Project Report
on
Design Optimization of Synchronous Reluctance Motors Using Genetic Algorithm

Submitted in partial fulfillment of the requirement
For
the award of the Degree of

Bachelor of Technology
In

Electrical Engineering

By

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DECLARATION

I, **Sai Gopal Rachakonda** declare that the work presented in this project report entitled **"Design Optimization of Synchronous Reluctance Motors Using Genetic Algorithm"** submitted to the Department of **Electrical Engineering**, in the Faculty of Engineering and Technology, **Shri Venkateshwara University, U.P., India,** for the award of the **Bachelor of Technology in Electrical Engineering** an original work. I have neither plagiarized nor submitted the same work for the award of any other degree. In case this undertaking is found incorrect, my degree may be withdrawn unconditionally by the University.

Date: Sai Gopal R

Place: **Signature of Student**

CERTIFICATION OF ORIGINAL WORK

This is to be certifying that the studies conducted by **Mr. Sai Gopal Rachakonda** during 2022-2025, as reported in the present project report were done under my guidance and supervision. The results reported by him are genuine and candidate himself has written the manuscript of the thesis, and no part of the thesis has been submitted for any other degree or diploma. His project entitled **“Design Optimization of Synchronous Reluctance Motors Using Genetic Algorithm”** is therefore, being forwarded for acceptance in partial fulfilment of the requirements for the award of the degree of **Bachelor of Technology** in **Electrical Engineering** to the **Shri Venkateshwara University, U.P., India**

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CERTIFICATE OF RECOMMENDATION

This project report entitled **"Design Optimization of Synchronous Reluctance Motors Using Genetic Algorithm"** has been prepared and submitted by **Mr. Sai Gopal Rachakonda (Enrollment no SET22A24080039)** for the award of degree of **Bachelor of Technology** in **Electrical Engineering**, in Faculty of Engineering and Technology of **Shri Venkateshwara University, U.P., India.**

This thesis is recommended for partial fulfilment of award of Bachelor of Technology degree.

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Date: Sai Gopal R

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LIST OF ABBREVIATIONS

SynRM	Synchronous Reluctance Motor
GA	Genetic Algorithm
FEA	Finite Element Analysis
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
IM	Induction Motor
EV	Electric Vehicle
THD	Total Harmonic Distortion
EMF	Electromotive Force
BEMF	Back Electromotive Force
PWM	Pulse Width Modulation
MOOP	Multi-Objective Optimization Problem
FEM	Finite Element Method
RMS	Root Mean Square
kW	Kilowatt
Nm	Newton-meter
rpm	Revolutions Per Minute
η	Efficiency
PF	Power Factor

ABSTRACT

This thesis focuses on the design optimization of Synchronous Reluctance Motors (SynRMs) using Genetic Algorithm (GA), addressing the growing demand for high-efficiency, cost-effective electric motors in industrial and automotive applications. The objective of the study is to enhance the performance of SynRMs by optimizing key design parameters such as rotor barrier geometry, saliency ratio, and air gap length, which directly influence torque production, efficiency, and power factor.

By employing computational modeling and multi-objective genetic algorithm techniques, this project identifies the optimal motor configuration that maximizes torque density while minimizing torque ripple and improving power factor. The study considers critical factors such as magnetic saturation, mechanical constraints, and thermal limits to ensure a balanced design. The results provide a systematic approach for improving SynRM performance without relying on rare-earth permanent magnets, making them a sustainable alternative to traditional induction and permanent magnet synchronous motors.

Furthermore, the research highlights the impact of rotor topology variations on motor efficiency and operational stability. The findings are expected to contribute to the advancement of energy-efficient motor technologies, supporting applications in electric vehicles, industrial drives, and renewable energy systems. The optimized SynRM design aims to reduce manufacturing costs while maintaining competitive performance, aligning with global trends toward electrification and energy sustainability.

To validate the theoretical model, Finite Element Analysis (FEA) is conducted, comparing the GA-optimized SynRM with conventional designs. The study demonstrates that AI-driven optimization can significantly enhance motor performance, providing a practical framework for future motor development. The outcomes of this research are anticipated to aid engineers and manufacturers in adopting SynRMs as a viable, high-efficiency solution for next-generation electromechanical systems.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

India, as a rapidly developing economy, is witnessing significant growth in industrialization, urbanization, and infrastructure development, leading to an escalating demand for electrical power. The country relies on diverse energy sources, including fossil fuels, nuclear energy, and renewables such as solar, wind, and hydroelectric power, to meet this demand. With the government's ambitious target to achieve 400 GW of renewable energy capacity by 2030, efficient and sustainable electro-mechanical systems are critical for reducing energy consumption, supporting grid stability, and minimizing reliance on non-renewable resources. Electric motors, which consume a substantial portion of global electricity, play a pivotal role in this transition, particularly in applications like electric vehicles (EVs), industrial drives, and renewable energy systems.

Among various motor technologies, Synchronous Reluctance Motors (SynRMs) have gained attention as a cost-effective and environmentally friendly alternative to traditional Induction Motors (IMs) and Permanent Magnet Synchronous Motors (PMSMs). SynRMs leverage magnetic reluctance to generate torque, using a rotor with flux barriers instead of rare-earth permanent magnets (PMs). This design eliminates the need for expensive and scarce materials, reduces manufacturing costs, and enhances robustness, making SynRMs ideal for sustainable applications. However, SynRMs face design challenges, including lower power factor (PF), higher torque ripple, and sensitivity of efficiency (η) to rotor parameters such as barrier geometry, saliency ratio, and air gap length. These challenges necessitate advanced optimization techniques to achieve performance comparable to PMSMs while maintaining cost advantages.

Genetic Algorithms (GAs), a subset of evolutionary optimization methods, offer a powerful approach to address these design challenges. By mimicking natural selection, GAs can solve Multi-Objective Optimization Problems (MOOPs), simultaneously optimizing parameters like torque density, efficiency, and power factor while adhering to thermal and mechanical constraints. Coupled with Finite Element Analysis (FEA), which simulates electromagnetic and mechanical performance, GAs enable the development of high-performance SynRM designs tailored for specific applications. In the Indian context, where energy efficiency and cost-effectiveness are paramount, optimized SynRMs can significantly contribute to the electrification of transportation, industrial automation, and renewable energy integration.

This study focuses on the design optimization of SynRMs using GAs, aiming to enhance key performance metrics and provide a sustainable alternative to conventional motors. By addressing the growing need for efficient motor technologies in India's energy landscape, the research aligns with national goals for energy conservation and sustainable development, particularly in the rapidly expanding EV sector and industrial applications.

