Thermal Parameter Tuning for Finite Element Model of PMSM

Research proposal for Master of Science

Student's Name

Main Supervisor: Dr. Mohd Azri Hizami Bin Rasid

Co-Supervisor: TBD

Field Supervisor: NA

Faculty of Manufacturing and Mechatronics Technology Engineering
Universiti Malaysia Pahang

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
FEM	Finite Element Method
FEMM	Finite Element Method Magnetics
LPTN	Lumped Parameter Thermal Network
PMSM	Permanent Magnet Synchronous Motor
RMSE	Root Mean Square Error
SPMSM	Surface-Mounted Permanent Magnet Synchronous Motor

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Permanent Magnet Synchronous Motors (PMSMs) are widely used in industrial applications, electric vehicles, and renewable energy systems due to their high efficiency and power density. However, thermal management remains critical as excessive temperature can cause permanent magnet demagnetization, insulation degradation, and reduced efficiency.

Accurate thermal modeling is essential for predicting temperature distribution and optimizing cooling systems. While Finite Element Analysis (FEA) provides detailed temperature predictions, its accuracy heavily depends on proper thermal parameter definition, particularly convection heat transfer coefficients. These parameters are difficult to determine analytically due to complex geometries and fluid flow patterns.

FEMM (Finite Element Method Magnetics) is an open-source software offering accessible thermal analysis capabilities with Python/MATLAB scripting. However, defining accurate thermal parameters in FEMM, especially convection coefficients, remains challenging. Commercial software like JMAG Express provides validated thermal analysis using Lumped Parameter Thermal Networks (LPTN) with empirical correlations for convection, offering a reliable reference for parameter tuning.

1.2 Problem Statement

While FEMM provides cost-free and flexible thermal analysis capabilities, several challenges limit its effective use:

1. Parameter Uncertainty: Convection heat transfer coefficients vary with surface geometry, orientation, and flow conditions, making their determination complex and uncertain in FEMM.

2. Limited Validation: Without experimental data or validated reference models, FEMM thermal models may produce significant prediction errors, undermining design decisions.

3. Systematic Tuning Methodology: No established framework exists for systematically calibrating FEMM thermal parameters using validated commercial software as a reference.

4. Parameter Sensitivity: Understanding which thermal parameters most significantly affect model accuracy is unclear, making it difficult to prioritize refinement efforts.

This research addresses these gaps by developing a systematic methodology for tuning FEMM thermal model parameters using JMAG Express as a validated reference, guided by local sensitivity analysis.

1.3 Objectives

The research aims to achieve the following objectives:

1. To conduct local sensitivity analysis to identify critical thermal parameters affecting the accuracy of FEMM thermal models for PMSMs.

2. To develop a systematic parameter tuning methodology for FEMM thermal models using JMAG Express as a validated reference, incorporating optimization algorithms to minimize temperature prediction errors.

3. To validate the tuned FEMM thermal model and assess its accuracy compared to the reference JMAG model across multiple operating conditions.

1.4 Scope

This research focuses on the following scope:

Motor Configuration:

- A selected PMSM with defined geometry and specifications (power rating: 1-10 kW)

- Surface-mounted or interior permanent magnet topology

- Natural or forced air cooling configuration

Thermal Analysis:

- Steady-state and transient thermal analysis
- Parameter tuning based on nodal temperature comparison
- Electromagnetic losses obtained from JMAG or analytical methods (not calculated in this study)

Sensitivity Analysis:

- Local sensitivity analysis of thermal parameters including:
- Convection coefficients (housing surfaces, airgap, endcaps)
- Thermal conductivities (windings, core materials)
- Contact thermal resistances (stator-housing, rotor-shaft)

Parameter Tuning:

- Automated tuning using optimization algorithms (Levenberg-Marquardt, Nelder-Mead, or Particle Swarm). We may start with a more basic manual tuning
- Multi-operating point calibration for robustness
- Target accuracy: RMSE < 5°C for critical temperatures

Exclusions:

- Experimental validation (computational validation only)
- Detailed CFD analysis of air flow patterns
- Mechanical stress and vibration analysis
- Electromagnetic loss calculation (external input)

1.5 Significance of the Study

This research contributes to electrical machine thermal analysis in several ways:

Practical Contribution: Enables accurate thermal analysis using free, open-source software (FEMM) without expensive commercial licenses, making thermal modeling accessible to small enterprises, academic institutions, and researchers in developing countries.

