (3-52) and (3-53) respectively [43]. These factors are used to explore the expected design outputs over the design plane x, b . R_{ro} and R_{so} represent the rotor outer radius and stator outer radius, respectively. B_{Fe} is the peak flux density in the stator yoke and B_g is the peak flux density in the air gap. All quantities are expressed in terms of x and b , so that torque and power factor can be defined as functions of (x, b) . This results in the design plane $T(x, b), \cos\phi(x, b)$, which visualizes the performance trends versus the geometric inputs. Most of the stator and rotor geometrical quantities depend on x and b . Factor b represents the per unit steel quantity and determines the cross-section of the iron elements in the core. As x increases, the rotor size increases, and stator slots become shorter, resulting in lower slot current and ultimately output

torque. In contrast, as b increases, stator and rotor steel elements get thicker, while stator slot and rotor barrier areas are reduced. In this case, the power factor improves.

3.3.2.2. Initial Torque /Power Factor Design Plane

Figure 3-9 shows the torque and power factor x, b plane results, using the input data of Table 3-6. The torque contours are plotted in red, and the power factor contours are in blue.

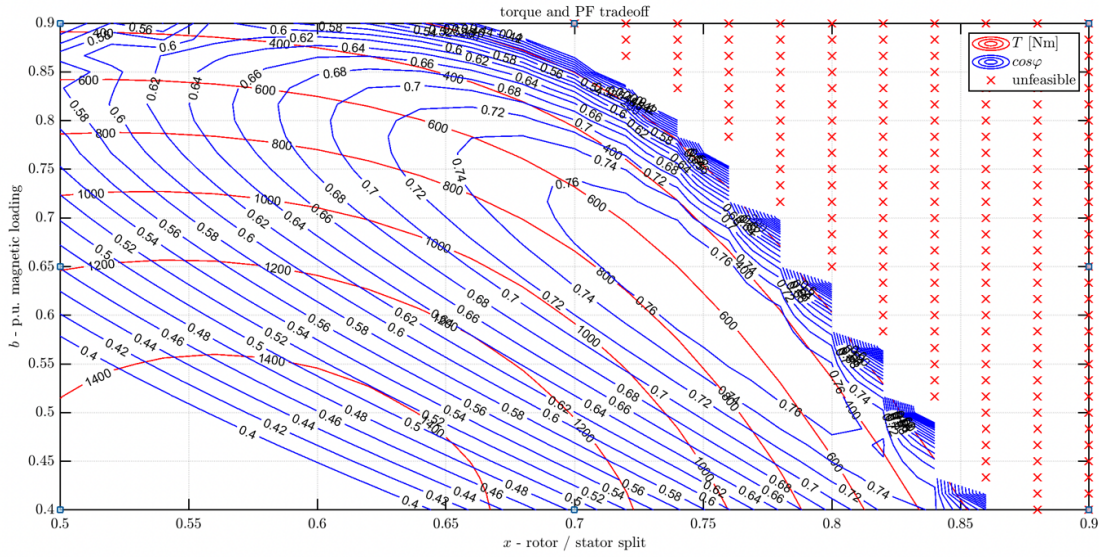


Figure 3-9: Torque/Power Factor parametric design plane from the analytical model.

One machine with coordinates $x=0.69$ and $b=0.65$ is extracted from the plane. The motor is expected to produce about 800Nm torque and to have a power factor of about 0.7. The rotor dimensions of the motor are reported in Table 3-7. When necessary (e.g., insufficient or too much torque), the initial inputs may be changed and the process is done again [11], [65].

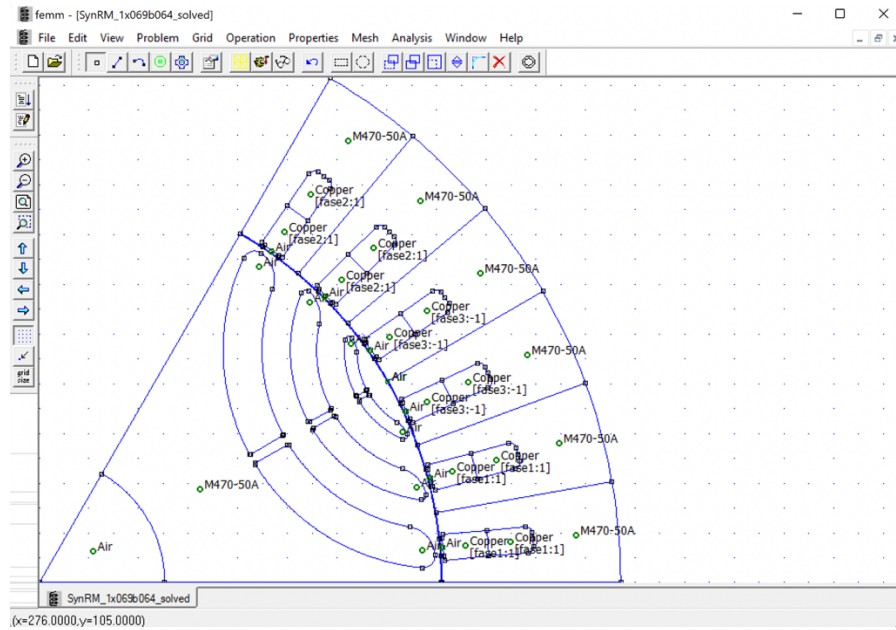


Figure 3-10: FEMM rendering of the selected motor.

Table 3-7: Dimension of the motor.

Parameter	Unit	Value
X	-	0.69
b	-	0.65
$\Delta\alpha$	degrees	8.7°
R_{ro}	mm	161.8 mm
$h_{c,1}$	mm	5.03mm
$h_{c,2}$	mm	10.58 mm
$h_{c,3}$	mm	15.6 mm
b_{ts}	mm	18.1 mm
h_{ss}	mm	34.58 mm
h_s	mm	37.38 mm

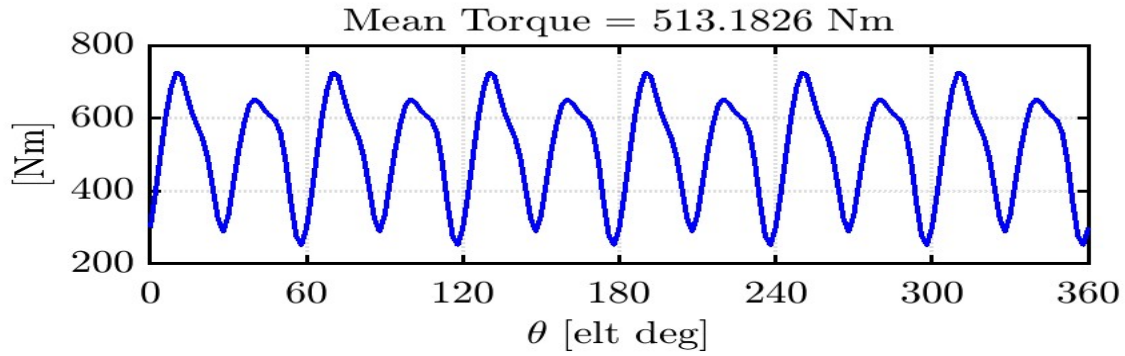


Figure 3-11: Maximum Torque characteristics of the chosen motor.

A quick single-point FEA analysis is performed on the machine. Figure 3-11 shows that the average maximum torque values deviate a lot from the selected torque of about 800Nm and power factor of about 0.7. This is due to the inaccuracies of the analytical model due to saturation in the rotor core; therefore, it is crucial to use FEAfix to account for the saturation errors and get a more accurate solution.

3.3.2.3. FEAfix Model Refinement

FEAfix refines the initial analytical model by accounting for saturation errors using quick FEA simulations. Two refinements on λ_d and λ_q are implemented to improve the accuracy of the initial design plane based on (2-5) and (2-6). The fix introduces three correction factors (k_{sat} , $k_{cross,d}$, and $k_{cross,q}$) to refine the flux linkage equations (3-55):

$$\begin{cases} \lambda_d = k_{cross,d} \left(\frac{L_{dm}}{k_{sat}} + L_\sigma \right) \cdot i'_d \\ \lambda_q = k_{cross,q} (L_{qm} + L_\sigma) \cdot i'_q \end{cases} \quad (3-53)$$

The factor k_{sat} accounts for the decrease in magnetizing inductance L_{dm} caused by the direct saturation of the d-axis. The other two factors $k_{cross,d}$ and $k_{cross,q}$ correct the cross-saturation effect and all residual errors. These corrective factors are used in the fast FEA approach FEAfix, to correct the initial analytical design errors. The apostrophes on the current components i'_d , i'_q show that when saturation is included in the equations, the operating points will vary from the previous

i_d , i_q values. Given that the peak flux density is imposed, the magnetizing current becomes $i'_d = k_{sat} i_d > i_d$ when accounting for saturation. The q current component reduces as $i'_q < i_q$. If i'_d is higher than i_s , the design is not feasible at the selected loading factors. Thus, it is reported as an error on the design plane [11].

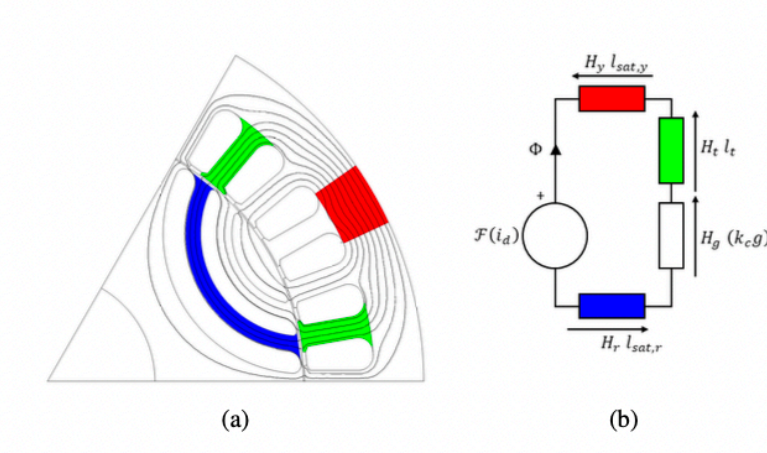


Figure 3-12 a) Additional iron section for the d-axis for saturation factor computation. b) equivalent magnetic circuit [11].

- **Saturation factor k_{sat}**

The initial d-axis model neglects the MMF drop in the iron core. This leads to L_{dm} overestimating and i_d underestimating. The refinement modifies the d-axis MMF using the simple magnetic circuit model of Figure 3-12. A single flux tube, representing the most loaded parts of the motor core along the d-axis, is considered. The regions of such flux tubes are:

- Two stator teeth (iron length equal to $2h_s$), shown in green
- A section of the stator yoke between two teeth (iron length equal to $l_{sat, y} = \frac{\pi}{3Pq} (R_{ro} - \frac{h_s}{2})$), shown in red
- One rotor flux carrier (iron length equal to $l_{sat, r}$), shown in blue

The magnetic circuit model is shown in Figure 3-12b, with the same colour coding as (a).

Ampere's law applied and the considered flux tube is:

$$\frac{3}{\pi} \frac{k_w N_{sp}}{P} i_d = H_g k_c g + H_t h_t + H_y l_{sat,y} + H_r l_{sat,r} \quad (3-54)$$

where $H_g \cdot k_c g = \mu_0 k_c g$ is the airgap MMF drop, like in (3-8). The other terms on the right-hand side account for the non-ideal iron. The magnetic fields $H_t = H$ and $H_y = H_r = H(B_{Fe})$ in the considered iron sections are obtained from the B – H curve of the steel lamination, imposing the reference flux densities. With the airgap term in evidence, (3-57) is rewritten in the form almost like (3-8):

$$\frac{3}{\pi} \frac{k_w N_{sp}}{P} i_d = \left(\frac{k_c g}{\mu_0} B_{Fe} b \right) \cdot k_{sat} \quad (3-55)$$

Saturation factor k_{sat} is:

$$k_{sat} = 1 + \frac{H_t l_t + H_y (l_{sat,y} + l_{sat,r})}{H_g (k_c g)} > 1 \quad (3-56)$$

Substituting geometric quantities (for symmetry they are referred to as half pole), the saturation factor becomes:

$$k_{sat} = 1 + \mu_0 \frac{H_t l_t + H_y \left[\left(R - \frac{l_y}{2} \right) \frac{\pi}{6Pq} + \frac{s_{nlay} + s_{nal} - 1}{2} \right]}{k_c g B_{Fe} b} \quad (3-57)$$

Given that the flux density is imposed in all the sections of the flux tube, evaluation of k_{sat} is done without the need for iteration. The magnetizing current changes from i_d to $i'_d = k_{sat} i_d$ [11].

- **Cross saturation factors**

Cross saturation influences each flux linkage component when another current is present on the other axis e.g., cross saturation of the d-axis in the presence of current in the q-axis. It is difficult to calculate the effects of cross-saturation with a purely analytical approach. Fast FEAfix corrects the analytical model using the coefficients $k_{cross, d}$ and $k_{cross, q}$ defined in (3-56). A few designs at specific points of the x, b plane are FEA simulated, at limited computational time. After FEA evaluates the d, q flux linkages of one design of the plane, the correction coefficients are evaluated for that motor as shown in (3-60) and (3-61), and then applied to all the designs of the plane:

$$k_{cross,d} = \frac{\lambda_{d,FEAfix1}}{(\frac{L_{dm}}{k_{sat}} + L_{\sigma})i'_d} \quad (3-58)$$

$$k_{cross,q} = \frac{\lambda_{q,FEAfix1}}{(L_{qm} + L_{\sigma})i'_d} \quad (3-59)$$

3.3.2.4. Fast FEA Evaluation of the initial Analytical Design

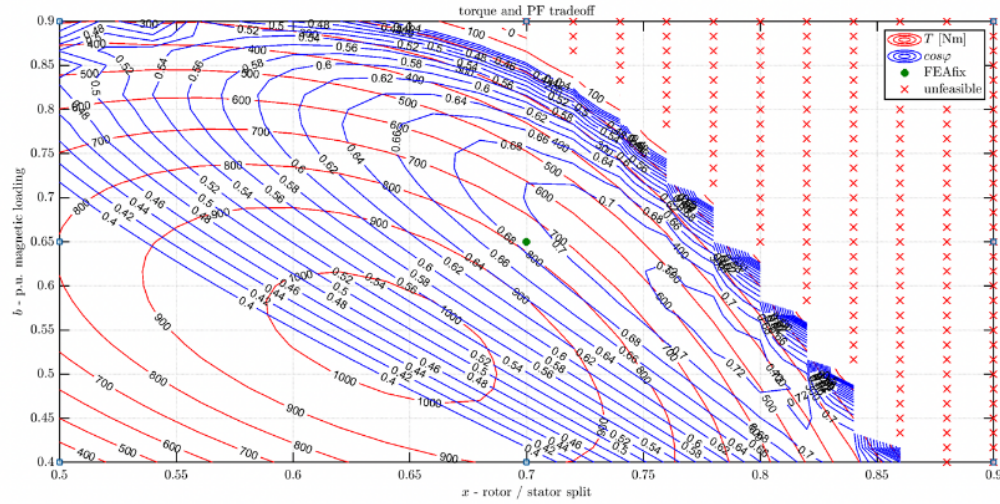


Figure 3-13: FEAfix Design Plane.