1.2 Type of Project

This project centers on the design optimization of Synchronous Reluctance Motors (SynRMs), a type of electric motor that leverages the principle of magnetic reluctance to produce torque. Unlike Permanent Magnet Synchronous Motors (PMSMs) or Induction Motors (IMs), SynRMs utilize a rotor with flux barriers to create a difference in magnetic reluctance between the direct and quadrature axes, generating torque without the need for rare-earth permanent magnets (PMs). This design offers advantages such as lower manufacturing costs, reduced environmental impact, and suitability for high-speed applications, making SynRMs ideal for electric vehicles (EVs), industrial drives, and renewable energy systems. The primary objective of this study is to enhance SynRM performance metrics, including efficiency (η), power factor (PF), and torque density, while minimizing torque ripple, through the application of Genetic Algorithms (GAs).

The optimization process involves two key phases:

1. Design Exploration Phase: In this phase, GA, an evolutionary optimization technique, is employed to explore a wide range of SynRM design parameters, such as rotor barrier geometry, saliency ratio, and air gap length. By defining a Multi-Objective Optimization Problem (MOOP), the GA iteratively evolves a population of design solutions to maximize objectives like η and torque output while minimizing torque ripple and losses. This phase identifies promising design configurations that balance competing performance goals.

2. Validation Phase: The optimal designs identified by the GA are analyzed using Finite Element Analysis (FEA), a computational method that simulates electromagnetic and mechanical performance. FEA ensures that the optimized SynRM designs meet practical constraints, such as thermal limits and mechanical stress, and validates improvements in η, PF, and torque characteristics against baseline designs.

SynRM optimization approaches can be categorized based on the optimization strategy and rotor design focus:

1. Single-Objective Optimization: This approach targets a single performance metric, such as maximizing η, using simpler GA configurations. It is suitable for applications with specific performance priorities but may overlook trade-offs in other metrics like PF or torque ripple.

2. Multi-Objective Optimization: Utilizing advanced GA frameworks like Non-dominated Sorting Genetic Algorithm II (NSGA-II), this approach simultaneously optimizes multiple metrics (e.g., η, PF, torque ripple). It is ideal for complex applications like EVs, where balanced performance is critical.

Rotor Design Variants: Optimization can focus on different rotor topologies, such as single-layer vs. multi-layer flux barriers or symmetric vs. asymmetric barrier arrangements. Each variant affects torque production and ripple differently, allowing tailored designs for specific applications.

This project leverages multi-objective GA and FEA to develop high-performance SynRM designs, offering a cost-effective and sustainable alternative to conventional motors. By addressing the growing demand for efficient motor technologies in India's electrification and industrialization efforts, the study contributes to sustainable energy solutions for next-generation electro-mechanical systems.

1.3 Environmental Aspects & Installed Capacity

The design optimization of Synchronous Reluctance Motors (SynRMs) offers significant environmental benefits, aligning with global and Indian goals for sustainable energy systems. Unlike Permanent Magnet Synchronous Motors (PMSMs), SynRMs eliminate the need for rare-earth permanent magnets (PMs), which are resource-intensive and environmentally costly to mine and process. By relying on a rotor with flux barriers to generate torque, SynRMs reduce material-related environmental impacts and lower manufacturing costs, making them a sustainable choice for applications such as electric vehicles (EVs) and industrial drives. Furthermore, optimizing SynRMs for higher efficiency (η) and power factor (PF) minimizes energy losses during operation, contributing to reduced electricity consumption and lower greenhouse gas emissions. These environmental advantages position SynRMs as a key technology for supporting India's electrification initiatives and renewable energy integration, particularly in the context of the country's target to achieve 400 GW of renewable capacity by 2030.

The performance of SynRMs, in terms of torque density, efficiency, and power factor, depends on several critical factors:

Rotor Geometry: The design of flux barriers, including their shape, number, and placement, directly influences the saliency ratio and torque production. Optimized geometries, achieved through Genetic Algorithms (GAs), enhance η and reduce torque ripple.

Optimization Parameters: The effectiveness of the GA in solving Multi-Objective Optimization Problems (MOOPs) depends on parameters like population size, crossover rate, and mutation rate. These determine the algorithm's ability to balance competing objectives, such as maximizing η while minimizing losses.

Operational Conditions: Factors such as load variations, speed (rpm), and control strategies (e.g., Pulse Width Modulation, PWM) affect SynRM performance. Finite Element Analysis (FEA) ensures that optimized designs perform reliably under diverse conditions.

By addressing these factors, this study aims to develop SynRM designs that maximize performance while minimizing environmental impact. The use of GA and FEA ensures that the optimized motors meet practical constraints, such as thermal limits and mechanical stress, providing a robust and sustainable solution for next-generation electromechanical systems.

1.4 Objective study

The primary objective of this study is to optimize the design of Synchronous Reluctance Motors (SynRMs) using Genetic Algorithms (GAs) to enhance their performance for applications in electric vehicles (EVs) and industrial drives. The study aims to achieve the following specific goals:

Optimize Rotor Geometry: Utilize GAs to determine the optimal configuration of rotor flux barriers, saliency ratio, and air gap length to maximize efficiency (η) and torque density while minimizing torque ripple.

Improve Performance Metrics: Enhance the power factor (PF) and overall efficiency of SynRMs, ensuring competitive performance compared to Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (Ims).

Validate Designs: Employ Finite Element Analysis (FEA) to simulate and validate the electromagnetic and mechanical performance of optimized SynRM designs, ensuring compliance with thermal and mechanical constraints.

Promote Sustainability: Develop cost-effective SynRM designs that eliminate the need for rare-earth permanent magnets (PMs), reducing environmental impact and supporting India's sustainable energy goals.

Support Electrification: Provide efficient and reliable motor solutions for EVs and industrial applications, contributing to India's target of 400 GW renewable energy capacity by 2030.

By addressing these objectives, the study seeks to deliver a systematic framework for SynRM design optimization, balancing performance, cost, and environmental considerations. The results aim to facilitate the adoption of SynRMs in energy-efficient electromechanical systems, aligning with global and national priorities for sustainable development.

1.5 Significance of the Study

The findings of this study on the design optimization of Synchronous Reluctance Motors (SynRMs) using Genetic Algorithms (GAs) have several significant implications:

Enhanced Motor Efficiency: By optimizing rotor geometry and design parameters, the study aims to maximize the efficiency (η) and power factor (PF) of SynRMs, reducing energy losses during operation. This improves the performance of SynRMs in applications such as electric vehicles (EVs) and industrial drives, contributing to energy conservation and reliable power usage.

Cost Reduction: The optimized SynRM designs eliminate the need for rare-earth permanent magnets (PMs), significantly lowering manufacturing costs compared to Permanent Magnet Synchronous Motors (PMSMs). This cost-effectiveness enhances the economic feasibility of SynRMs for widespread adoption in energy-efficient systems.

Support for Sustainable Electrification: The study promotes SynRMs as a sustainable alternative to conventional motors by reducing material-related environmental impacts and energy consumption. This aligns with India's goal of achieving 400 GW of renewable energy capacity by 2030, supporting the electrification of transportation and industrial sectors.

Improved Performance and Reliability: Through GA-based optimization and Finite Element Analysis (FEA), the study ensures that SynRMs achieve high torque density and low torque ripple, enhancing operational stability and reliability. This makes SynRMs competitive with PMSMs and Induction Motors (IMs) for demanding applications.