Methodological Contribution: Provides a systematic framework for improving simplified thermal model accuracy using validated commercial software as reference, extendable to other electrical machines.

Academic Contribution:Sensitivity analysis insights guide future research efforts and help prioritize experimental characterization activities.

Economic Contribution: Reduces product development costs and time-to-market by enabling accurate thermal predictions with free software.

CHAPTER 2

LITERATURE REVIEW

1.6 Thermal Modeling of Electrical Machines

1.6.1 Thermal Analysis Methods

Three primary methodologies exist for motor thermal modeling: Lumped Parameter Thermal Networks (LPTN), Finite Element Analysis (FEA), and Computational Fluid Dynamics (CFD).

LPTN models simplify motor geometry into discrete thermal nodes connected by resistances and capacitances, offering computational efficiency and rapid solutions suitable for early design stages. However, LPTN provides limited spatial resolution and may not capture complex 3D heat transfer accurately.

FEA provides detailed spatial temperature distribution by discretizing geometry into numerous elements, capturing complex geometries and multi-dimensional heat flow with high fidelity. Drawbacks include longer computational time and requirements for accurate material properties and boundary conditions.

CFD offers the most detailed convective heat transfer representation but demands significant computational resources and expertise, making it impractical for routine design iterations.

1.6.2 PMSM Thermal Characteristics

PMSMs exhibit unique thermal characteristics with primary heat sources including copper losses in stator windings, core losses in laminated steel, permanent magnet eddy current losses, and mechanical losses in bearings. Heat dissipation occurs through conduction, convection, and radiation pathways.

The winding region typically experiences highest temperatures due to concentrated copper losses and poor insulation thermal conductivity. Permanent magnets are temperature-sensitive, as excessive heating causes irreversible demagnetization. Thermal time constants vary significantly across components, necessitating careful steady-state and transient analysis.

1.7 FEMM and JMAG for Thermal Modeling

1.7.1 FEMM Software Capabilities

FEMM is an open-source finite element analysis suite for 2D electromagnetic and heat flow problems. For thermal analysis, FEMM solves steady-state and time-harmonic heat conduction equations using finite element methods with automatic mesh generation and scripting capabilities through Python and MATLAB.

Key challenges include: (1) 2D limitation requiring 3D heat flow approximations, (2) simplified convection boundary conditions requiring user-specified coefficients, (3) material property uncertainty for composite materials and contact resistances, and (4) loss distribution complexity.

1.7.2 JMAG Express LPTN Modeling

JMAG Express provides template-based motor analysis including thermal analysis using pre-configured LPTN models validated against experimental data. The software incorporates empirical correlations for convection heat transfer based on motor geometry and cooling configuration, automatically calculating electromagnetic losses and mapping them to thermal nodes.

The LPTN structure divides motors into discrete thermal regions (stator core, windings, rotor core, magnets, shaft, housing) characterized by thermal capacitances, with thermal resistances representing heat transfer paths through conduction, convection, and radiation. Examples are as shown in Figure below.