FEAfix is performed using the initial analytical design parameters. After performing the FEAfix it generates a new design plane shown in Figure 3-13 with less saturation and cross-coupling errors. A new FEAfixed design is then selected from the plane. The selected design is expected to account for saturation and cross-coupling errors hence it will have characteristics close to those selected in the plane i.e., torque and power factor i.e., a torque output of about 700Nm and a power factor of about 0.7. Motor with coordinates $x = 0.72$ and $b = 0.64$ on the design plane is chosen. The motor's parameters are shown in Table 3-8 below.

Table 3-8: Parameters of the motor.

Parameter	Unit	Value
x	-	0.72
b	-	0.63
$\Delta\alpha$	degrees	8.7°
R_{ro}	mm	161.8 mm

$h_{c,1}$	mm	5.25 mm
$h_{c,2}$	mm	11.33 mm
$h_{c,3}$	mm	16.86 mm
b_{ts}	mm	18.55 mm
h_{ss}	mm	35.39 mm
h_s	mm	29.08 mm

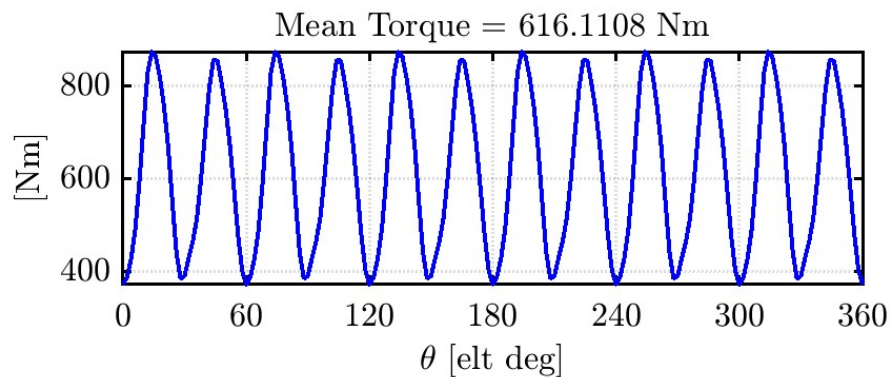


Figure 3-14: Torque and Power Factor characteristics of the chosen motor from FEAfix.

Table 3-9: Torque and power factor values for initial and FEAfix machine.

Motor	Torque (Nm)	Power Factor
Reference Machine	689	0.74
Initial Analytical Machine	513	0.585
FEAfix Machine	616	0.71

A quick FEA analysis of the FEAfix machine is performed. The values in Table 3-9 show that the FEAfix machine accounts for the saturation and cross-coupling errors hence its average maximum torque and power factor are closer to the desired and selected torque and power factor of 700Nm and 0.7 compared to the initial analytical design. Therefore, this FEAfix machine will be chosen for optimization. After motor selection, the next step is optimization

3.4. Design Optimization

3.4.1. Decision Variables

The rotor geometric variables and current phase angle are the decision variables. The rotor geometry is defined in Figure 3-15. The set of parameters that describe the rotor geometry plays a pivotal role in the optimization of the design. The literature presents various barrier shape types full of parameters, however, simplification is needed to keep the optimization as simple as possible. Each of the variables should have a reasonably significant impact on at least one of the performance indexes of the optimization. [48] showed that circular barriers shown in Figure 3-15, that have two input variables per layer are able to get close to the performance of more complex geometries despite having a very basic set of parameters. The geometric variables for circular layers are:

- the layer angular positions at the airgap $\Delta\alpha_j$;
- the layer heights hc_j ;

The phase angle θ of the current vector with respect to the synchronous d -axis (maximum permanence axis), is also an optimization variable. Each motor is evaluated at a single current angle. When the optimization finishes, θ is always very close to the MTPA angle condition θ_{MTPA} , which maximizes the torque per joule loss. The set of decision variable constraints used is shown in Table 3-10 and (3-62). The design optimization is done with reference to a current value that is two or three times i_s , corresponding to transient overload conditions. Optimizing for overload conditions results in motor designs with a torque ripple more insensitive to load variations [28].

Table 3-10: Constraints of The Search Space for the Global Search.

Parameter	Min Value	Max Value	Units
hc_i ($i=1 \dots n_{lay}$)	0.2	1	p.u.
$\Delta\alpha_1$	15	27	degrees
$\Delta\alpha_i$ ($j = 2, \dots, n_{lay}$)	0.33	0.67	p.u.
θ	40	80	degrees

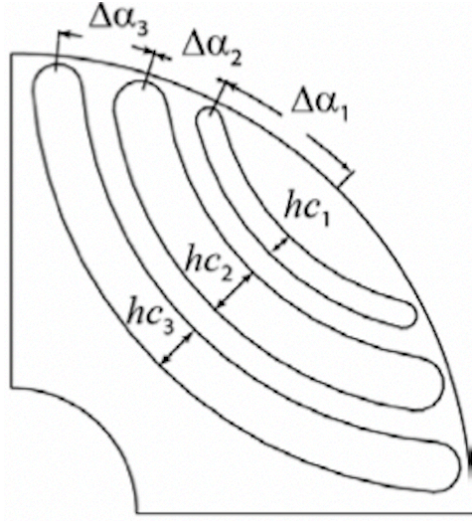


Figure 3-15: Rotor geometry with 3 circular barrier layers, $\Delta\alpha_i$ angles are layer positions, whilst hc_i are the layer heights.

3.4.2. Objective Function Evaluation

The average maximum torque, torque ripple and power factor are the objective functions of the optimization as shown in (3-61). Each candidate solution's maximum torque is calculated using FEA in n equally spaced rotor positions covering one stator slot pitch (τ_{st}). The average value of the maximum torque (3-59), the standard deviation of such n -points torque values (3-60), and the power factor are the objective functions of the optimization. The stator slot pitch is selected because it represents the torque ripple's most significant harmonic component. The choice of n is discussed in [47]. Although very few positions are considered (e.g., five positions are used in this optimization), the aliasing of significant torque harmonics is prevented by a random position offset at each evaluation [47]. The MOOA evaluates the candidate solutions by calculating the electromagnetic torque for a single current amplitude and phase condition over five rotor positions via FEA. The first position is randomly decided [28]. Where the objective function is negative, the respective quantity is maximized e.g., minimization of negative maximum average torque, whilst if it is positive, the quantity is minimized e.g., torque ripple as shown in (3-61).

$$T_{avg} = \frac{1}{n} \sum_{i=1}^n T_i \quad (3-60)$$

$$T_{ripple} = \sqrt{\frac{\sum (T_i - T_{avg})^2}{n}} \quad (3-61)$$

$$\min. (-T_{avg}, -\cos\varphi, T_{ripple}) \quad (3-62)$$

$$s. t. \begin{cases} hc_i(i = 1..n_{lay}) \leq 1 \\ hc_i(i = 1..n_{lay}) \geq 0.2 \\ \theta \geq 40^\circ \\ \theta \leq 80^\circ \\ \alpha_j(j = 1..n_{lay}) \geq 0.33 \\ \alpha_j(j = 1..n_{lay}) \leq 0.67 \end{cases} \quad (3-63)$$

3.4.3. The Optimization steps in SyR-e

The design optimization is performed with the MODE algorithm. The steps in setting up the optimization are

- Definition of the optimization size, i.e., the number of generations and number of individuals for each generation
- Definition of the time stepping during MODE
- Definition of the time stepping during the re-evaluation of the Pareto front after MODE ends
- Selection of the optimization variables and boundaries
- Selection of the optimization objectives and penalization limits.

The optimization process is carried out at constant thermal loading (i.e., constant copper loss, since the stator outer radius is constant). The current angle is included in the optimization variables, to automatically find the MTPA during optimization. In order to improve the convergency, penalization is performed on the quantities that are bigger than some limit. These are defined as penalization limits. Where the limit is negative, the respective quantity is maximized e.g., minimization of minus maximum torque, whilst if the penalization limit is positive, the quantity is minimized e.g., torque ripple. The results of the optimization are saved containing all the motors

on the pareto front of the optimization. A structural check is performed on each motor. This adds another objective related to structural simulations, that penalize the structurally-weak motors.

3.4.4. Simulation Set-Up

Each function call consists of five FEA simulations for five rotor positions using static-magnetic simulations. Each candidate takes about 3 seconds on a MacBook Air M1 laptop (8-core Apple M1 chip, 2.10 GHz, 12 MB Cache). The search is performed in the search bounds shown in Table 3-10, known as the Global Search bounds. Despite the small population size, the penalty function is applied in order to obtain Pareto fronts with a good density of solutions. The penalty function is used with the objective torque ripple, power factor, and maximum torque solutions that are way out of specification. This results in a final Pareto front that is concentrated in the area of interest of the torque-torque ripple-power factor space.

The optimization steps in the simulation are:

1. Global Search MODE (GS-MODE) of a SynRM machine
2. Local Search MODE refinement (LS-MODE)

The rotor geometry is optimized (i.e., the $\Delta\alpha_j$ angles and the layer heights h_{c_j} as defined in the preliminary stage). A three-objective MODE run maximizing the torque and power factor and minimizing the torque ripple is used. Geometrical constraints that ensure the mechanical feasibility of the output geometry are adopted. This first step is the GS-MODE. During the GS, the bounds of the search space are coarse, thus all the feasible rotors are considered as potential solutions. The GS is repeated many times so as to avoid local minima. After the GS-MODE, one solution machine is chosen from the pareto front (GS-solution) on the basis of its performances (i.e., torque, torque ripple, power factor), feasibility, and mechanical robustness (regularly spaced layers are preferable). The second optimization step refines the machine output from GS-MODE. A second three-objective MODE run is with the constraints close to the parameters of the GS solution: with a plus or minus 15% change permissible for each single parameter. This second optimization is the LS-MODE. The two-step procedure allows better precision to find a good approximation of the optimal solution with a reasonably low computational time [48].

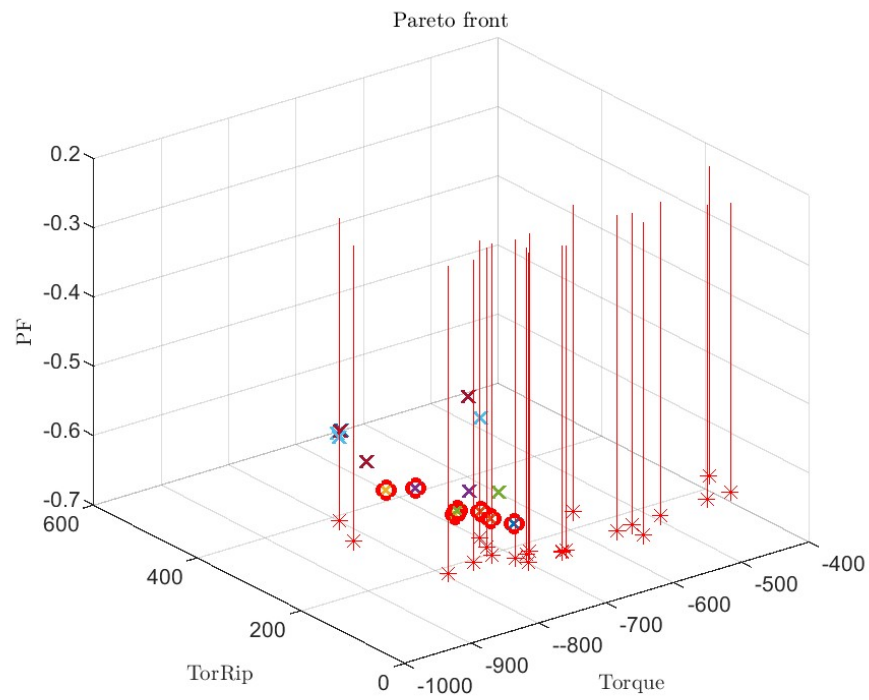


Figure 3-16: Pareto front of the optimization.

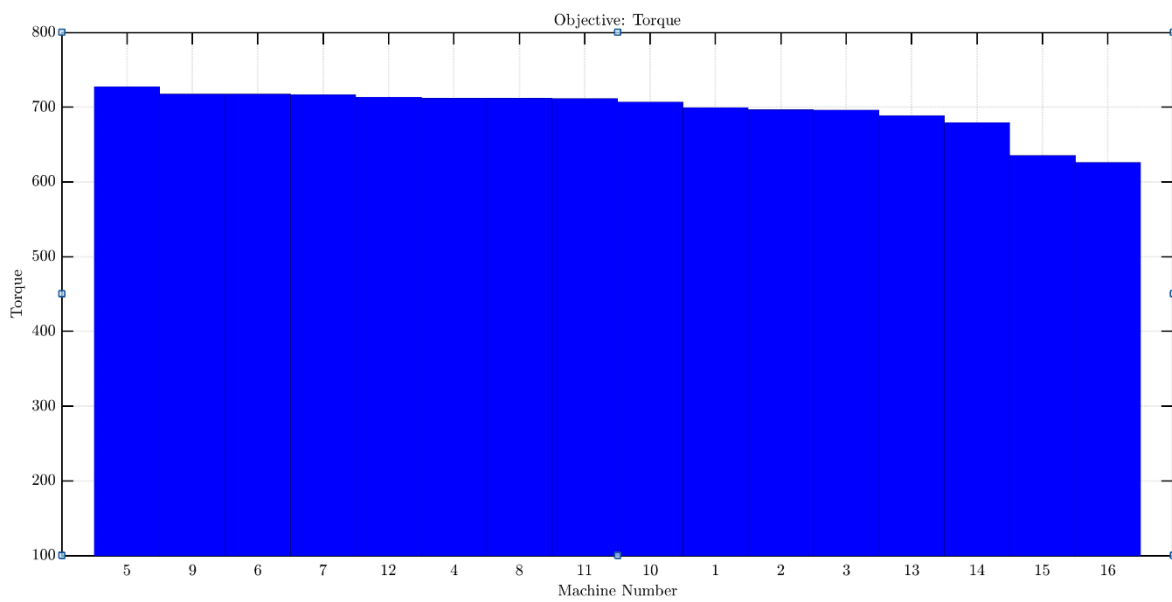


Figure 3-17: Torque values of the chosen machines after optimization.