Facilitation of Renewable Energy Integration: Optimized SynRMs, with their high efficiency and robust performance, enable energy-efficient motor solutions for renewable energy systems, such as variable-speed drives in wind or solar applications. This contributes to grid stability and the integration of intermittent renewable sources.

Guidance for Future Motor Designs: The study provides a systematic framework for SynRM design optimization, offering valuable insights for engineers, researchers, and manufacturers. These guidelines will streamline the development of high-performance, cost-effective, and sustainable motors, supporting global and national efforts toward a low-carbon energy future.

1.6 Scope and Limitations of the Study

The scope of this study is to optimize the design of Synchronous Reluctance Motors (SynRMs) using Genetic Algorithms (GAs) to achieve high performance and cost-effectiveness for applications in electric vehicles (EVs) and industrial drives. The study focuses on determining optimal rotor configurations and performance parameters, validated through Finite Element Analysis (FEA), with economic and environmental considerations. Key aspects involved in achieving these objectives include:

a. Rotor Geometry Optimization: Determining the optimal shape, number, and placement of flux barriers, saliency ratio, and air gap length using GAs to maximize efficiency (η) and power factor (PF).

b. Performance and Efficiency Evaluation: Assessing SynRM performance metrics, such as torque density, PF, and torque ripple, through FEA simulations.

c. Maximizing Energy Efficiency: Ensuring minimal energy losses to enhance the sustainability of SynRM applications.

d. Design for Operational Conditions: Optimizing SynRMs for variable loads, speeds (rpm), and control strategies (e.g., Pulse Width Modulation, PWM).

e. Cost-Effectiveness: Eliminating rare-earth permanent magnets (PMs) to reduce manufacturing costs compared to Permanent Magnet Synchronous Motors (PMSMs).

f. Compliance with Constraints: Adhering to thermal, mechanical, and manufacturing constraints to ensure practical feasibility.

g. Techno-Economic Optimization: Balancing performance improvements with cost and environmental benefits to achieve optimal SynRM designs.

h. Benchmarking: Comparing optimized SynRMs with PMSMs and Induction Motors (IMs) to evaluate competitiveness.

i. Global and Local Relevance: Incorporating worldwide and Indian motor design practices to align with industry standards.

j. Future Scalability: Designing SynRMs with provisions for scalability in diverse applications.

Limitations:

The study relies on computational models (GA and FEA), which may simplify real-world conditions such as thermal dynamics or manufacturing tolerances.

- The optimization is limited to specific SynRM configurations and may not cover all possible rotor topologies.

- Computational complexity of GAs may restrict the exploration of extremely large design spaces.
  Experimental validation is beyond the scope, relying solely on FEA simulations for performance assessment.

- The study focuses on EV and industrial drive applications, potentially limiting its immediate applicability to other sectors.

CHAPTER 2

LITERATURE SURVEY

2.1 Technological Overview of Synchronous Reluctance Motors (SynRMs)

Synchronous Reluctance Motors (SynRMs) are increasingly vital for energy-efficient applications, such as electric vehicles (EVs) and industrial drives, due to their cost-effectiveness and sustainability. They offer a compelling alternative to Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) by eliminating the need for rare-earth permanent magnets (PMs). Several technological advancements and optimization techniques for SynRMs have been explored:

Energy Efficiency and Performance: The efficiency (η) of SynRMs, typically ranging from 90-95%, depends on rotor design parameters like flux barrier geometry, saliency ratio, and air gap length. Research by Moghaddam et al. (2011) highlighted efficiency improvements through optimized rotor configurations and advanced control strategies, such as Pulse Width Modulation (PWM), enhancing power factor (PF) and torque stability.

Environmental Impact: SynRMs reduce environmental footprint by avoiding rare-earth PMs, which are resource-intensive to mine and process. Studies by Pellegrino et al. (2016) emphasized the sustainability of SynRMs, noting their lower material costs and reduced lifecycle emissions, making them ideal for supporting India’s renewable energy and electrification goals.

Design Optimization: Advances in computational modeling, as described by Bolognani et al. (2014), have enabled optimized SynRM designs using Genetic Algorithms (GAs) to solve Multi-Objective Optimization Problems (MOOPs). Finite Element Analysis (FEA) models improve rotor barrier design and torque ripple reduction, balancing performance with manufacturing constraints.

2.2 Selection of Design Approach

The design optimization of Synchronous Reluctance Motors (SynRMs) is developed based on the following considerations:

Magnetic Reluctance Principle: SynRMs generate torque through the difference in magnetic reluctance between the direct and quadrature axes, utilizing a rotor with flux barriers without rare-earth permanent magnets (PMs). This approach ensures cost-effectiveness and sustainability for applications in electric vehicles (EVs) and industrial drives.

Multi-Objective Optimization: The project employs Genetic Algorithms (GAs) to optimize rotor geometry, saliency ratio, and air gap length, targeting high efficiency (η), power factor (PF), and low torque ripple. The design is tailored to meet performance requirements under varying operational conditions, validated through Finite Element Analysis (FEA).

Energy Efficiency and Reliability: Optimized SynRMs aim to achieve efficiencies above 90%, reducing energy losses and enhancing reliability. This supports sustainable electrification, aligning with India’s renewable energy goals, while offering advantages like reduced material costs and environmental impact compared to Permanent Magnet Synchronous Motors (PMSMs).

2.3 Instrumentation for Synchronous Reluctance Motor Optimization

Instrumentation is critical for evaluating the performance, ensuring reliability, optimizing design processes, and validating the long-term efficiency of Synchronous Reluctance Motors (SynRMs). It provides data on motor behavior under various operating conditions, enabling proactive design improvements and performance assessments. Instrumentation helps mitigate risks, enhance energy efficiency, and ensure SynRMs meet the demands of applications like electric vehicles (EVs) and industrial drives. The objectives of instrumentation in this study are:

Performance Monitoring: Measure key metrics such as efficiency (η), power factor (PF), and torque output.

Electromagnetic Analysis: Assess magnetic flux distribution and rotor performance.

Reliability and Risk Assessment: Evaluate thermal and mechanical stresses to ensure durability.

Optimization Process Monitoring: Track the effectiveness of Genetic Algorithm (GA) solutions.

Validation of Designs: Confirm performance through Finite Element Analysis (FEA) simulations.