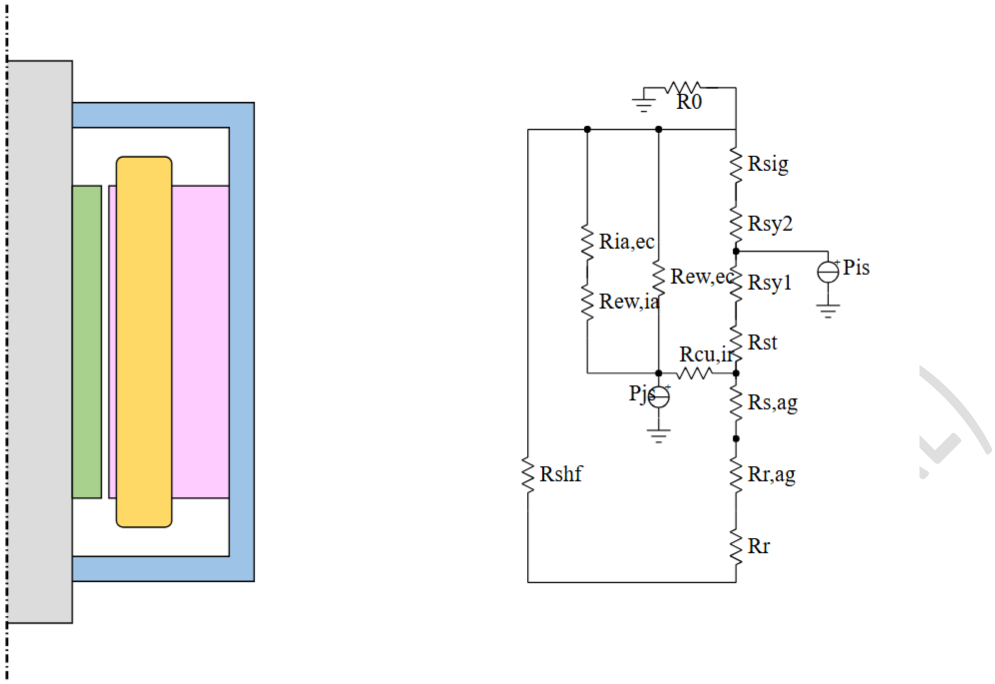

Figure. The cross section of the PMSM motor (left) and the lumped-parameter thermal model (right). The corresponding thermal resistance components of the LPTN model

Detail(Thermal Resistance)

- [ ] Rsy1:Outside Stator Yoke, K/W:
- [ ] Rsy2:Inside Stator Yoke, K/W:
- [ ] Rst:Stator Teeth, K/W:
- [ ] Rr:Rotor, K/W:
- [ ] Rshf:Shaft, K/W:
- [ ] R0:Natural Convection, K/W:
- [ ] Reca:Forced Convection, K/W:
- [ ] Rewec:Stator Winding-External Case, K/W:
- [ ] Rcuir:Stator Copper-Stator Slot, K/W:
- [ ] Rsig:Stator Core-External Case, K/W:
- [ ] Rsag:Stator Teeth-Airgap, K/W:
- [ ] Rrag:Rotor-Airgap, K/W:
- [ ] Riaec:Internal Air-Endcap, K/W:
- [ ] Rewia:Stator Winding-Inner Air, K/W:

1.8 Parameter Identification and Tuning Methods

1.8.1 Experimental Parameter Identification

Experimental determination involves temperature measurements under controlled conditions using thermocouples, RTDs, or infrared cameras. Inverse heat transfer methods estimate unknown parameters by minimizing differences between measured and predicted temperatures. While providing reliable values, this approach requires prototypes, specialized instrumentation, and controlled test conditions.

1.8.2 Computational Parameter Estimation

CFD simulations predict convection coefficients by solving detailed fluid flow equations. Semi-empirical correlations based on dimensionless numbers (Nusselt, Reynolds, Prandtl) provide estimates for standard geometries. Model-to-model parameter tuning adjusts simplified model parameters to match validated higher-fidelity model predictions, offering a practical compromise avoiding experimental costs.

1.8.3 Optimization-Based Tuning

Optimization algorithms systematically adjust model parameters to minimize prediction errors. Gradient-based methods (Levenberg-Marquardt) offer rapid convergence for smooth functions. Gradient-free methods (Particle Swarm, Genetic Algorithms) prove robust for non-smooth problems but require more evaluations.