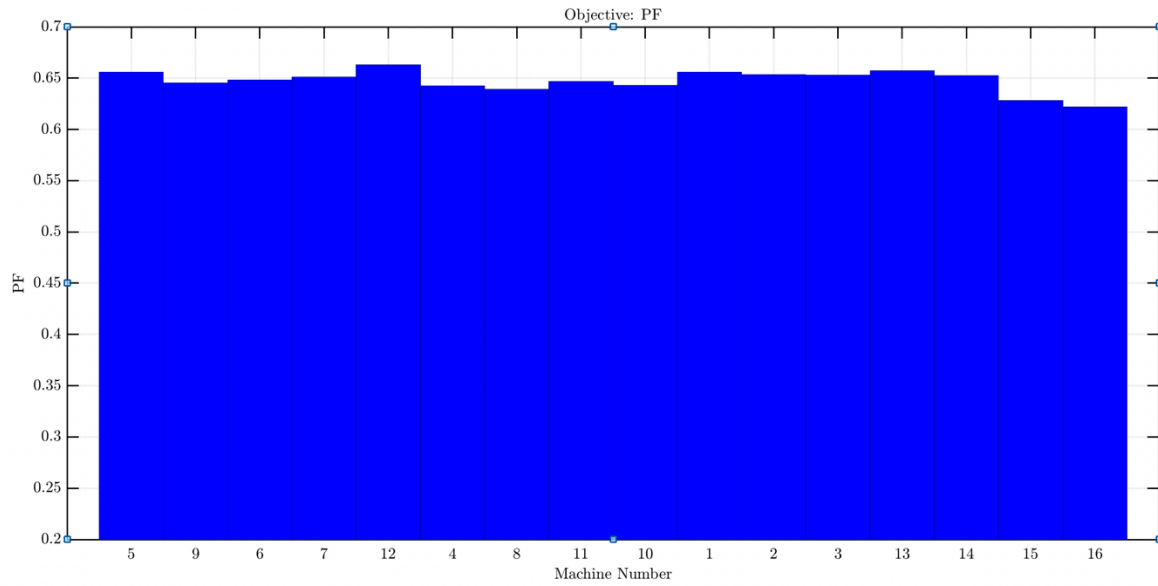


Figure 3-18: Power Factor values of the chosen machines after optimization.

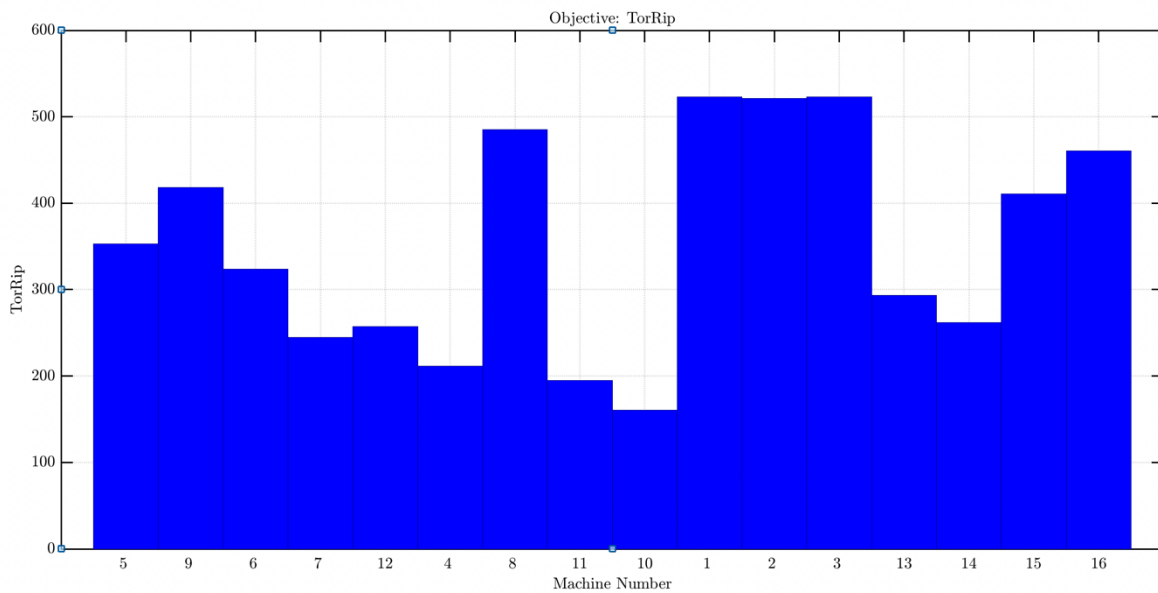


Figure 3-19: Torque ripple values of the chosen machines after optimization.

At the end of the optimization, a Pareto front of optimal solutions is obtained as shown above in Figures 3-16 to 3-19. One solution machine is then manually selected from the optimal solutions

on the basis of both its performances (maximum torque, torque ripple, power.) Motor number 10 is chosen because of a combination of good maximum torque, torque ripple, and power factor values. The parameters and the rendering of the motor structure in FEMM are shown below in Table 3-11 and Figure 3-20.

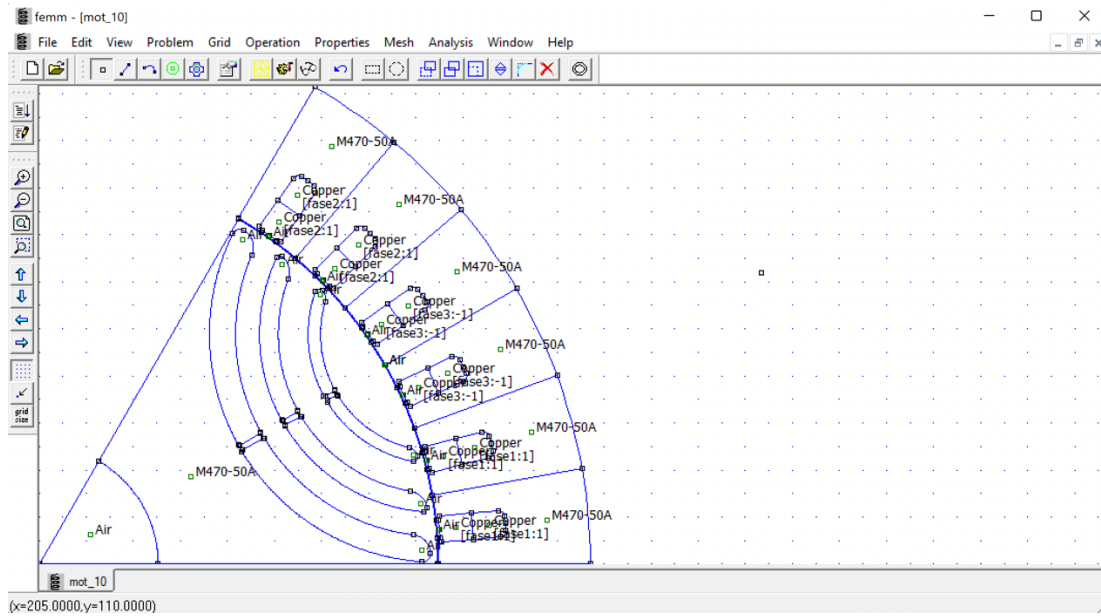


Figure 3-20 : Motor number 10 rendered in FEMM

Table 3-11: Parameters of Motor number 10.

Parameter	Unit	Value
$\Delta\alpha_{1,2,3}$	degrees	14.4°, 7.5°, 6.6°
R_{ro}	mm	161.8 mm
$h_{c,1}$	mm	5.3 mm
$h_{c,2}$	mm	7.99 mm
$h_{c,3}$	mm	11.06 mm
b_{ts}	mm	18.55 mm
h_{ss}	mm	35.39 mm
h_s	mm	29.08 mm

3.5. Finite Element Analysis (FEA)

3.5.1. Proposed Method Validity and Evaluation

The dimensions, electrical, and magnetic parameters of the SynRM motor are identified based on the proposed sizing and refined using FEAfix and optimization. In order to validate the size obtained throughout the design process as well as to evaluate the motor's performance, in comparison to the reference motor, an FEA analysis of the motor is first performed. FEA emphasizes design physics and also deals with the nonlinear characteristics of the SynRM in order to analyze the motor characteristics [8]. After the performance evaluation, the design is then compared with the reference motor.

3.5.2. SyR-e Simulation

FEA serves three main purposes in this research. It is used to quickly analyze and account for saturation and cross-coupling errors during FEAfix, analyze every potential solution during optimization and then analyze the performance of the final solution. The main FEA simulation engine adopted with SyR-e is FEMM. The FEA simulation is done in FEMM using a static magnetic solver. The solver emulates rotor movement by running a number of simulations at different rotor positions, an emulation of continuous rotor rotation. The imposition of phase currents is done relative to the rotor position and the input d-q currents. Accuracy and computational time trade-offs are done by choosing a proper angular span of the rotation and the number of rotor positions that must be simulated. For standard three-phase distributed winding motors, usually 60 electrical degrees of rotation is adequate (exploiting symmetry). 30 rotor positions result in good harmonic resolution, while 6 rotor positions can get the average values. The FEA simulations are controlled from the simulation tab of the main GUI[11], [66].

Boundary conditions play a crucial role in accurate motor analysis. For this model, a Dirichlet boundary condition has been applied to the outer boundaries. This enables the prescribed flux to pass normally to the boundary. Due to air having a much higher reluctance than the motor's material, a flux linkage of 0 *Wb* has been imposed through the outer boundaries.

$$A = 0 \quad (3-64)$$

Where A is the vector potential of the flux density B :

$$B = \nabla \times A \quad (3-65)$$

The possible FEA simulations include:

- Single Point
 - Flux Map
 - Iron Loss – Single Point
 - Iron Loss – Flux Map
 - Structural Analysis
- 1) Single Operating Point Simulation: The simplest FEA simulation is the single-point simulation. It evaluates a single (i_d, i_q) point, using the defined current amplitude (in p.u. of the rated current) and current angle, computed from the d-axis.
 - 2) Flux Maps Evaluation: The flux and torque maps over a regular (i_d, i_q) domain are computed. The current amplitude and number of current levels define the domain (valid for both axes)[10].
 - 3) Iron Loss Evaluation: Iron loss may be computed for single point or flux maps. The computation of the iron loss in FEMM is performed by simulating the complete rotation with a good number of rotor positions. The results are the stator and rotor hysteresis and eddy-current iron loss, for a given simulation speed. The modified Steinmetz equations are used [66].
 - 4) Structural Analysis: Structural analysis is performed using MATLAB's PDE (Partial Differential Equation) Toolbox. The input is the rotor speed, whilst mesh and boundary conditions are set automatically. The rotor structure is modeled as a unique body, with material properties adapted for a given region.

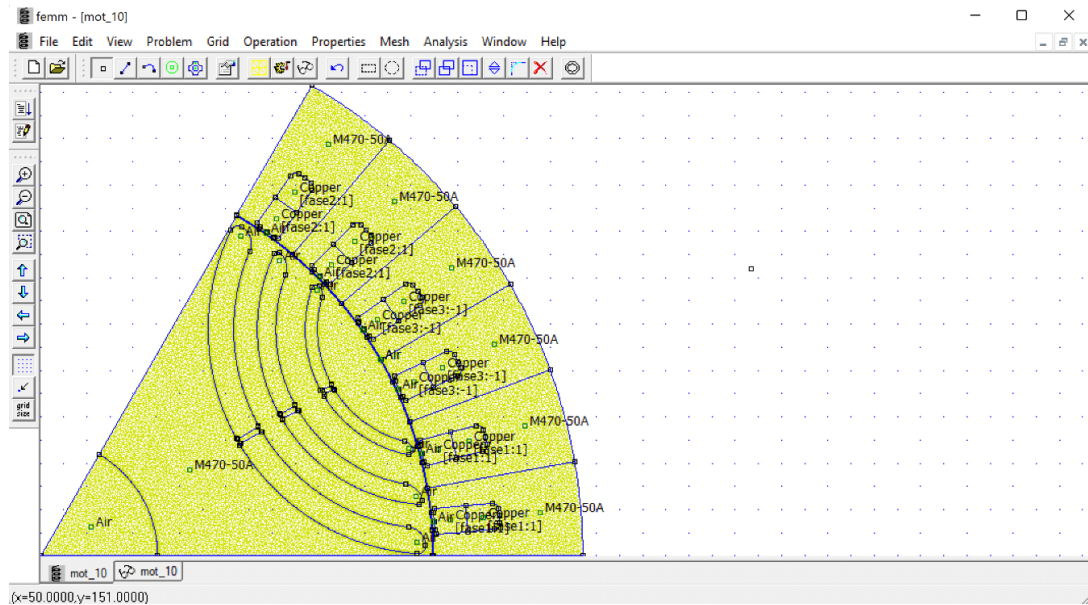


Figure 3-21: Single pole machine of the chosen machine in FEMM.

FEA verifies and evaluates the proposed motor's performances in different modes of operation. The geometry of the rotor is modified and optimized so as to have the maximum possible saliency ratio and output torque. The proposed motor is then examined by FEA to evaluate its performance. The single pole mesh profile of the proposed motor is shown in Figure 3-21. The motor's most important electromagnetic parameters like the electromagnetic torque, electromotive force, and flux depend on the air gap's characteristics, therefore to improve accuracy a very fine mesh is defined in the air gap area. However, this also increases the simulation time. Critical points like the stator teeth, tangential ribs, and radial ribs are also modeled with fine mesh to observe the effects of saturation and increase the accuracy of the FEA calculations[6].

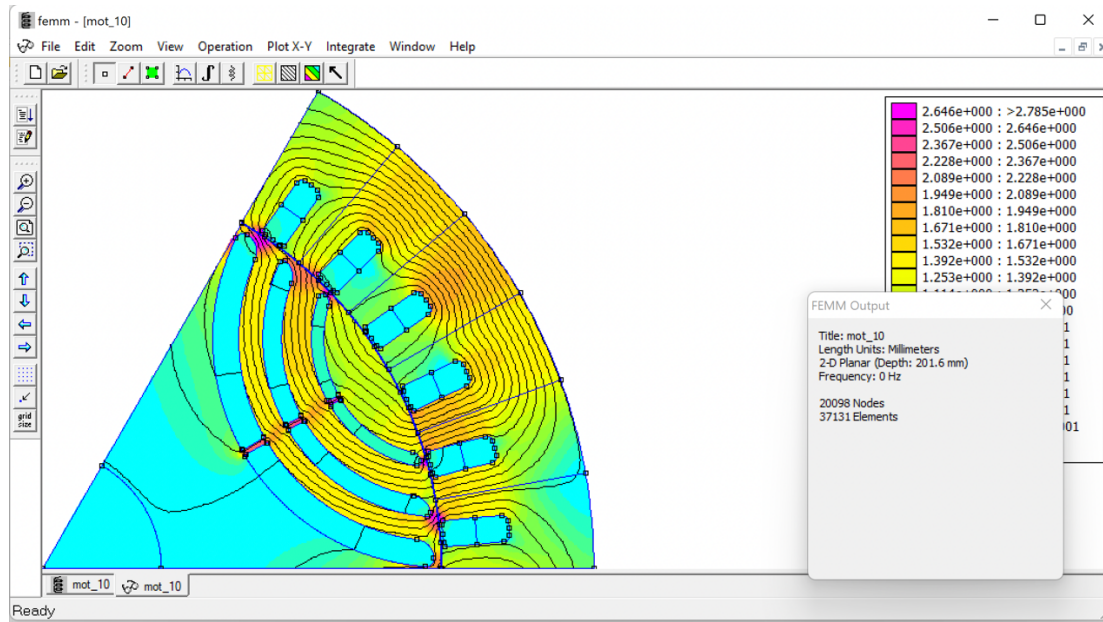


Figure 3-22: Flux density distribution in a single pole of the SynRM.