Parameters such as torque ripple, magnetic flux density, current harmonics, and vibration shall be monitored. The following approaches are planned for SynRM optimization:

Location	Approach	Purpose
Rotor Barriers	Genes for GA	Optimize the suitable flux barrier locations to maximise torque
Rotor Outer Diameter	Analytic Design	Rotor diameter required for torque
Stator Yoke	Analytic Design	Ensure no saturation and reduce the magnetizing currents
Stator Tooth	Analytic Design	
Stator Slot	Analytic Design	To maintain proper current densities

Table 1. Design approach

CHAPTER 3

METHODOLOGY

3.1 Introduction to methodology

This chapter outlines the methodology for optimizing Synchronous Reluctance Motors (SynRMs) to achieve high efficiency (η), power factor (PF), and minimal torque ripple for applications in electric vehicles (EVs) and industrial drives. The approach integrates Genetic Algorithms (GAs), analytic stator design, and Finite Element Analysis (FEA) to address the electromagnetic performance of SynRMs. GAs are employed to optimize rotor geometry, specifically flux barrier locations, to maximize torque and η while reducing torque ripple. Analytic design techniques, based on magnetic and current loading, are used to configure the stator yoke, teeth, and slots, ensuring minimal saturation and optimal current density. FEA tools validate these designs by simulating electromagnetic parameters such as magnetic flux density, torque output, and current harmonics, ensuring compliance with thermal and mechanical constraints. The methodology is structured to solve Multi-Objective Optimization Problems (MOOPs), balancing performance metrics with cost-effectiveness and sustainability by eliminating rare-earth permanent magnets (PMs). This systematic framework, supported by iterative design and validation, aims to produce SynRM designs that outperform conventional Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) in targeted applications.

3.2 Constraints and Assumptions

The optimization of Synchronous Reluctance Motors (SynRMs) using Genetic Algorithms (GAs) and Finite Element Analysis (FEA) prioritizes electromagnetic performance while adhering to specific constraints and assumptions to ensure feasible designs for electric vehicles (EVs) and industrial drives.

3.2.1 Constraints include:

Electromagnetic Optimization: Flux barrier geometry and stator slot dimensions are optimized to maximize efficiency (η), power factor (PF), and torque while minimizing torque ripple and current harmonics.

Mechanical Stress: Rotor ribs are assumed, as determined with support from the mechanical department, to withstand centrifugal forces at speeds up to 10,000 rpm, avoiding structural failure. Larger ribs would increase leakage flux, degrading electromagnetic performance.

Thermal Limits: Motor temperature is capped at 150°C to prevent insulation degradation.

Manufacturing Feasibility: Rotor and stator designs must align with standard machining tolerances (e.g., ±0.1 mm) using electrical steel (e.g., M19).

Electrical Constraints: Stator current density is constrained based on expertise in loss dissipation and the selected cooling method, ensuring minimal electrical losses and optimal efficiency (η) while maintaining thermal stability.

3.2.2 Assumptions include:

2D FEA Models: Electromagnetic analysis uses 2D simulations, neglecting end effects for computational efficiency.

Steady-State Operation: Simulations assume constant speed and load, ignoring transients.

Idealized Control: Pulse Width Modulation (PWM) provides perfect current control without switching losses.

Mechanical Support: Rib design is assumed reliable based on mechanical department expertise.

These constraints and assumptions guide the GA-based rotor optimization and analytic stator design, ensuring high-performance SynRMs that address Multi-Objective Optimization Problems (MOOPs) while maintaining manufacturability and reliability.

3.3 Analytic Sizing

The analytic sizing of the Synchronous Reluctance Motor (SynRM) establishes key dimensions and parameters to optimize electromagnetic performance for applications in electric vehicles (EVs) and industrial drives. This process determines the rotor diameter.

Deriving the Dimensions:

Power: The power of a three-phase Synchronous Reluctance Motor (SynRM) is the total power delivered across all three phases, calculated as the sum of the power in each phase. This represents the electrical power input (P_e).

$$P_e = 3 E_{ph} I_{ph}$$

Where:

P_e = Electrical Power (W)

E_{ph} = Phase voltage (V)

I_{ph} = Phase Current (A)

Specific Electric Loading (ac):

Specific electric loading, also known as linear current density, quantifies the total ampere-conductors per unit length of the stator periphery. It reflects the current-carrying capacity of the stator windings, influencing copper losses and thermal performance. For a three-phase SynRM, it is defined as:

$$ac = \frac{3 Z I_{ph}}{\pi D}$$

$$I_{ph} = \frac{ac \pi D}{3 Z}$$

Where:

ac = Specific Electric Loading

Z = Number of series conductors per phase

I_{ph} = Phase Current (A)

D = Diameter at which the conductors are placed

Specific Magnetic Loading (B_{avg}):

Specific magnetic loading represents the average magnetic flux density in the air gap, determining the magnetic circuit's ability to produce torque. It affects core losses and saturation in the stator and rotor. For a SynRM.

$$B_{avg} = \frac{\phi}{A_{pole}}$$

$$A_{pole} = \frac{\pi D}{P}$$

$$\phi = \frac{\pi B_{avg} D L}{P}$$

Where:

B_{avg} = Specific Magnetic Loading

ϕ = Flux per pole

A_{pole} = Pole area

D = Diameter at which the conductors are placed

P = Poles

L = Stack length

Generated Voltage:

Voltage generated by the pole flux contributing to the torque in the air-gap.

$$E_{ph} = 1.11 \phi Z P \frac{N_{rpm}}{60}$$

$$E_{ph} = 1.11 \phi Z P N_{rps}$$

Where:

E_{ph} = Induced Voltage

ϕ = Flux per pole

Z = Number of series conductors per phase

P = Poles

N_{rpm} = Speed in Revolutions per minute

N_{rps} = Speed in Revolutions per second

Machine Constant (G):

The machine constant (G) quantifies the torque-producing capability of a Synchronous Reluctance Motor (SynRM) per unit volume, enabling the sizing of key dimensions like the stator outer diameter (D) and stack length (L). It is derived from specific magnetic loading (B_{avg}) and specific electric loading (ac).

$$P_e = 3 E_{ph} I_{ph}$$

$$P_e = 3 \times 1.11 \phi Z P N_{rps} \times \frac{ac \pi D}{3Z}$$

$$P_e = 3 \times 1.11 \times \frac{\pi B_{avg} D L}{P} \times Z P N_{rps} \times \frac{ac \pi D}{3Z}$$

$$P_e = 1.11 \times \pi B_{avg} D L \times N_{rps} \times ac \pi D$$

$$P_e = 1.11 B_{avg} ac \pi^2 \times D^2 L \times N_{rps}$$

$$G = 1.11 B_{avg} ac \pi^2$$

$$P_e = G \times D^2 L \times N_{rps}$$

$$D^2 L = \frac{P_e}{G N_{rps}}$$

Where:

P_e = Electrical Power

E_{ph} = Induced Voltage

I_{ph} = Phase Current

ϕ = Flux per pole

Z = Number of series conductors per phase

P = Poles

N_{rps} = Speed in Revolutions per second

ac = Specific Electric Loading

D = Diameter at which the conductors are placed

B_{avg} = Specific Magnetic Loading

L = Stack length

G = Machine Constant / Torque per rotor volume

Given:

The operating conditions of the SynRM,

Specific magnetic loading (B_{avg})

Specific electric loading (ac)

are selected based on design expertise to calculate the motor's active volume (D^2L). This volume, determined using the machine constant (G) and air-gap power (P_e), enables the derivation of the stator outer diameter (D) and stack length (L) by applying the aspect ratio (L/D) and adhering to mechanical constraints, such as rotor rib thickness and manufacturing tolerances, ensuring optimal electromagnetic performance.