1.9 Sensitivity Analysis in Thermal Modeling

Sensitivity analysis quantifies how input parameter variations affect model outputs, guiding experimental characterization and uncertainty quantification. Local sensitivity analysis examines small perturbations around nominal values, computing partial derivatives. Global sensitivity explores entire parameter spaces.

Applications in electrical machine thermal modeling identify critical convection coefficients, material properties requiring precise characterization, and potential for model simplification. Studies generally find convection coefficients on external surfaces and winding thermal conductivity among the most influential parameters.

1.10 Research Gaps and Opportunities

Literature review reveals several gaps: (1) limited accessibility of validated thermal models using free software, (2) insufficient systematic parameter tuning methodologies using validated references, (3) lack of comprehensive sensitivity analysis guidance for different motor topologies, and (4) limited integration between different software tools.

This research addresses these gaps by developing a systematic methodology for tuning FEMM thermal models using JMAG Express as validated reference, incorporating sensitivity analysis to prioritize parameters, and providing an accessible framework for accurate PMSM thermal analysis using open-source software.

CHAPTER 3

METHODOLOGY

1.11 Introduction

The research follows five main phases:

1. Reference Model Development: Create validated thermal model in JMAG Express

2. FEMM Model Development: Develop corresponding FE thermal model with scripting

3. Sensitivity Analysis: Conduct local sensitivity analysis identifying critical parameters

4. Parameter Tuning: Optimize FEMM parameters matching JMAG temperature predictions

5. Validation and Assessment: Evaluate tuned FEMM model accuracy

1.12 Motor Selection and Specifications

A representative PMSM will be selected based on:

- Power rating suitable for research scope (1-10 kW)
- Common topology (surface-mounted or interior permanent magnets)
- Natural or forced air cooling configuration
- Availability of geometric and material specifications

Motor specifications will include geometric parameters, winding configuration, magnetic materials, and rated operating conditions.

1.13 JMAG Express Thermal Model Development

1.13.1 Model Setup

1. **Geometry Definition**: Input motor geometric parameters into JMAG Express templates
2. **Material Property Assignment**: Assign thermal properties for all components (steel, magnets, copper, insulation, housing)
3. **Loss Calculation**: Calculate electromagnetic losses using JMAG Express electromagnetic analysis (copper losses, core losses, magnet losses, mechanical losses)
4. **Boundary Conditions**: Define ambient temperature and convection coefficients (automatically calculated by JMAG)

1.13.2 Analysis Configuration

Perform two analysis types:

- **Steady-State Analysis**: Equilibrium temperature distribution under rated load

- **Transient Analysis**: Thermal response from cold start to steady-state (once steady state completed)

Multiple operating conditions will be analyzed: rated load (100%), partial loads (25%, 50%, 75%), and overload conditions if applicable.

1.13.3 Reference Data Extraction

Extract temperature data from JMAG Express for comparison:
- Winding hot spot and average temperature
- Stator core maximum temperature
- Rotor magnet maximum temperature
- Housing surface temperature
- Temperature distribution along specific paths

1.14 FEMM Thermal Model Development

1.14.1 Geometry Creation

Create 2D axisymmetric or cross-sectional representation with:

- 2D cross-section capturing radial heat flow
- Axial heat flow represented through equivalent boundary conditions
- End-windings modeled with adjusted thermal properties
- Meshing strategy: finer mesh in high-gradient regions, coarser in uniform regions

1.14.2 Material Property Assignment

Initial properties based on literature:

- Stator/rotor core: 30 W/m·K
- Permanent magnets: 8 W/m·K
- Winding equivalent: 0.5-1.5 W/m·K (to be tuned)
- Housing: 205 W/m·K (aluminum)
- Airgap: 0.026 W/m·K

1.14.3 Heat Source Definition

Define volumetric heat generation rates (W/m³) based on JMAG losses:

- Copper losses distributed in winding volume
- Core losses distributed in core volume
- Magnet losses distributed in magnet volume