3.6. Traction Motor Drive Simulation

syreDrive is used to automatically generate a control system for the SynRM within the SyR-e motor design environment. Simulations are performed in FEMM and the results are automatically streamlined to MATLAB for further post-processing and elaborations. Functions for the flux maps elaboration compute optimal control trajectories and operating limits and efficiency maps. Data processing is performed to build a dynamic model of the motor in Simulink, including the data of the drive and the adopted control strategy [54]. The setup is shown in Figures 3-23 and 3-24. The blue block represents the control, the yellow one is the inverter and the orange one is the motor.

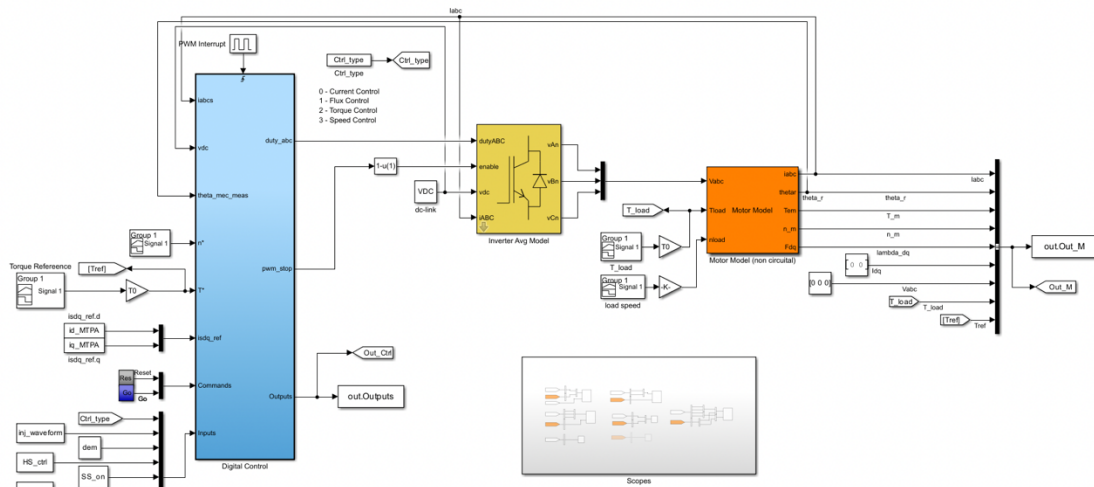


Figure 3-23: Setup for the complete SynRM drive simulation in Simulink.

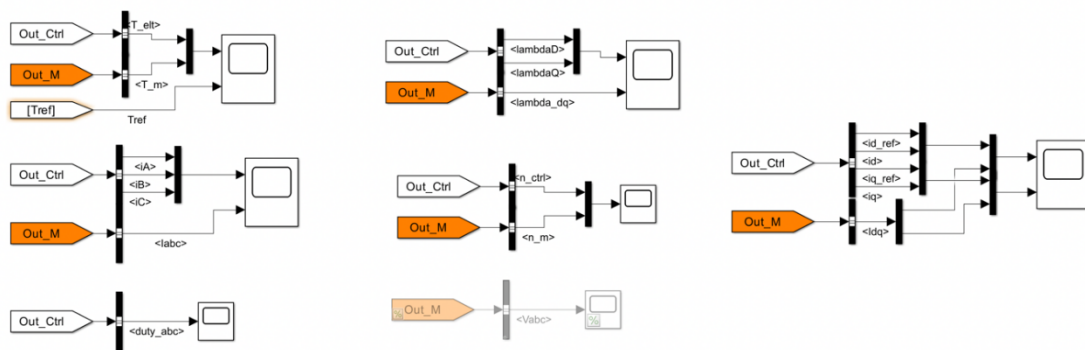


Figure 3-24: Scopes to measure the signals.

4. Results Analysis and Discussion

This chapter presents and discusses the results of the SynRM FEA analysis and control simulation. The analysis shows the performance of the motor and control in comparison to the required LRT performance characteristics. The chapter also compares the designed motor to the reference motor in terms of performance, convenience, and cost. The performance of the designed motor relative to the LRT requirements and its performance in comparison to the reference motor is then used to validate it.

4.1. SynRM Motor Results Analysis and Discussion

The goal of the SynRM results analysis and discussion is to assess the performance of the motor relative to the requirements. The requirements (main performance indicators) are the direct/target parameters like torque, efficiency, power factor, etc. that affect the traction requirements. Therefore, these are assessed at various operating conditions e.g., speed, current, rotor position, etc. to see their characteristics and assess if they meet the requirements. The analysis is mainly done using graphs and maps plotted from the FEA data, that show the relationships between the target parameters and various operating conditions. However, to assess these performance indicators fully, it is imperative that we also analyze and discuss some of the indirect parameters that affect them. These indirect parameters include flux, inductance, saliency, torque ripple, MTPA locus, power losses, etc. at various operating conditions. The analysis shows their characteristics and how they influence the performance indicators. The results ultimately show how the motor operates at various conditions, its capabilities, and also how to manipulate the operating conditions in order to get optimum performance. The analysis also includes structural analysis of the motor to assess its ability to withstand the stress its subjected to. Therefore, the results analysis and discussion will be based on these aforementioned parameters and how they affect the overall performance of the machine.

4.2. Flux, Inductance, and Saliency

Flux, inductance, and saliency are indirect parameters that affect torque, torque ripple, and power factor. This section analyses and discusses the characteristics of these parameters in the designed

motor relative to supply current, and rotor position in order to assess their behavior. This provides information on the capabilities of the motor and how to manipulate the operating conditions in order to optimize the parameters for optimal motor performance.

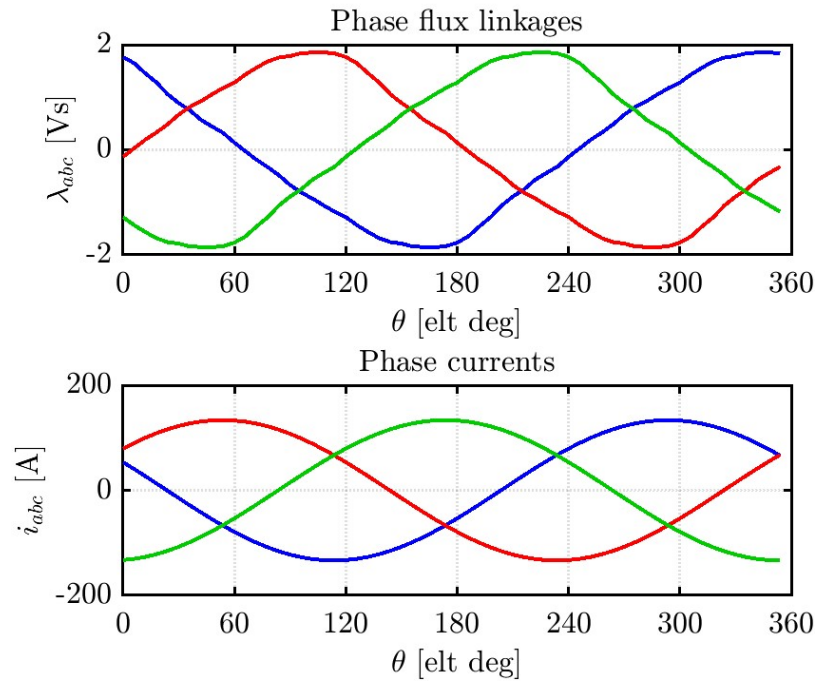


Figure 4-1: 3 phase AC current and Flux vs electrical angle.

Figure 4-1 shows the 3-phase sinusoidal AC current supplied to the stator (ABC stator stationary reference frame) and the corresponding stator flux (λ_{abc}), plotted against the electrical angle. The current results in the flux flowing from the stator to the rotor through the air gap. The graphs of the flux are almost sinusoidal, almost following that of the current. This shows an almost direct relationship between the three-phase currents and the resultant three-phase flux. This shows that there are few harmonic distortions to the flux transmitted to the rotor. Less harmonic distortion results in less torque ripple. This is good as this will ultimately determine the performance of the motor in terms of torque output.

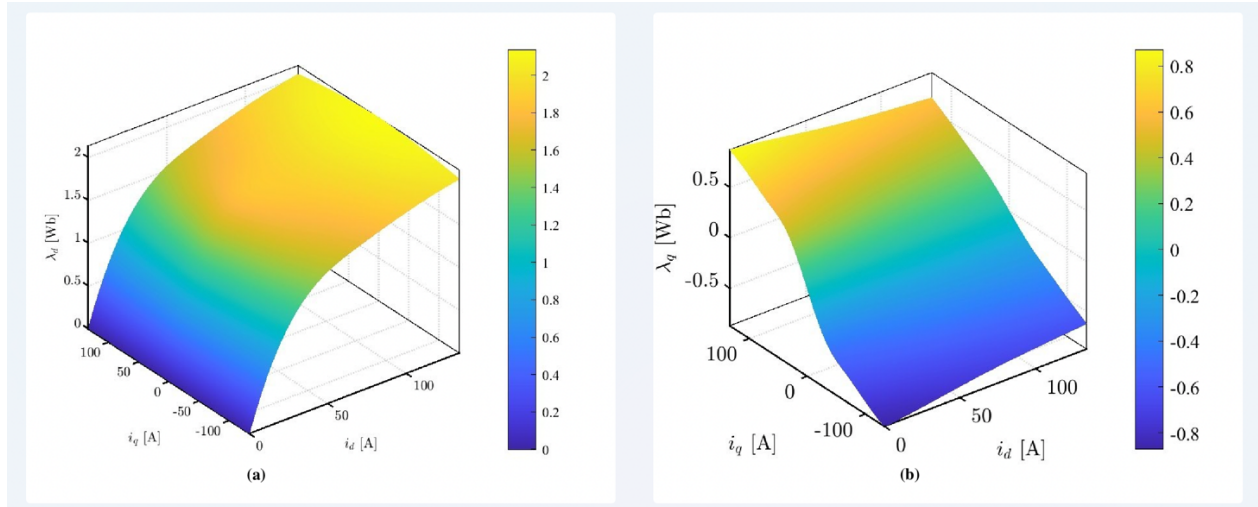


Figure 4-2: a and b showing d and q axis flux nature.

Figure 4-2 shows the relationship between the d-axis and q-axis flux and their d- q currents, respectively. In both cases, the flux increases with an increase in current in its axis until it starts to saturate. Thus, the currents are managed by the MTPA control to almost saturation levels in the q-axis, avoiding saturation in the d-axis in order to maximize the saliency ratio.

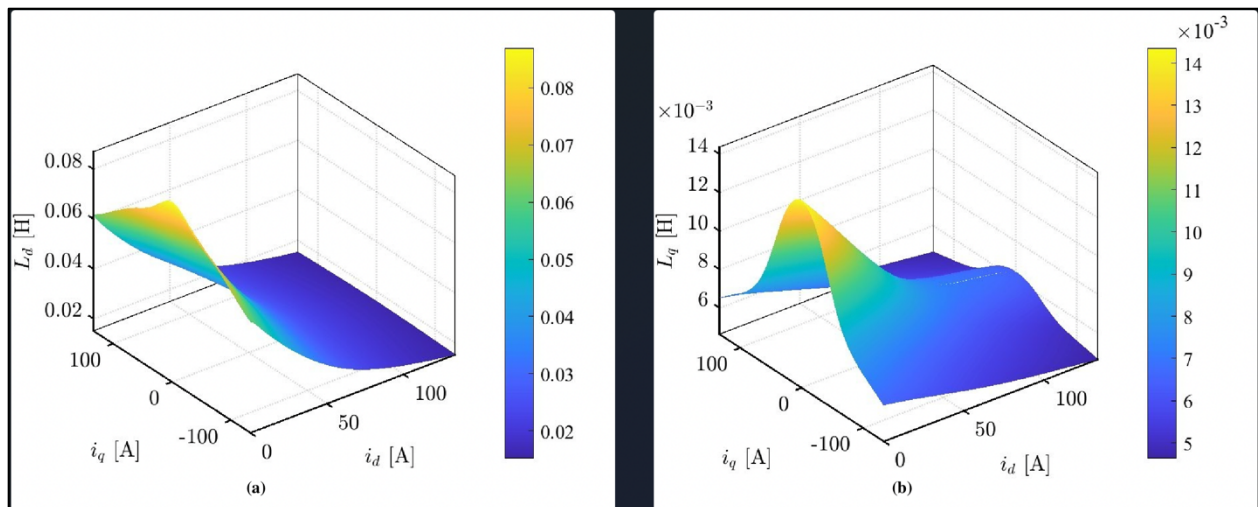


Figure 4-3: a and b showing d and q axis inductance nature

In order to fully comprehend the torque and power factor of the SynRM, it is important to consider the effects of saturation and cross-coupling on its inductances, L_d and L_q . Cross-coupling refers to the magnetic coupling between the d- and q-axis of the machine. The SynRM employs a flux barrier rotor, and its inductances are greatly impacted by saturation and cross-coupling [67], [68].

FEA is used to determine these inductances for SynRM, and Figure 4-3 displays the results. This map shows the characteristics of the SynRM, i.e., the cross-coupling between the d-axis and q-axis and saturation.

The inductances in the d-q axis depend on both the current of the stator and the angle of the current [26]. For a given d-axis current, the d-axis inductance is influenced not only by the d-axis current but also by the q-axis current, which causes a decrease in inductance as the q-axis current increases. This same principle also applies to the q-axis inductance [5], [26], [33]. The impact of cross-coupling on the d-axis inductance is minimal, while it greatly reduces the q-axis inductance, particularly at low q-axis currents. This cross-coupling enhances the saliency ratio and power factor of the machine. However, when the d-axis current is low, the d-axis inductance as well as the q-axis inductance vary significantly with the q-axis current [68].

Another crucial factor to consider is the impact of saturation. As the load increases, the d-axis inductance decreases. Consequently, a higher current angle is necessary to restore the d-axis inductance and the inductances' difference. The q-axis is less affected by saturation due to the significant amount of air in the q-axis flux path [26]. The MTPA manages the two currents to obtain the optimal saliency ratio. The optimal saliency ratio results in optimal torque and power factor.

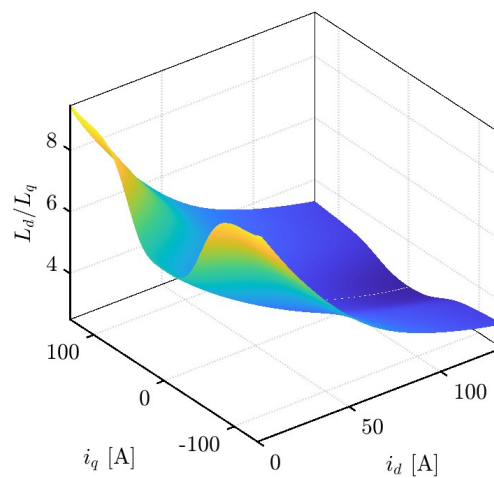


Figure 4-4-4: Saliency ratio vs i_d , i_q currents.