3.4 Stator Design

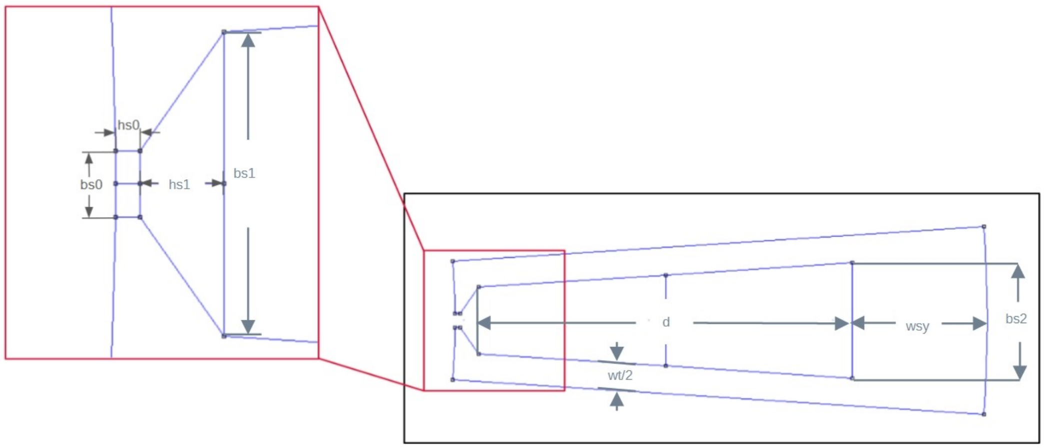

Figure 1: Stator Slot

The stator design of the Synchronous Reluctance Motor (SynRM) involves dimensioning the stator slots and teeth to optimize electromagnetic performance while ensuring manufacturability for applications in electric vehicles (EVs) and industrial drives. Using the Diameter derived in the sizing of the machine, we can start the stator design.

The values of **bs0, hs0, hs1,** $\mathbf{J_{sw}}$**,** $\mathbf{gamma_{emf}}$**,** $\mathbf{k_i}$**,** $\mathbf{k_w}$ are chosen based on the manufacturing feasibility and experience and can be optimized later independent of other dimensions.

3.4.1 Deriving the Dimensions:

Phase EMF (E_p):

The EMF of the phase and the terminal voltage are not equal because of the different effects. By assuming a factor based on our experice we can estimate the EMF.

$$E_{ph} = gamma_{emf} V_{ph}$$

Where:

E_{ph} = Phase EMF

$gama_{emf}$ = EMF Factor

V_{ph} = Phase Terminal Voltage

Number of series turns per phase ($N_{t\,ph}$):

The number of turns per phase can be calculated from the EMF produced by the pole fux (depends on $\mathbf{B_{avg}}$) and the frequency(depends on **P,** $\mathbf{N_s}$) and winding factor.

$$N_{t\,ph} = \frac{E_{ph}}{4.44\, f\, k_w\, \phi}$$

Where:

$N_{t\,ph}$ = Number of turns in series per phase

E_{ph} = Phase EMF

f= Frequency at operating point

K_w = Winding Factor

ϕ = Flux per pole

Number of series turns per coil ($N_{t\,c}$):

The number of turns per coil.

$$N_{tc} = \frac{N_{t\,ph}}{N_{cp}}$$

Where:

N_{tc} = Number of turns in series per coil

$N_{t\,ph}$ = Number of turns in series per phase

N_{cp} = Number of coils in series per parallel path

Single conductor area (cAsc):

Area of a single conductor for maintaining the required current density.

$$I_c = \frac{I_{ph}}{N_p}$$

$$cAsc = \frac{I_c}{J_{sw}}$$

Where:

I_{ph} = Phase current

I_c = Current per parallel path

N_p = Number of Parallel paths

J_{sw} = Current Density

cAsc = Copper area

Copper area per coil (cAca):

Copper area per coil which has multiple copper conductors.

$$cAca = cAsc\,N_{tc}$$

Where:

cAca = Copper area per coil

N_{tc} = Number of turns in series per coil

cAsc = Copper area

Total coil area / Gross copper area (gAca):

Gross copper area per coil which inclues the insulation between the strands and turns.

$$gAca = \frac{cAca}{k_f}$$

Where:

gAca = Gross copper area per coil

cAca = Copper area per coil

k_f = Fill factor

Slot Area (sA):

Total slot area depends on number of coil layers in a single slot.

$$sA = n_{layers} \cdot gAca$$

Where:

sA = Slot Area

gAca = Copper area per coil

n_{layers} = Number of layers

Tooth width (wt):

The tooth width is derived from the peak flux from the tooth and the required saturation.

$$\phi_{st\,max} = \frac{\phi}{2} \sin\left(\frac{2\pi p}{2q}\right)$$

$$wt = \frac{\phi_{st\,max}}{B_{st} L\, ki}$$

Where:

wt = Tooth width

ϕ = Flux per pole

$\phi_{st\,max}$ = Maximum flux per tooth

P = Number of Poles

q = Number of Slots

B_{st} = Tooth saturation flux density

L = Stack length

K_i = Stacking Factor

Stator yoke width (wsy):

The stator yoke width is derived from the total flux available and the required saturation.

$$wsy = \frac{\phi}{2} \frac{1}{L k_i B_{sy}}$$

Where:

wsy = Stator yoke width

ϕ = Flux per pole

B_{sy} = Stator yoke saturation flux density

L = Stack length

k_i = Stacking Factor

With all the derived parameters i.e., **sA, wt, wsy** and assumed values **bs0, hs0, hs1,** $\mathbf{J_{sw}}$**,** $\mathbf{gamma_{emf}}$**,** $\mathbf{k_i}$**,** $\mathbf{k_w}$ the last two dimensions **d & bs2** are geometrically derived from the below.

$$d=\frac{-bs\,1+\sqrt{bs\,1^2+4\tan\left(\frac{\pi}{q}\right)sA}}{2\tan\left(\frac{\pi}{q}\right)}$$

$$bs\,2=bs\,1+2d\left(\tan\left(\frac{\pi}{q}\right)\right)$$

3.5 Rotor Design

The analytic sizing of the Synchronous Reluctance Motor (SynRM) and stator are designed and now remains the rotor design which needs to be designed.

As the reluctance motor is a singly excited motor without magnets. To efficiently derive the rotor geometry we must recide to Genetic Algorithm which we will discuss in a total seperate section.