4.2.1. Torque, Power Factor, and Torque Ripple

This section analyses and discusses the torque, torque ripple, and power factor characteristics of the designed motor relative to the supply current, current d-q components, current angle relative to the d-axis, and the rotor position (electrical angle). It also shows the MTPA locus, showing how the d-q currents are optimized for maximum torque at minimum current. The section shows how the operating conditions may be manipulated in order to get optimal performance.

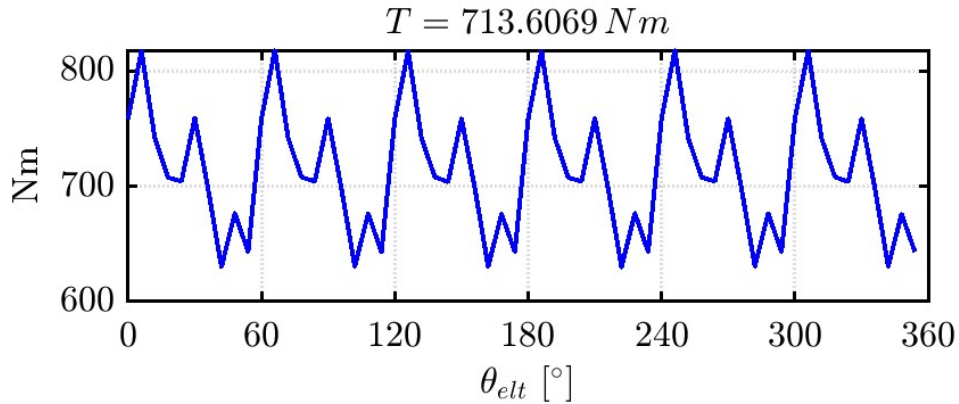


Figure 4-5: Torque and Power Factor vs electrical angle.

Figure 4-5 shows the torque and IPF against the electrical angle waveform of the design, evaluated with FEA, at rated current and MTPA conditions. It shows the variation of torque and IPF with the rotor position (electrical angle). The average torque is 713 Nm, which satisfies the required torque for each motor. The optimization improves the torque and the torque ripple. However, the IPF is slightly less. The torque and torque ripple improvements confirm the advantages of the optimization algorithm [31].

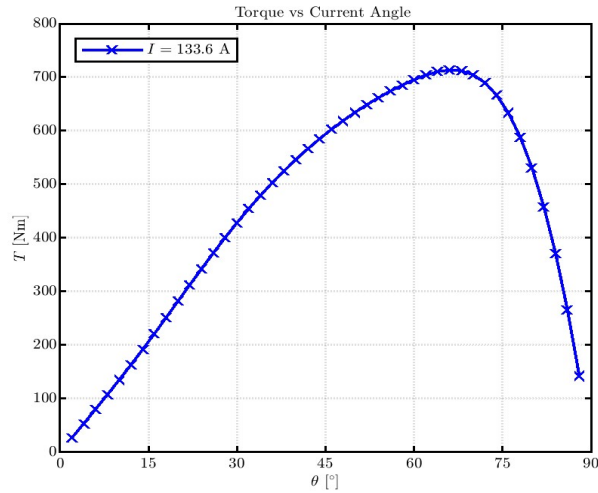


Figure 4-6: Torque vs current angle.

Figure 4-6 shows the torque-current angle profile of the SynRM at maximum current (133A). The current angle (θ) is measured from the d-axis. The torque is maximum when θ is about 70 degrees. The current control technique is required in order to control the machine from zero up to base speed. Therefore, knowledge of the proper current angle is necessary in order to get maximum torque. The angle is not a particularly unique parameter, rather it depends on the current and varies with respect to the magnitude of the phase current as shown in Figure 4-7 which shows that the current along MTPA starts at an angle of about 45 degrees and increases to about 70 degrees at maximum current. This is because, for a given rotor, the saliency ratio is not only sensitive to rotor position, but it also depends on phase current.

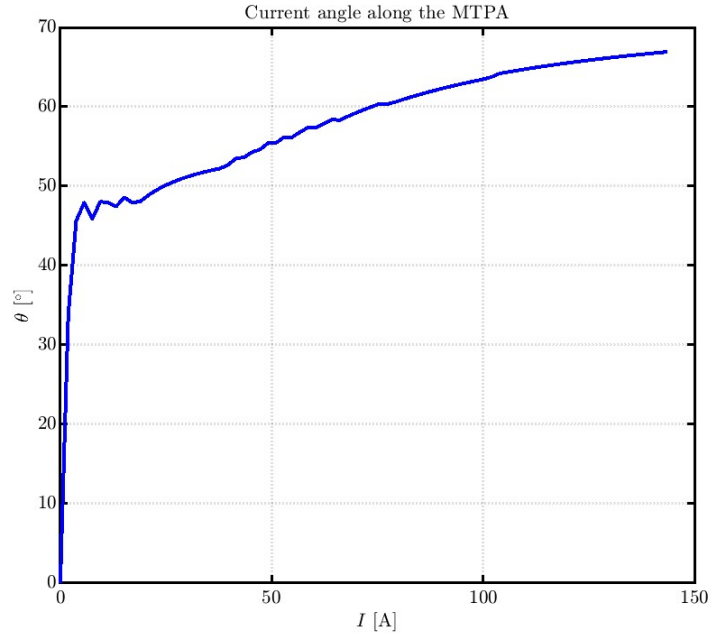


Figure 4-7: Current angle along the MTPA.

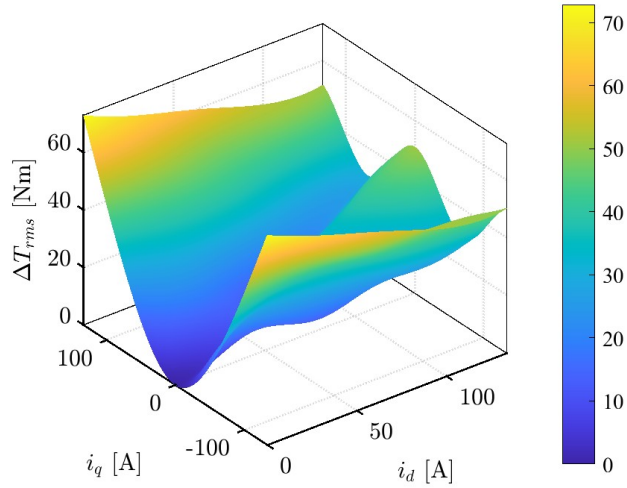


Figure 4-8: Torque ripple vs d-q currents

The maximum torque ripple is about 60 Nm which is almost 10%. The torque ripple increases with q-axis current, reaching its maximum at maximum current. This may be attributed to the increase in torque due to an increase in i_q , as Figure 4-9 shows that increasing torque results in an increase

in torque ripple. The increase of torque ripple with current shows why it was important to optimize at 2 or 3 times the maximum current so as to come up with a solution that is well optimized for torque ripple.

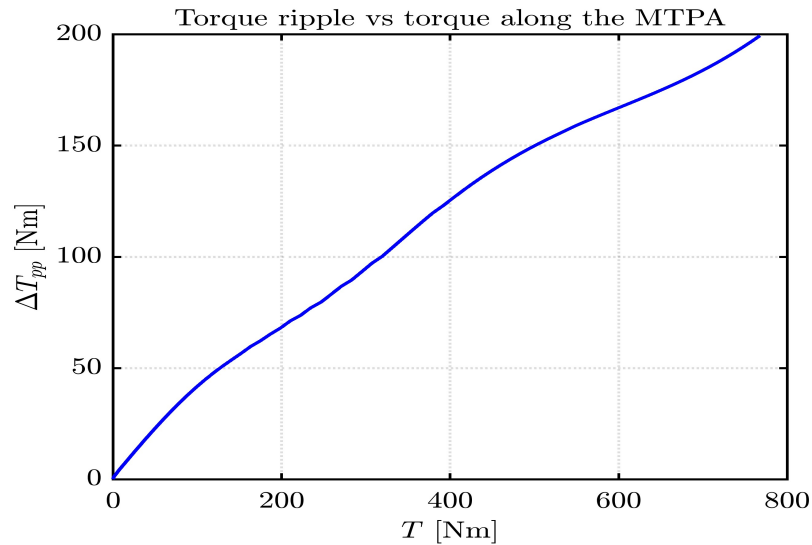


Figure 4-9: Torque ripple vs Torque along the MTPA.

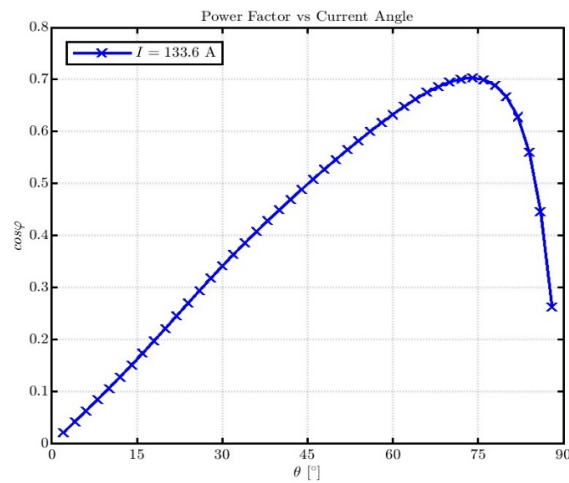


Figure 4-10: Power Factor vs Current Angle.

Figure 4-10 shows that the power factor increases with the current angle until it reaches its maximum at about 75 degrees current angle. This shows that the current angle of the maximum power factor is not necessarily equal to the angle of the current angle of maximum torque.

Therefore, there has to be a compromise between the two depending on the priority of the design.

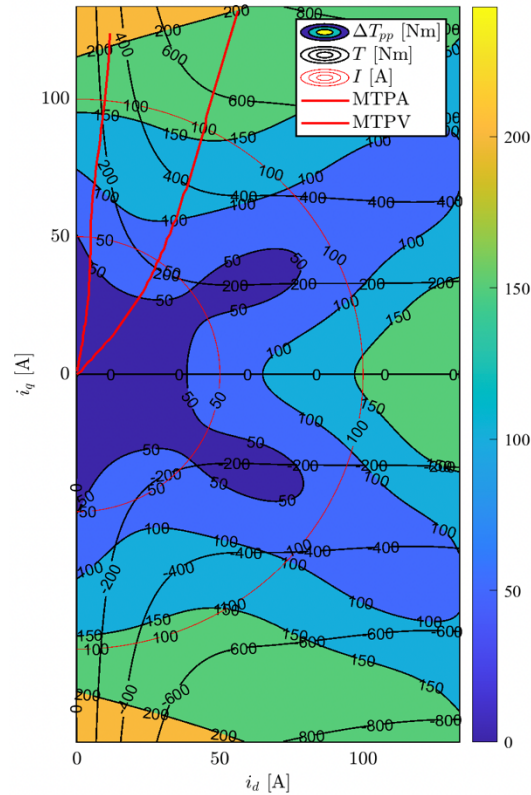


Figure 4-11: Torque, Torque ripple, and Current together with MTPA and MTPV paths.

Figure 4-11 shows the map of the torque and torque ripple relative to the d-q current values. The red lines show the path that gives the MTPA and MTPV control. For optimal MTPA control, the LUT is made up of these values. The graph in Figure 4-12 clearly shows the LUT i_d and i_q combinations for MTPA control. The i_d values are lower than the i_q values as expected for maximum saliency and high performance. The optimized design has a lower ripple at any current load and phase angle. The minimum torque ripple in the i_d - i_q plane follows the expected (MTPA) trajectory of a SynRM machine.

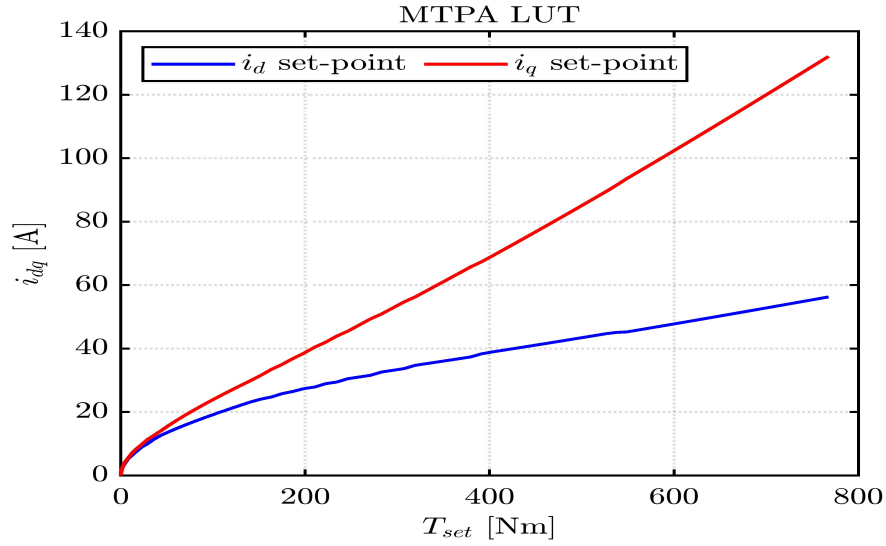


Figure 4-12: MTPA LUT.

4.2.2. Power and Torque/Speed Envelop

The final performance metrics of the motor study are the torque, power curves, as well as efficiency maps. The torque and power graphs are calculated from flux maps and MTPA control laws calculated earlier. To get efficiency, the loss calculations are also incorporated into the calculation [65]. This section analyses and discusses the torque/speed graph, power/speed graph, and efficiency map of the designed motor to assess its overall performance. It also discusses the power losses which are used to calculate the efficiency map.

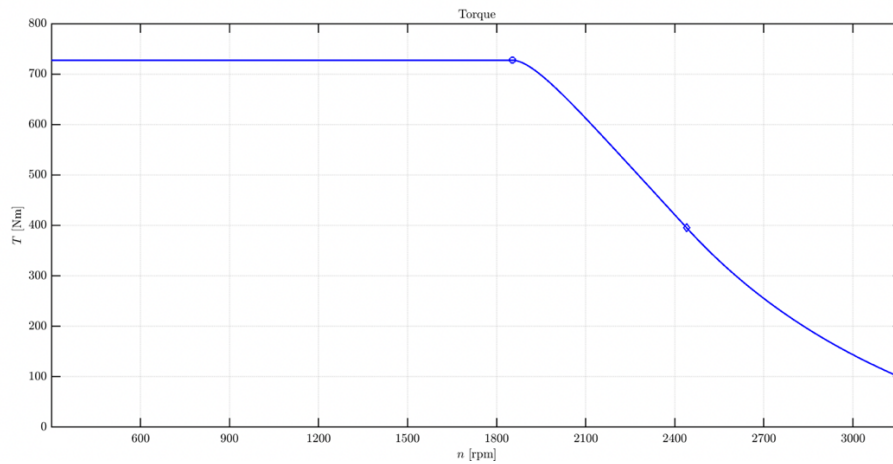


Figure 4-13: Torque-Speed Graph of the SynRM motor.

Figure 4-13 shows that the motor has high starting torque and can maintain it until it passes its rated speed of 1800 rpm. The average output torque is 713 Nm. After the rated speed the torque begins to fall gradually with an increase in speed up to the maximum speed. The torque/speed envelope matches the requirements for each traction motor in the AALRT traction system.

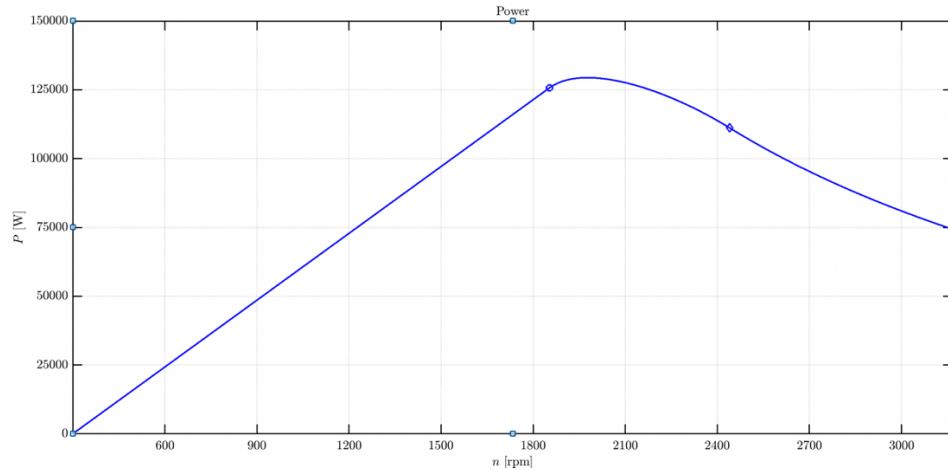


Figure 4-14: Power-Speed Graph of the SynRM motor.

As shown in Figure 4-14, power increases up to a peak slightly above the rated speed. It then begins to decline slowly as the speed increases towards maximum speed. The use of magnets in the barriers can help maintain maximum power at speeds above the rated speed [65]. The power profile is capable of meeting the AALRT requirements.

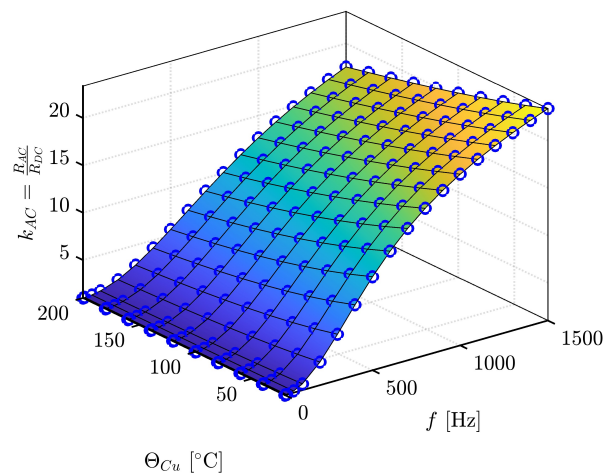


Figure 4-15: Copper losses vs temperature and frequency map.

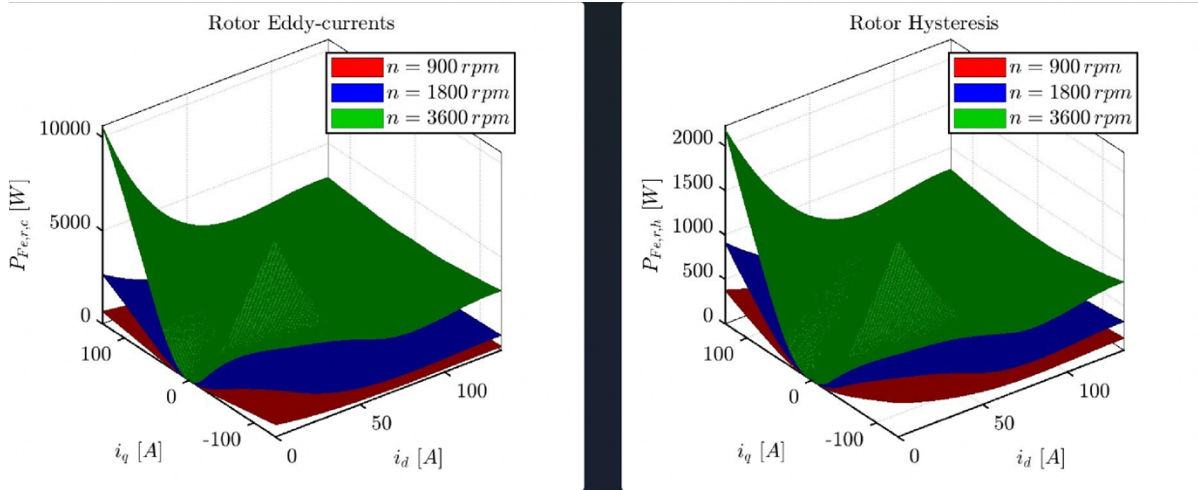


Figure 4-16: Rotor iron power losses at different speeds vs i_d and i_q .

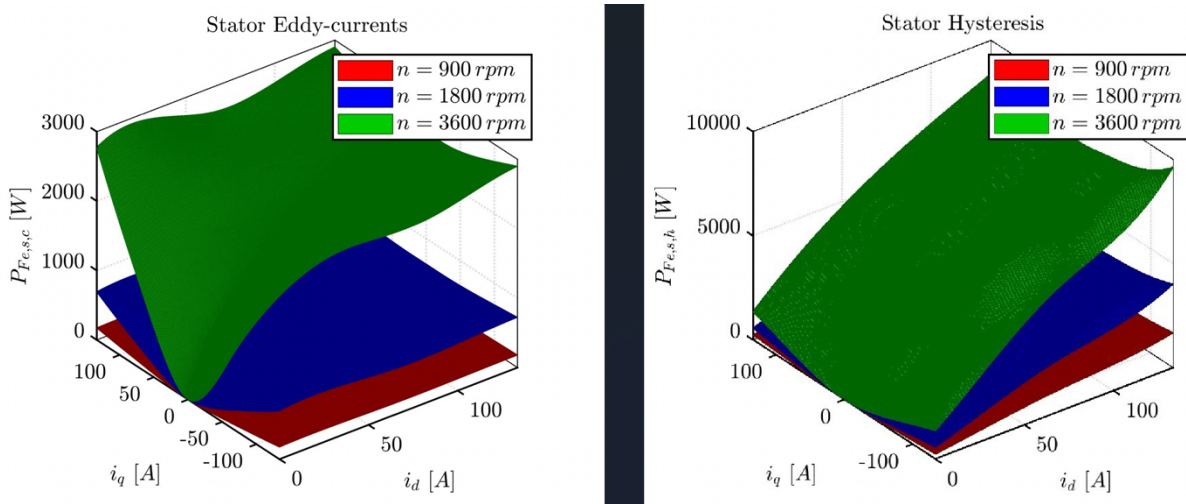


Figure 4-17: Stator iron power losses at different speeds vs i_d and i_q .

The iron losses of the machine are mapped over the d-q current domain at a single value of speed. Speed variation is then accounted for using the Steinmetz loss model of the electrical steel [66]. The iron loss maps of the motor are shown in Figures 4-15 to 4-17. Rotor excursion of 180° is covered by the FEA simulation of each (i_d, i_q) point and then uses the symmetry properties of the waveforms to get information about the whole electrical period. Iron loss computation contemplates both major and minor hysteresis loops together with the DC bias effect for the rotor.

Below rated speed the iron losses are low, however they increase and become significant at higher speeds. Details on the flux and iron loss maps may be found in [66], [69].

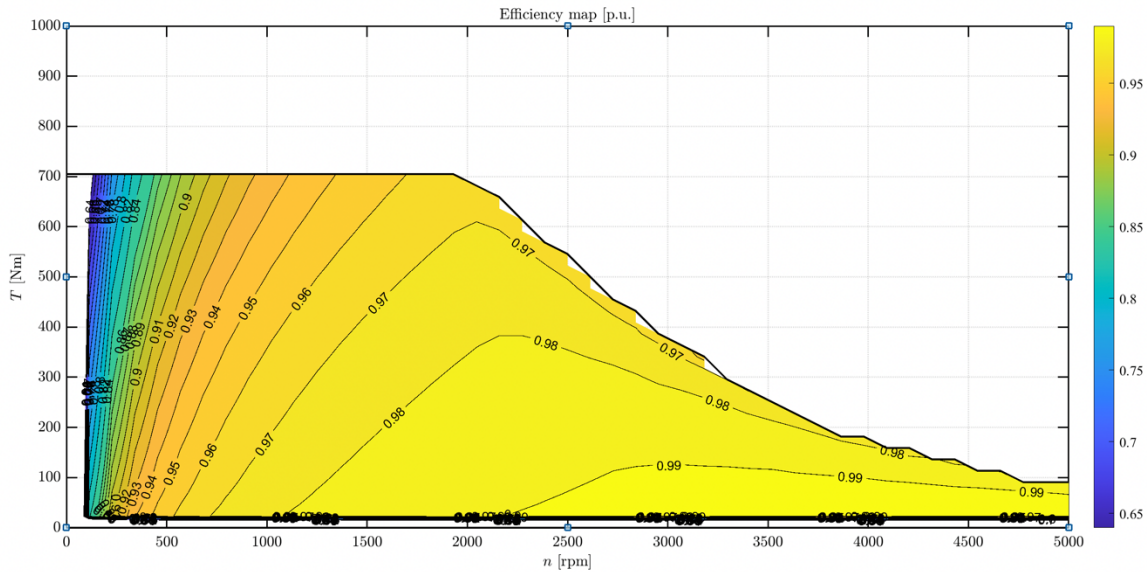


Figure 4-18: Efficiency map of the SynRM machine.

The evaluation of the efficiency map of the motor is done using flux and loss maps. When the flux and loss maps are scaled, each speed and torque combination's optimal working point is found taking into consideration the MTPA and MTPV laws and also the current and voltage limits. Figure 4-19 shows the efficiency map of the machine. The map refers to fixed copper temperature values. The designed SynRM motor has a rated efficiency of 97.0% (rated speed and load), thus it is above the IE4 limit according to the standard IEC 60034-30-1 (where the minimum requirement is 96% for the given motor) [34], [53]. Its efficiency is slightly higher than the IM (92%).

4.2.3. Structural Analysis

Centrifugal stress in the motor structure at maximum speed is evaluated by SyR-e using simplified structural equations for the design. The rotor experiences most of its stress in the rotor segments and the ribs. However, the stresses are little compared to the yield stress hence they are able to withstand them and not experience much deformation. The yield stress of the material is 295 MPA which is way above the stress the rotor is experiencing as shown in Figure 4-19.

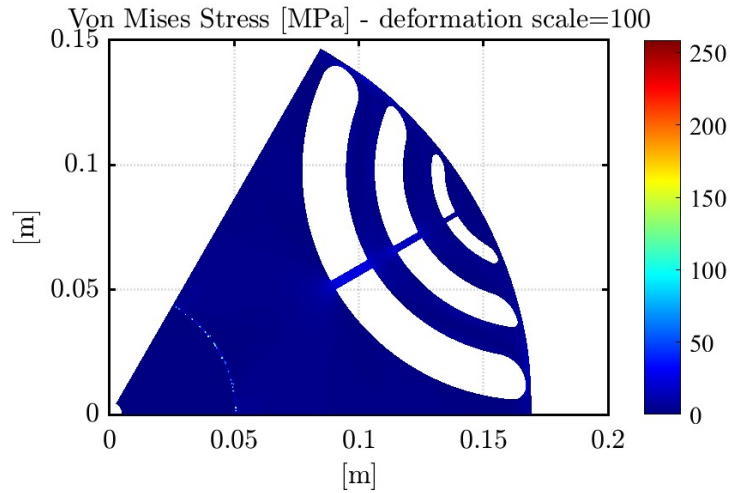


Figure 4-19: Von Mises stresses on the rotor structure.

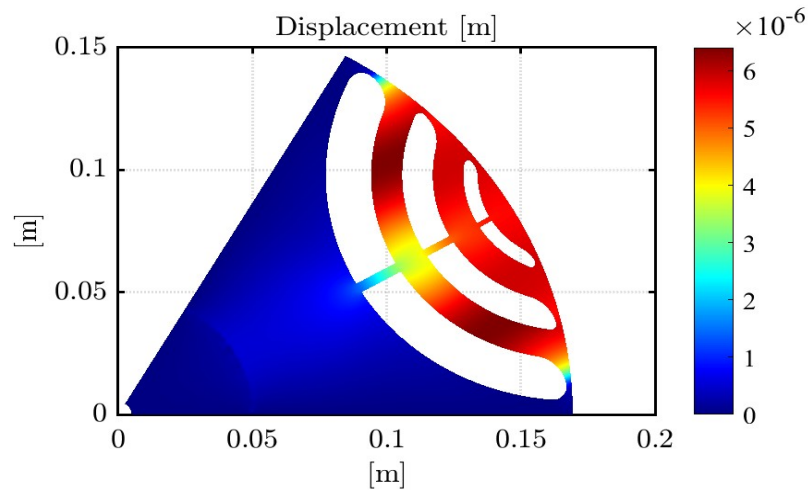


Figure 4-20: Structural displacement analysis.

4.3. Comparison of the Designed and Reference Machines

The designed motor is then compared with the AALRT reference induction motor in terms of performance, convenience, and cost. Performance refers to parameters like torque output and efficiency; convenience refers to parameters such as size and weight, and lastly, cost refers to the general cost of the material used to make the motors. Table 4-1 shows the parameter values for the two motors. In terms of performance, the designed motor can achieve the required torque for

AALRT traction, and its torque output is 4% higher than the reference motor. In terms of power factor, the designed motor has a slightly lower power factor than the reference machine. Low power factor is a problem that plagues SynRM motors. This can be attributed to the rotor needing a high level of magnetization, leading to an increase in reactive power. However, the power factor value is significant enough for the required application. In terms of efficiency, the motor has a 5% higher efficiency than the reference motor. The efficiency also surpasses the 96% required IEC [70]. Thus, the designed SyR motor is environmentally friendly, effective, and efficient.

In terms of convenience, the designed motor draws a lower current than the reference motor. This results in lower power losses, lower heat emission, and use of smaller cables amongst other advantages that come with less current. The motor can produce more torque per unit current, which is convenient regarding cable sizes and cooling systems. It has a smaller volume and more torque per unit volume, which are convenient in terms of the available space for the motor in the vehicle. It has less mass and more torque per unit mass, which is convenient in terms of the load carried by the vehicle. Finally, the motor is less expensive in terms of material cost. Thus, it is cheaper to produce than the reference motor. The cost comparison with IM is shown in Table 4-2 and Table 4-3. Therefore, using SynRM has several benefits and is worthy of consideration. However, there is also a need to improve several factors, such as its power factor and design standardization.