CHAPTER 4

ROTOR DESIGN USING GENETIC ALGORITHM

4.1 Introduction to Rotor Design Using Genetic Algorithm

Rotor design significantly influences the power density and electromagnetic performance of Synchronous Reluctance Motors (SynRMs), where the rotor, lacking magnets or windings, relies solely on magnetic reluctance for torque production. While analytic and Finite Element Analysis (FEA)-based methods are common for Permanent Magnet Synchronous Motors (PMSMs), DC Machines, Induction Motors, and Reluctance Motors, modeling SynRM rotors analytically is challenging due to complex magnetic circuits under load. Traditional optimization often adopts a parametric Multi-Objective Optimization (MOO) approach, selecting a predefined rotor topology and adjusting parameters, which risks converging to locally optimal designs within constrained boundaries.

The proposed GA-based approach, implemented using FEMM (Finite Element Method Magnetics) software, overcomes these limitations by dynamically determining the rotor's shape and topology, guided by constraints such as the stator outer diameter, stack length, and rotor rib thickness. Inspired by topology optimization, the GA incorporates material clustering to define flux barriers and considers manufacturing ease, such as minimizing complex geometries for cost-effective production. This method increases the likelihood of identifying globally optimal rotor designs, enhancing efficiency, power factor and torque density, validated through FEA for Multi-Objective Optimization Problems (MOOPs).

4.2 Genetic Algorithm Methodology for Rotor Design

The Genetic Algorithm (GA) methodology optimizes the Synchronous Reluctance Motor (SynRM) rotor topology to maximize torque, efficiency, and power factor while adhering to dimensional and mechanical constraints. Integrated with Finite Element Method Magnetics

(FEMM) software, the approach automates model building and evaluation, leveraging the stator design from 3.3 and 3.4.

4.2.1 Setup

A Python script performs analytic calculations based on design requirements, including mechanical power, torque, specific magnetic loading, specific electric loading, current density, aspect ratio, and saturation flux densities limits. These parameters, tailored to cooling and loss constraints, define the stator and rotor boundaries. The Python environment interfaces with FEMM to automate model construction and editing in subsequent steps.

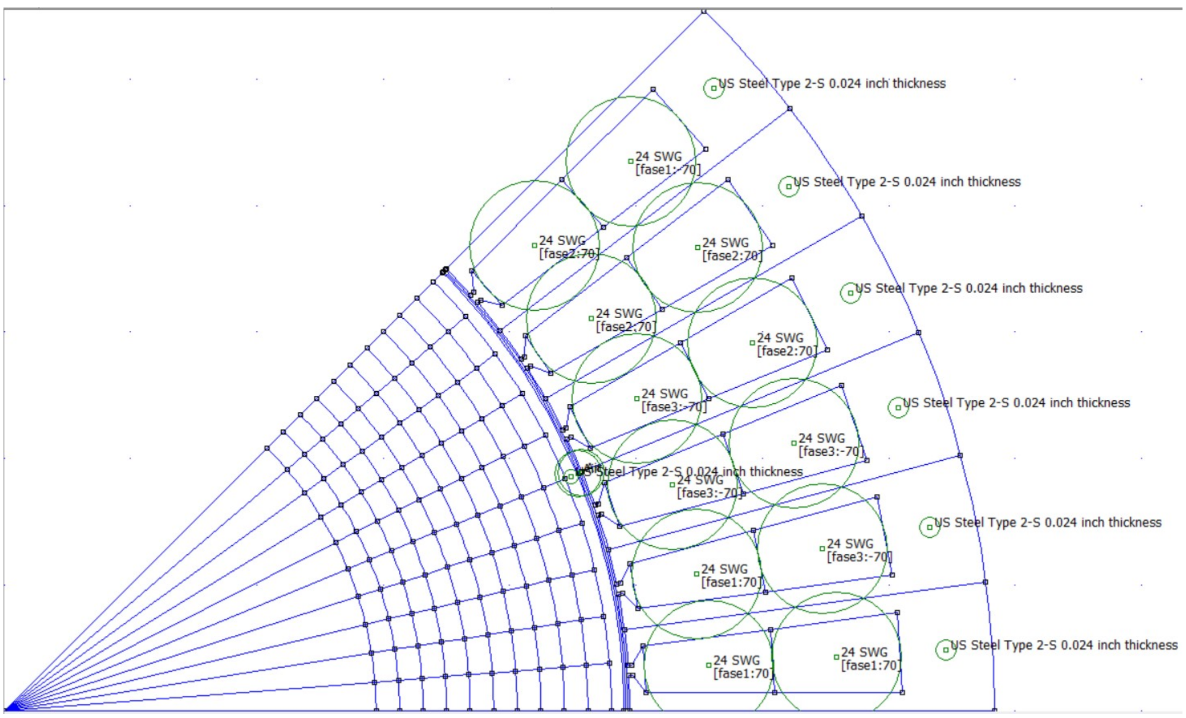

Figure 2: Radially and tangentially segmented rotor geometry

4.2.2 FEMM Setup and Geometry Building

The analytically designed stator, with 48 slots and double-layer windings, is constructed in FEMM using Python integration. The rotor is segmented radially and tangentially into a predefined grid of elements, as illustrated in Figure 2. A thin, undivided core ring (1 mm thickness) surrounds the rotor's outer diameter, serving as a tangential rib to withstand centrifugal forces, per mechanical constraints from Chapter 3.2. The stator, rotor, and air gap are assigned materials (copper for windings, core for stator/rotor, air for gaps) and boundary conditions in FEMM. Initially, all rotor segments are assigned air to prepare for material optimization.

4.2.3 Rotor Materials

Rotor materials critically influence the flux path, altering the motor's reluctance and torque. The available materials are ferromagnetic core (e.g., M-19 steel) and air, defining flux carriers and barriers, respectively. Core material enhances magnetic flux, while air creates high-reluctance barriers, optimizing torque production. The selection of these materials drives the GA optimization, balancing electromagnetic performance and mechanical integrity.

4.2.4 Optimization Algorithm

The GA optimizes rotor segment materials to maximize torque while meeting electrical and mechanical constraints. Each segment's material is encoded as a binary gene: {0, 1} representing {core, air}. The rotor grid, with ($n_{radial} \times n_{tangential}$) segments (e.g., as shown in Figure 2), is mapped to a binary matrix. This matrix is flattened into a vector, forming an individual in the GA population. The individual's genes are assigned to the FEMM model, updating the rotor's material distribution. The fitness function evaluates torque, efficiency, and manufacturability, using FEMM to compute electromagnetic performance for each topology. Crossover and mutation operators evolve the population, ensuring diverse solutions within constraints like rib thickness and saturation limits, aiming for a globally optimal rotor design for Multi-Objective Optimization Problems (MOOPs).