Table 4-1: Comparison of the reference motor and designed motor parameters.

Parameters of Motors	Reference	Designed
Torque (Nm)	689	713
Power Factor	0.74	0.67
Efficiency	92.4%	97%
Current (A)	215	135
Torque/Current (Nm/A)	5.14	3.33
Torque/Volume (Nm/dm ³)	8.285	22.613
Stator Outer Diameter(mm)	442	468
Stack Length (mm)	540	201
Stack Volume (dm ³)	83.1	31.5
Mass (kg)	443	238

Number of poles	6	6
Cost (Birr)	66337.83	38055.53

Designed SynRM and reference IM cost calculation.

Table 4-2: Cost of the SynRM.

Material	Material (Weight/Unit)	Material Cost/unit	Total Cost (Birr)
Silicon Steel	205 kg	109.20 Birr /kg [71]	22385.61
Copper	35 kg	447.71 Birr/kg [72]	15669.92
Total			38055.53

To calculate the estimated cost of induction motors, several factors need to be considered, such as machine geometry, material cost (including scrap material), staff salary, and operational cost of equipment. A comprehensive estimation of the motor can be derived by taking into account these factors. However, this study only considered the material cost for the sake of simplicity.

Table 4-3: Cost of the IM.

Material	Material (Weight/Unit)	Material Cost/unit	Total Cost (Birr)
Silicon Steel	390 kg	109.20 Birr /kg	42587.25
Copper	53kg[73], [74]	447.71 Birr/kg	23750.58
Total			66337.83

4.4. Drive Simulation Results Analysis and Discussion

The drive results analysis and discussion aim to assess the control's performance relative to expectations. The main performance indicator is the ability of the controller to get the motor to the reference state. Therefore, to assess this the reference value is varied, and then the actual values of the motor parameters are recorded and plotted. The results of the simulations are shown in Figures 4-22 and 4-23. The load is changed from zero to 700 NM and then back to the negative load condition, while the reference speed changes from zero and accelerates to 1000 rpm.

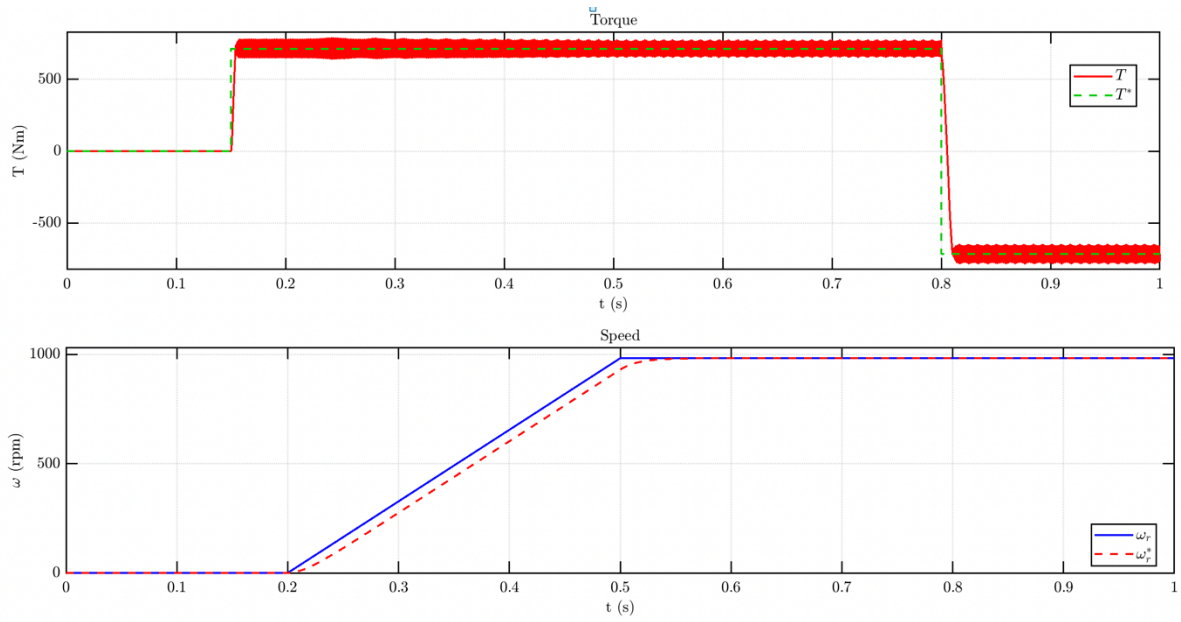


Figure 4-21: Torque and Speed plots.

Figure 4-22 has two subplots for torque and speed. The first subplot shows the reference torque T^* , the actual motor torque T . There is no much difference noticed when the torque plots are compared. However, there is some torque ripple. The second plot shows the reference speed sequence performed in the simulation and the observed speed. The speed imposed reaches a maximum value of 1000 rpm. The observed speed follows the reference.

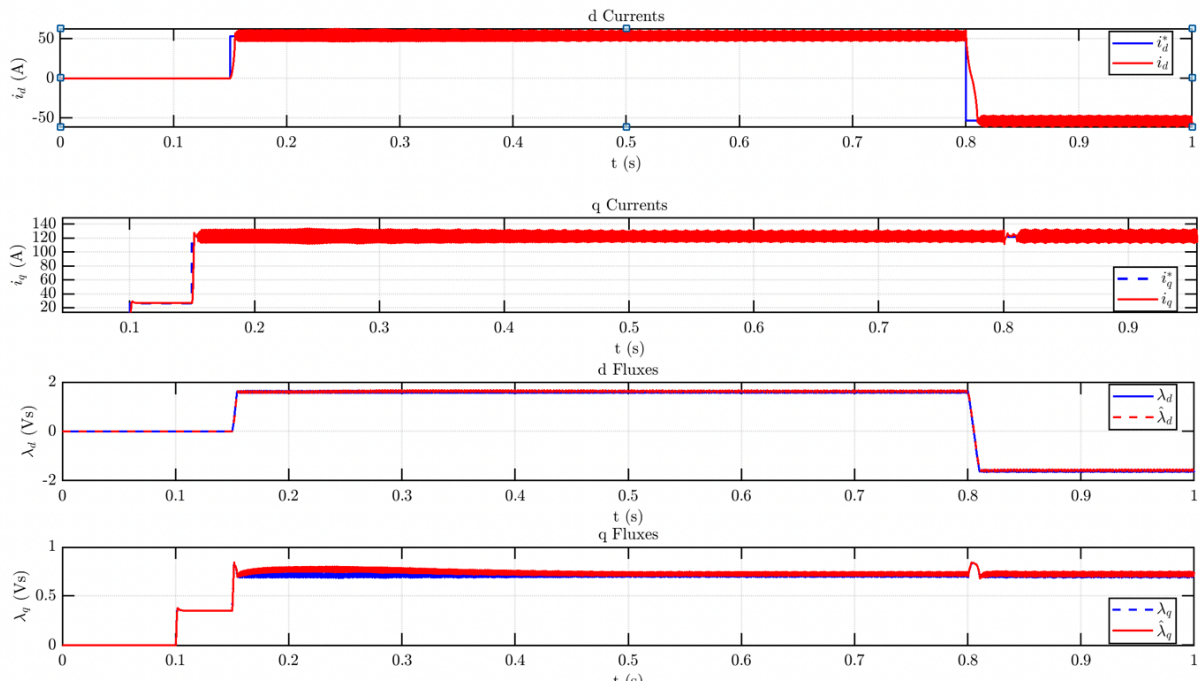


Figure 4-22: Currents and Flux plots.

Figure 4-23 shows the plots of the reference and measured the d and q-axis currents and also the d and q-axis fluxes. It shows that the average values are approximately the same, but there are some ripples for the measured values. Not many variations are seen in the graphs showing that the control is working well. Therefore, the control can control the motor stably and dynamically and may be implemented for LRT traction.

5. Conclusion and Recommendations

5.1. Conclusion

The thesis research was performed to design an alternative Synchronous Reluctance Motor for Light Rail Transit. The SynRM has higher efficiency than the IM due to the absence of rotor losses, and it is less expensive than PMSMs because it has no permanent magnets in the rotor like PMSMs. Therefore, the alternative would help improve the efficiency relative to IMs and reduce the cost of the motor in comparison to PMSMs. The research was performed to assess the requirements of LRT systems. The Addis Ababa Light rail was selected as a reference system; thus, the research design was modeled for the AALRT. From the research, the torque-speed envelope of the system was obtained, which showed that each wagon on a vehicle required a maximum of 1240 Nm from two motors at a maximum power rating of 160 kW. To achieve this system uses two 130kW AC Induction motors with a rated torque of 689 Nm. Therefore, this induction motor was used as a reference model, and some of the technical parameters of the induction motor were used as the target design parameters (initial data). The research was then performed on the characteristics of the SynRM to design for the LRT. A design model was obtained using analytical methods coupled with automated optimization. The design was evaluated using FEA analysis. The design model had a 4% higher average torque output of 713 NM, and 5% better efficiency than the reference IM. It also had 50% less material cost, 40% less weight, and less volume than the IM. However, it had a poor power factor compared to the IM. A drive was then generated and simulated for the motor using SyR-e software. The drive has some ripples, however, it exhibited dynamic and stable control over time. Therefore, the controller is capable of stable and dynamic control of the motor. The results showed that the designed motor meets the requirements for LRT traction and it has several advantages over the reference IM. Therefore, the motor and drive are suitable for LRT applications and they are worthy of consideration in the future.

5.2. Recommendations

To improve the design and implementation of the synchronous reluctance motor and drive, a lot can be done. Improvements may be made in terms of optimal design strategies, machine analysis, control improvement and prototyping. Optimal design strategies may be improved by adopting

other optimization methods, like the use of optimal barrier shapes, asymmetry in the barriers, sleeves to maintain the rotor structure, and the inclusion of permanent magnets in the rotor. All these might help to improve the performance of the motor. A lot more analysis may be performed, including 3D analysis, harmonics analysis, thermal analysis, and mechanical analysis. The control may be improved by introducing strategies like sensorless control. A physical working model was not made in this study. Therefore, prototyping of the motor can be done to validate the simulated results. Good performance capability and removal of rare earth magnets and conductors from the rotor are important for environmental, operational, and ethical reasons. Thus, more efforts toward the implementation of SynRMs are encouraged.

6. References

- [1] S. M. de Pancorbo, G. Ugalde, J. Poza, and A. Egea, “Comparative study between induction motor and Synchronous Reluctance Motor for electrical railway traction applications,” in *2015 5th International Electric Drives Production Conference (EDPC)*, Sep. 2015, pp. 1–5. doi: 10.1109/EDPC.2015.7323219.
- [2] M. Murataliyev, M. Degano, M. Di Nardo, N. Bianchi, and C. Gerada, “Synchronous Reluctance Machines: A Comprehensive Review and Technology Comparison,” *Proc. IEEE*, vol. 110, no. 3, pp. 382–399, Mar. 2022, doi: 10.1109/JPROC.2022.3145662.
- [3] S. Nategh *et al.*, “A Review on Different Aspects of Traction Motor Design for Railway Applications,” *IEEE Transactions on Industry Applications*, vol. 56, no. 3, pp. 2148–2157, May 2020, doi: 10.1109/TIA.2020.2968414.
- [4] B. Ban, S. Stipetić, and M. Klanac, “Synchronous Reluctance Machines: Theory, Design and the Potential Use in Traction Applications,” in *2019 International Conference on Electrical Drives & Power Electronics (EDPE)*, Sep. 2019, pp. 177–188. doi: 10.1109/EDPE.2019.8883905.
- [5] P. Ragazzo, S. Ferrari, N. Riviere, M. Popescu, and G. Pellegrino, “Efficient Multiphysics Design Workflow of Synchronous Reluctance Motors,” in *2020 International Conference on Electrical Machines (ICEM)*, Gothenburg, Sweden: IEEE, Aug. 2020, pp. 2507–2513. doi: 10.1109/ICEM49940.2020.9270670.
- [6] S. Taghavi, “Design of Synchronous Reluctance Machines for Automotive Applications,” p. 195.
- [7] A. Gunnarson and L. Johansson, “Synchronous Reluctance Motor and Drive System Design for Handheld Applications,” 2022, Accessed: Jul. 10, 2023. [Online]. Available: <https://hdl.handle.net/20.500.12380/304658>
- [8] H. Cai, B. Guan, L. Xu, and W. Choi, “Optimal design of synchronous reluctance machine : A feasible solution to eliminating rare earth permanent magnets for vehicle traction applications,” *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 33, no. 5, pp. 1569–1586, Jan. 2014, doi: 10.1108/COMPEL-09-2013-0287.
- [9] E. Kuci *et al.*, “Design Optimization of Synchronous Reluctance Machines for Railway Traction Application Including Assembly Process Constraints,” in *2020 International*

- Conference on Electrical Machines (ICEM)*, Gothenburg, Sweden: IEEE, Aug. 2020, pp. 117–123. doi: 10.1109/ICEM49940.2020.9270859.
- [10] S. Ferrari, P. Ragazzo, G. Dilevrano, and G. Pellegrino, “Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps,” in *2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, Modena, Italy: IEEE, Apr. 2021, pp. 76–81. doi: 10.1109/WEMDCD51469.2021.9425678.
- [11] S. Ferrari and G. Pellegrino, “FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines,” *IEEE Trans. on Ind. Applicat.*, vol. 56, no. 1, pp. 256–266, Jan. 2020, doi: 10.1109/TIA.2019.2954797.
- [12] H. Heidari *et al.*, “A Review of Synchronous Reluctance Motor-Drive Advancements,” *Sustainability*, vol. 13, no. 2, Art. no. 2, Jan. 2021, doi: 10.3390/su13020729.
- [13] Y. Wang, N. Bianchi, and R. Qu, “Comparative Study of Non-Rare-Earth and Rare-Earth PM Motors for EV Applications,” *Energies*, vol. 15, no. 8, Art. no. 8, Jan. 2022, doi: 10.3390/en15082711.
- [14] J. Gieras and N. Bianchi, “Electric Motors for Light Traction,” *Epe Journal*, vol. 14, pp. 12–23, Feb. 2004, doi: 10.1080/09398368.2004.11463549.
- [15] “Spec no. 141 Nov. 2018.pdf.”
- [16] S. Paul, P.-W. Han, J. Chang, Y.-D. Chun, and J.-G. Lee, “State-of-the-art review of railway traction motors for distributed traction considering South Korean high-speed railway,” *Energy Reports*, vol. 8, pp. 14623–14642, Nov. 2022, doi: 10.1016/j.egyr.2022.10.411.
- [17] J. Pyrhonen, T. Jokinen, and V. Hrabovcová, *Design of rotating electrical machines*. Chichester, West Sussex, United Kingdom ; Hoboken, NJ: Wiley, 2008.
- [18] H.-S. Han and D.-S. Kim, *Magnetic Levitation*, vol. 13. in Springer Tracts on Transportation and Traffic, vol. 13. Dordrecht: Springer Netherlands, 2016. doi: 10.1007/978-94-017-7524-3.
- [19] A. T. Woldegiorgis, X. Ge, S. Li, and M. Hassan, “Extended Sliding Mode Disturbance Observer-Based Sensorless Control of IPMSM for Medium and High-Speed Range Considering Railway Application,” *IEEE Access*, vol. 7, pp. 175302–175312, 2019, doi: 10.1109/ACCESS.2019.2957274.
- [20] A. Patel, “Design and performance of high efficiency Synchronous reluctance motor for an industrial application.”

- [21] P. Ragazzo, G. Dilevrano, S. Ferrari, and G. Pellegrino, "Design of IPM Synchronous Machines Using Fast-FEA Corrected Design Equations," in *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain: IEEE, Sep. 2022, pp. 1–7. doi: 10.1109/ICEM51905.2022.9910753.
- [22] Max, "What is Switched Reluctance Motor: Construction and Operation | Linqip," Mar. 01, 2021. <https://www.linqip.com/blog/switched-reluctance-motor/> (accessed Nov. 17, 2022).
- [23] "IE5 synchronous -reluctance motors | ABB," *News*, Jul. 22, 2021. <https://new.abb.com/news/detail/80775/ie5-synchronous-reluctance-motors> (accessed Aug. 18, 2023).
- [24] S. Ferrari, P. Ragazzo, G. Dilevrano, and G. Pellegrino, "Determination of the Symmetric Short-Circuit Currents of Synchronous Permanent Magnet Machines Using Magnetostatic Flux Maps," in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada: IEEE, Oct. 2021, pp. 3697–3704. doi: 10.1109/ECCE47101.2021.9595806.
- [25] "Design, Analysis and Testing Procedures for Synchronous Reluctance and Permanent Magnet Machines." <https://iris.polito.it/handle/11583/2836788> (accessed Jul. 10, 2023).
- [26] R. R. Moghaddam, "Synchronous Reluctance Machine (SynRM) Design," p. 90.
- [27] "SynRM | A new giant in the electrical world - YouTube." <https://www.youtube.com/watch?v=vvw6k4ppUZU&t=4s> (accessed Sep. 05, 2023).
- [28] F. Cupertino, G. Pellegrino, and C. Gerada, "Design of Synchronous Reluctance Motors With Multiobjective Optimization Algorithms," *IEEE Trans. on Ind. Applicat.*, vol. 50, no. 6, pp. 3617–3627, Nov. 2014, doi: 10.1109/TIA.2014.2312540.
- [29] A. Ozdil and Y. Uzun, "Design and Analysis of a Rotor for a 22 kW Transversally Laminated Anisotropic Synchronous Reluctance Motor," *Elektronika ir Elektrotechnika*, vol. 27, Sep. 2021, doi: 10.5755/j02.eie.29046.
- [30] G. Pellegrino, F. Cupertino, and C. Gerada, "Automatic Design of Synchronous Reluctance Motors Focusing on Barrier Shape Optimization," *IEEE Trans. on Ind. Applicat.*, vol. 51, no. 2, pp. 1465–1474, Mar. 2015, doi: 10.1109/TIA.2014.2345953.
- [31] R. Leuzzi, P. Cagnetta, S. Ferrari, P. Pescetto, G. Pellegrino, and F. Cupertino, "Transient Overload Characteristics of PM-Assisted Synchronous Reluctance Machines, Including

- Sensorless Control Feasibility,” *IEEE Trans. on Ind. Applicat.*, vol. 55, no. 3, pp. 2637–2648, May 2019, doi: 10.1109/TIA.2019.2897969.
- [32] M. Gamba, “Design of non conventional Synchronous Reluctance machine,” 2017, doi: 10.6092/POLITO/PORTO/2669965.
- [33] R. Rajabi Moghaddam, “Synchronous Reluctance Machine (SynRM) in Variable Speed Drives (VSD) Applications,” 2011, Accessed: Jul. 10, 2023. [Online]. Available: <https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-33804>
- [34] S. Ferrari, G. Pellegrino, M. J. Mohamed Zubair, and I. Husain, “Computationally Efficient Design Procedure for Single-Layer IPM Machines,” in *2019 IEEE International Electric Machines & Drives Conference (IEMDC)*, San Diego, CA, USA: IEEE, May 2019, pp. 1288–1295. doi: 10.1109/IEMDC.2019.8785394.
- [35] C. Lu, S. Ferrari, G. Pellegrino, C. Bianchini, and M. Davoli, “Parametric design method for SPM machines including rounded PM shape,” in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH: IEEE, Oct. 2017, pp. 4309–4315. doi: 10.1109/ECCE.2017.8096743.
- [36] S. Ferrari, E. Armando, and G. Pellegrino, “Torque Ripple Minimization of PM-assisted Synchronous Reluctance Machines via Asymmetric Rotor Poles,” in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, Baltimore, MD, USA: IEEE, Sep. 2019, pp. 4895–4902. doi: 10.1109/ECCE.2019.8912470.
- [37] R. Leuzzi, P. Cagnetta, F. Cupertino, S. Ferrari, and G. Pellegrino, “Performance assessment of ferrite- and neodymiumassisted synchronous reluctance machines,” in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH: IEEE, Oct. 2017, pp. 3958–3965. doi: 10.1109/ECCE.2017.8096693.
- [38] T. Mohanarajah, “Analysis, design optimisation and experimental performance of synchronous reluctance and permanent magnet assisted synchronous reluctance machines,” 2019, Accessed: Sep. 04, 2023. [Online]. Available: <https://researchdirect.westernsydney.edu.au/islandora/object/uws%3A56902/>
- [39] B. Wu and M. Narimani, *High-Power Converters and AC Drives*. John Wiley & Sons, 2017.
- [40] S. Taghavi, “Design of Synchronous Reluctance Machines for Automotive Applications”.

- [41] S. Taghavi and P. Pillay, “A Sizing Methodology of the Synchronous Reluctance Motor for Traction Applications,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 2, pp. 329–340, Jun. 2014, doi: 10.1109/JESTPE.2014.2299235.
- [42] H. Kim *et al.*, “A Study on the Rotor Design of Line Start Synchronous Reluctance Motor for IE4 Efficiency and Improving Power Factor,” *Energies*, vol. 13, no. 21, Art. no. 21, Jan. 2020, doi: 10.3390/en13215774.
- [43] S. Tahi, R. Ibtouen, and M. Bounekhla, “Design Optimization of Two Synchronous Reluctance Machine Structures with Maximized Torque and Power Factor,” *Progress In Electromagnetics Research B*, vol. 35, pp. 369–387, Jan. 2011, doi: 10.2528/PIERB11091101.
- [44] S. Ferrari, G. Pellegrino, M. Davoli, and C. Bianchini, “Reduction of Torque Ripple in Synchronous Reluctance Machines through Flux Barrier Shift,” in *2018 XIII International Conference on Electrical Machines (ICEM)*, Alexandroupoli: IEEE, Sep. 2018, pp. 2290–2296. doi: 10.1109/ICELMACH.2018.8507223.
- [45] M. Gamba, G. Pellegrino, and F. Cupertino, “Optimal number of rotor parameters for the automatic design of Synchronous Reluctance machines,” in *2014 International Conference on Electrical Machines (ICEM)*, Berlin, Germany: IEEE, Sep. 2014, pp. 1334–1340. doi: 10.1109/ICELMACH.2014.6960355.
- [46] S. Ferrari, G. Dilevrano, P. Ragazzo, and G. Pellegrino, “The dq-theta Flux Map Model of Synchronous Machines,” in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada: IEEE, Oct. 2021, pp. 3716–3723. doi: 10.1109/ECCE47101.2021.9595187.
- [47] G. Pellegrino and F. Cupertino, “FEA-based multi-objective optimization of IPM motor design including rotor losses,” in *2010 IEEE Energy Conversion Congress and Exposition*, Atlanta, GA: IEEE, Sep. 2010, pp. 3659–3666. doi: 10.1109/ECCE.2010.5618310.
- [48] F. Cupertino, G. M. Pellegrino, E. Armando, and C. Gerada, “A SyR and IPM machine design methodology assisted by optimization algorithms,” in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, NC, USA: IEEE, Sep. 2012, pp. 3686–3691. doi: 10.1109/ECCE.2012.6342478.

- [49] F. Wang, Z. Zhang, X. Mei, J. Rodríguez, and R. Kennel, “Advanced Control Strategies of Induction Machine: Field Oriented Control, Direct Torque Control and Model Predictive Control,” *Energies*, vol. 11, no. 1, Art. no. 1, Jan. 2018, doi: 10.3390/en11010120.
- [50] B. Akin and M. Bhardwaj, “Sensored Field Oriented Control of 3-Phase Induction Motors”.
- [51] R. H. Kumar, A. Iqbal, and N. C. Lenin, “Review of recent advancements of direct torque control in induction motor drives – a decade of progress,” *IET Power Electronics*, vol. 11, no. 1, pp. 1–15, 2018, doi: 10.1049/iet-pel.2017.0252.
- [52] K. S. Holkar and L. M. Waghmare, “An Overview of Model Predictive Control,” *International Journal of Control and Automation*, vol. 3, no. 4, 2010.
- [53] D. Brunelli, G. Pellegrino, A. Varatharajan, and S. Ferrari, “syreDrive: A New Add-on to the Motor Design Framework for Automated Sensorless Control Simulation”.
- [54] A. Varatharajan, D. Brunelli, S. Ferrari, P. Pescetto, and G. Pellegrino, “syreDrive: Automated Sensorless Control Code Generation for Synchronous Reluctance Motor Drives,” in *2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, Modena, Italy: IEEE, Apr. 2021, pp. 192–197. doi: 10.1109/WEMDCD51469.2021.9425649.
- [55] A. T. Woldegiorgis, X. Ge, H. Wang, and M. Hassan, “A New Frequency Adaptive Second-Order Disturbance Observer for Sensorless Vector Control of Interior Permanent Magnet Synchronous Motor,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 12, pp. 11847–11857, Dec. 2021, doi: 10.1109/TIE.2020.3047065.
- [56] G. Pellegrino, E. Armando, and P. Guglielmi, “Field Oriented Control of IPM Drives for Flux Weakening Applications,” *EPE Journal*, vol. 20, no. 1, pp. 50–57, Jan. 2010, doi: 10.1080/09398368.2010.11463748.
- [57] S. A. Assefa, A. B. Kebede, and D. Legese, “Harmonic analysis of traction power supply system: case study of Addis Ababa light rail transit,” *IET Electrical Systems in Transportation*, vol. 11, no. 4, pp. 391–404, 2021, doi: 10.1049/els2.12019.
- [58] “Maintenance Manual.pdf.”
- [59] K. Yared, “Development of Adaptive Control for Railway Vehicles Braking System: Case study for AA-LRT,” Thesis, Addis Ababa University, 2017. Accessed: Jul. 10, 2023. [Online]. Available: <http://etd.aau.edu.et/handle/123456789/15703>

- [60] M. Odette, "Study of Multiphase Induction Motor Applicability in DC Electrified Conventional Railway," Thesis, Addis Ababa University, 2022. Accessed: Jul. 10, 2023. [Online]. Available: <http://etd.aau.edu.et/handle/123456789/32191>
- [61] "Design of stator winding - Design of Synchronous Machines," *BrainKart*. https://www.brainkart.com/article/Design-of-stator-winding---Design-of-Synchronous-Machines_12328/ (accessed Sep. 01, 2023).
- [62] S. Ferrari and G. Pellegrino, "FEA-Augmented Design Equations for Synchronous Reluctance Machines," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, Portland, OR, USA: IEEE, Sep. 2018, pp. 5395–5402. doi: 10.1109/ECCE.2018.8557451.
- [63] A. Mlot, M. Korkosz, and M. Lukaniszyn, "Iron loss and eddy-current loss analysis in a low-power BLDC motor with magnet segmentation," *Archives of Electrical Engineering*, vol. 61, Mar. 2012, doi: 10.2478/v10171-012-0003-5.
- [64] A. Vagati, G. Franceschini, I. Marongiu, and G. P. Trogia, "Design criteria of high performance synchronous reluctance motors," in *Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting*, Oct. 1992, pp. 66–73 vol.1. doi: 10.1109/IAS.1992.244463.
- [65] C. Lu, S. Ferrari, and G. Pellegrino, "Two Design Procedures for PM Synchronous Machines for Electric Powertrains," *IEEE Trans. Transp. Electrification*, vol. 3, no. 1, pp. 98–107, Mar. 2017, doi: 10.1109/TTE.2016.2646738.
- [66] S. Ferrari, P. Ragazzo, G. Dilevrano, and G. Pellegrino, "Flux and Loss Map Based Evaluation of the Efficiency Map of Synchronous Machines," *IEEE Trans. on Ind. Applicat.*, vol. 59, no. 2, pp. 1500–1509, Mar. 2023, doi: 10.1109/TIA.2022.3221381.
- [67] M. J. Karnper and A. F. Volschenk, "Effect of rotor dimensions and cross magnetisation on f_d and L , inductances of reluctance synchronous machine with cageless flux barrier rotor".
- [68] M. J. Kamper, "Design optimisation of cageless flux barrier rotor reluctance synchronous machine," Stellenbosch : Stellenbosch University, 1996. Accessed: Aug. 30, 2023. [Online]. Available: <http://hdl.handle.net/10019.1/55041>
- [69] G. Dilevrano, P. Ragazzo, S. Ferrari, G. Pellegrino, and T. Burrell, "Magnetic, Thermal and Structural Scaling of Synchronous Machines," in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA: IEEE, Oct. 2022, pp. 1–8. doi: 10.1109/ECCE50734.2022.9947472.

- [70] “Electric motors | IEC.” <https://www.iec.ch/government-regulators/electric-motors> (accessed Jul. 10, 2023).
- [71] “M470-50a Non-oriented Electrical Steel Sheet In Coil - Buy Non-oriented Electrical Steel Sheet,M470-50a Electrical Steel Sheet,Non-oriented Electrical Steel Plate Product on Alibaba.com.” https://www.alibaba.com/product-detail/M470-50a-Non-oriented-Electrical-Steel_1600581158957.html (accessed Jul. 10, 2023).
- [72] “Copper PRICE Today | Copper Spot Price Chart | Live Price of Copper per Ounce | Markets Insider,” *markets.businessinsider.com*, Jun. 25, 2023. <https://markets.businessinsider.com/commodities/copper-price> (accessed Jul. 11, 2023).
- [73] “Copper content in the electric motor Depending on Power, RPM and Weight - How much copper is in the electric motor depending on types and dimensions - Copper content in the electric motor.” https://metall.biz.ua/en/index.php?route=extension/blog/blog&blog_id=152 (accessed Jul. 10, 2023).
- [74] V. Hundak, T. Cox, G. Vakil, and C. Gerada, “Mass Production Costing of Induction Machines for Automotive Applications,” in *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*, Jun. 2018, pp. 500–505. doi: 10.1109/ITEC.2018.8450116.