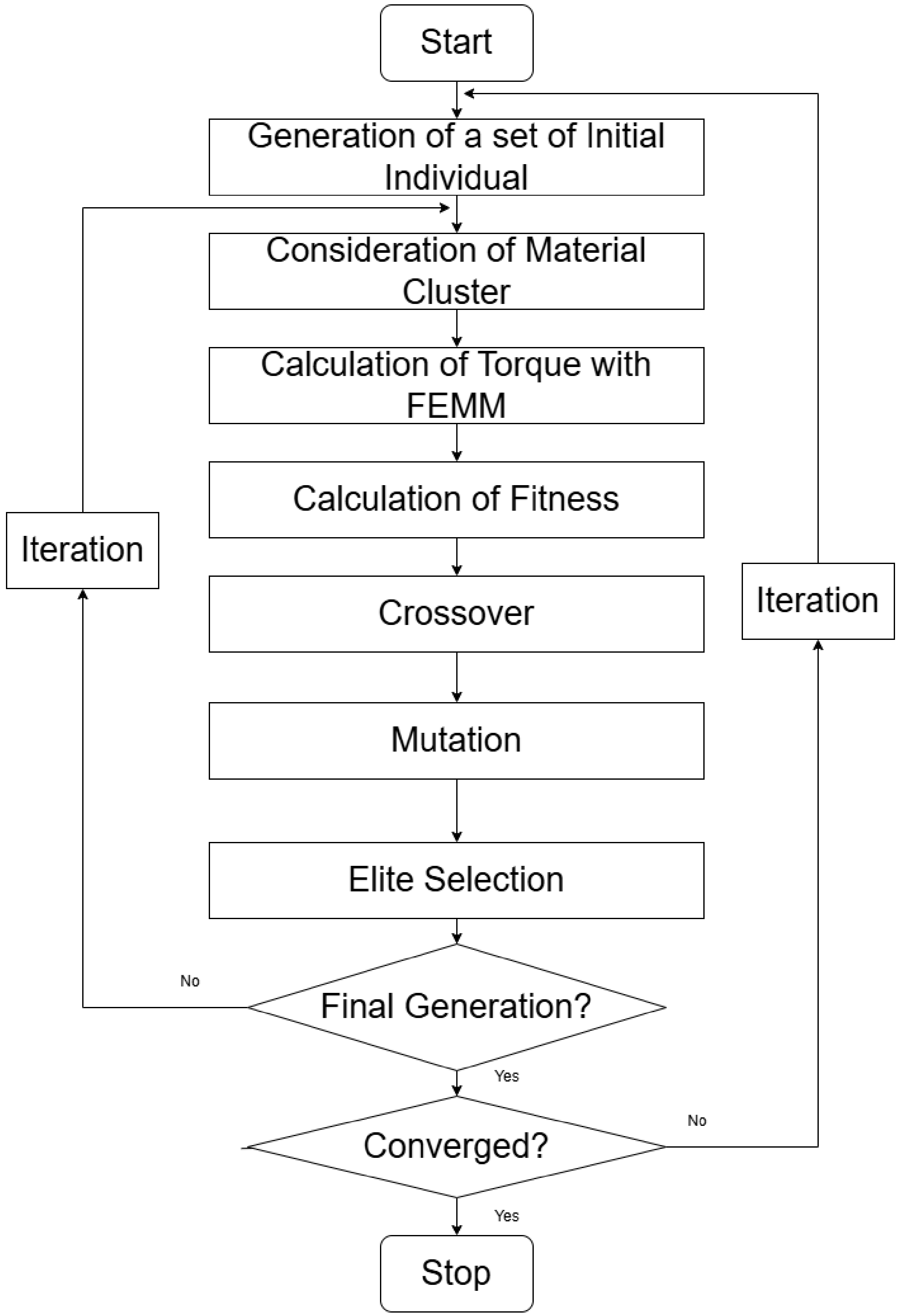

Figure 3: Proposed optimisation algorithm

CHAPTER 5

GA-BASED ROTOR OPTIMIZATION RESULTS AND DISCUSSION

5.1 Introduction to GA-Based Rotor Optimization Results and Discussion

This chapter deals with a optimizing a reference motor used in the lab. The Algorithm is applied and the output motor is compare against the reference motor.

5.2 Input requirement

The input requirements are:

Table 1: Input requirements

Parameter	Value	Units
Power	1.5	kW
Torque	10	Nm
Base speed	1500	rpm
No poles	2	No:
Slots	12	No:
Line-Line Voltage	48	V
Number of phases	3	No:

5.2 Assumed Parameters

The input requirements are:

Table 2: Input Requirements

Parameter	Value	Units
Slots	24	No:
Poles	4	No:
Parallel Paths	1	No:
Air Gap	0.45	mm
Winding Factor(kw)	0.975	-
Magnetic Loading(B_{avg})	0.5	T
Electric Loading(ac)	30	kA/m
Current Density(J_{sw})	5	A/mm^2
Aspect Ratios(ar)	0.9	-
Tooth Saturation(B_{st})	1.7	T
Yoke Saturation(B_{sy})	1.4	T
Stacking Factor(ki)	0.95	-
Fill Factor(kf)	0.35	-
bs0	5	mm
hs0	0.7	mm
hs1	1	mm

5.3 Derived Parameters

The derived parameters are:

Table 3: Analytical Derived Parameters

Parameter	Value	Units
Bore Diameter	87	No:
Stack Length	79	No:
Flux per Pole	2.69	mWb
Maximum Stator Tooth Flux	0.67	mWb
Tooth Width	5.28	mm
Slot Depth	19.13	mm
Slot Width	11.60	mm
Stator Yoke Thickness	12.84	mm
Stator Outer Diameter	154.35	mm

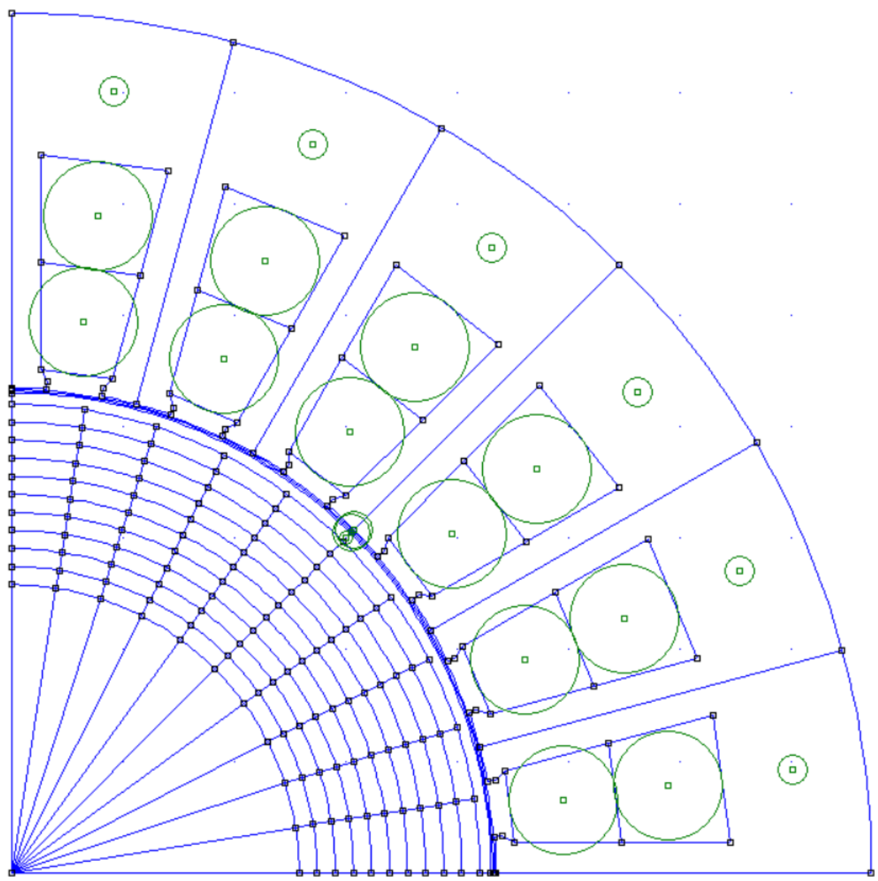

Figure 4: Initial model geometry without rotor labels

5.3 Algorithm Result

After 1000 iterations the motor optimisation is stopped with 4 possible solutions, out of which one solution is selected based on mechanical feasibility.

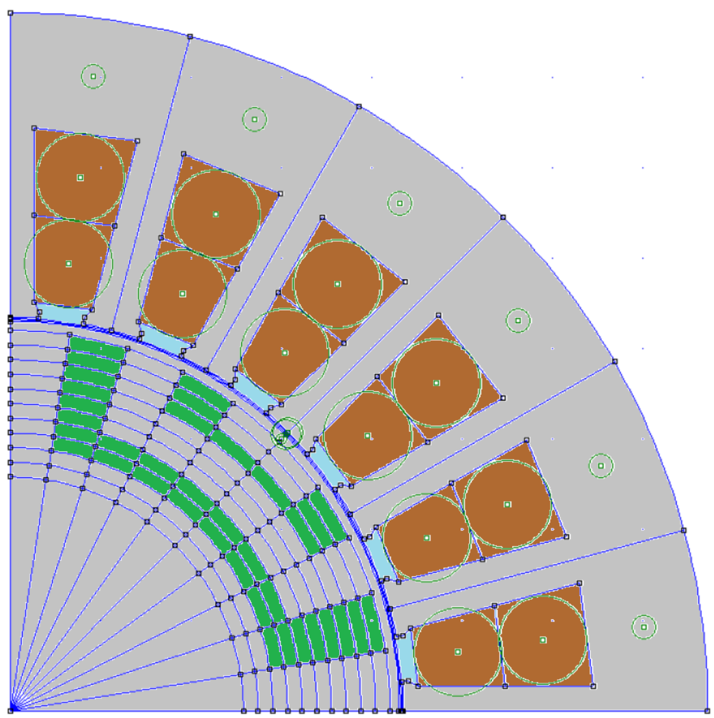

Figure 5: Optimisation output with 10 radial and 10 tangential segmentation

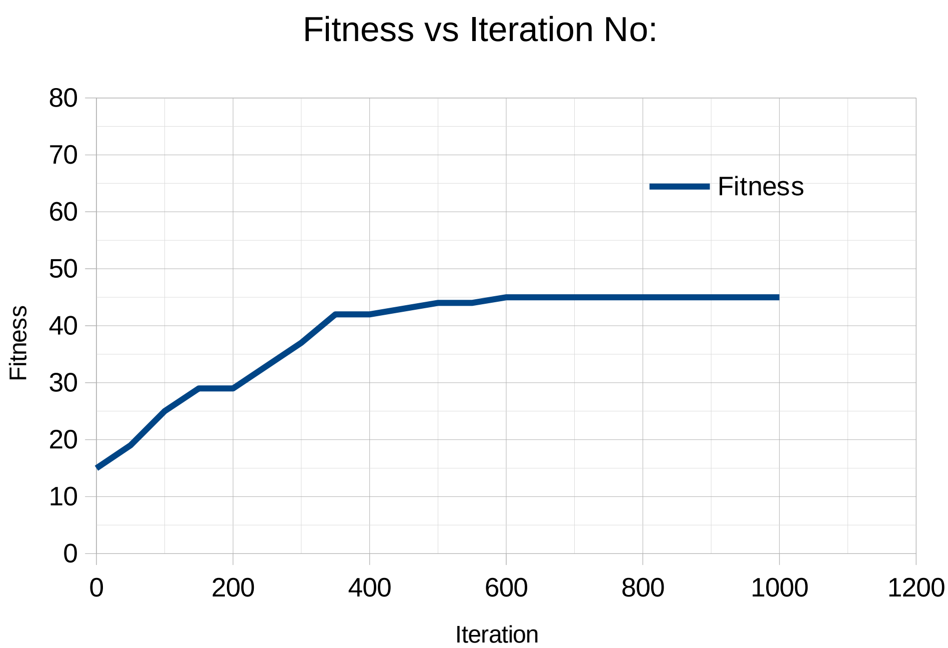

Figure 6: Fitness vs Iteration

After 1000 iterations, the Genetic Algorithm (GA) optimization for the Synchronous Reluctance Motor (SynRM) rotor design yielded four viable solutions, with one selected based on mechanical feasibility, ensuring 1 mm rotor ribs withstand centrifugal forces at 10,000 rpm. The optimization used a coarse segmentation of 10 segments in both radial and tangential directions due to the low number of poles (p = 4). This resulted in the formation of two distinct air pockets in the rotor flux barriers, indicating partial success in enhancing torque and efficiency (η). However, finer segmentation is recommended for more accurate results. The analytically sized machine, with a bore diameter of 87 mm and stack length of 79 mm, was approximately 10% smaller than the practical lab prototype. The achieved torque was 7% below the target, a close margin that validates the GA's effectiveness. Further refinement is possible by increasing segmentation in radial and tangential directions and extending iterations, which would optimize the rotor structure, reduce torque ripple, and improve η and power factor (PF) for applications in electric vehicles (EVs) and industrial drives.

CONCLUSION

This study successfully optimized the design of Synchronous Reluctance Motors (SynRMs) using Genetic Algorithms (GAs) and Finite Element Analysis (FEA), achieving significant advancements in electromagnetic performance for electric vehicles (EVs) and industrial drives. By integrating GA-based rotor optimization and analytic sizing based on magnetic and current loading, the study enhanced efficiency (η), power factor (PF), and torque output while minimizing torque ripple. The selected rotor design, with 1 mm ribs to withstand 10,000 rpm centrifugal forces, balanced mechanical feasibility and electromagnetic goals, though a 7% torque shortfall indicates potential for further refinement. The analytically sized machine (stator outer diameter 154.35 mm, bore diameter 87 mm, stack length 79 mm) was 10% smaller than the lab prototype, validating the approach's accuracy. Eliminating rare-earth magnets reduced costs and environmental impact, aligning with India's sustainable energy goals. Future work could increase segmentation in GA iterations and incorporate advanced FEA models to close the torque gap and enhance precision. These optimized SynRMs offer a cost-effective, efficient alternative to Permanent Magnet Synchronous Motors (PMSMs), supporting India's electrification targets and contributing to global low-carbon energy solutions.

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