1.14.4 Boundary Conditions

Initial convection coefficient estimates:

- Housing surfaces (natural convection): 3-10 W/m²·K
- Airgap (rotating): 50-500 W/m²·K depending on speed
- Contact resistances between components

1.14.5 Scripting and Automation

Develop Python/MATLAB scripts for:

1. Parametric geometry generation
2. Material property assignment
3. Mesh generation

4. Boundary condition application
5. Solution execution
6. Post-processing and data extraction
7. Parameter sweeps for sensitivity analysis
8. Integration with optimization algorithms

1.15 Local Sensitivity Analysis

1.15.1 Sensitivity Analysis Parameters

Examine influence of:
- **Convection Coefficients**: h_housing (top/side/bottom), h_airgap, h_endcap
- **Thermal Conductivities**: k_winding, k_stator_core (radial/tangential)
- **Contact Resistances**: R_rotor_shaft, R_stator_housing

1.15.2 Sensitivity Coefficient Calculation

Calculate local sensitivity using central finite difference:

$$S_i = \partial T/\partial p_i \approx [T(p_i + \Delta p_i) - T(p_i - \Delta p_i)] / (2\Delta p_i)$$

Normalized sensitivity coefficient for comparison:

$$S_{i,norm} = (p_i / T) \times (\partial T/\partial p_i)$$

1.15.3 Sensitivity Analysis Procedure

1. Run baseline simulation with nominal parameters
2. Perturb each parameter ±5-10%
3. Calculate sensitivity coefficients
4. Rank parameters by sensitivity magnitude
5. Create visualization (tornado diagrams, sensitivity matrices)

1.16 Parameter Tuning and Optimization

1.16.1 Tuning Problem Formulation

Minimize sum of squared errors between FEMM and JMAG temperatures:

$$J(p) = \Sigma\, w_i \times [T_{FEMM,i}(p) - T_{JMAG,i}]^2$$

Subject to physical parameter bounds.

1.16.2 Optimization algorithm Selection

Evaluate multiple algorithms: Example of algorithm. (we may use a simpler method first)
- **Levenberg-Marquardt**: For least-squares problems
- **Nelder-Mead**: Gradient-free, robust for non-smooth functions
- **Particle Swarm Optimization**: Global optimization, less prone to local minima

Idea: Use hybrid strategy: coarse exploration (PSO) followed by refinement (Levenberg-Marquardt).

1.16.3 Multi-Operating Condition Tuning

Optimize across multiple load cases simultaneously:

$$J_{total}(p) = \Sigma_j\, \alpha_j \times \Sigma_i\, w_i \times [T_{FEMM,i,j}(p) - T_{JMAG,i,j}]^2$$

Ensures robust parameters across operating range.

1.17 Performance Metrics

Quantify performance using:
- **RMSE**: Root Mean Square Error
- **Maximum Absolute Error**
- **Correlation Coefficient (R^2)**
- **Target**: RMSE < 5°C for critical temperatures, < 10°C for secondary temperatures

1.18 Research Timeline

Months 1-3: Literature review, software familiarization, motor selection

Months 4-6: JMAG Express reference model development

Months 7-9: FEMM model development and scripting

Months 10-12: Sensitivity analysis

Months 13-16: Parameter tuning and optimization

Months 17-20: Validation and comparison

Months 21-24: Thesis writing and defense

CHAPTER 4

RESULTS AND DISCUSSION (EXPECTED)

1.19 Expected JMAG Express Reference Results

JMAG Express thermal analysis is expected to provide comprehensive temperature distribution:

Steady-State Temperatures (Rated Load):

- Winding hot spot: °C
- Average winding: °C
- Stator core maximum: °C
- Magnet maximum: °C
- Housing surface: °C

Thermal Time Constants:

- Winding:
- Stator core:
- Housing:
- Overall motor:

1.20 Expected Sensitivity Analysis Results

- Highly Sensitive Parameters (normalized sensitivity > 0.2): Components?
- Moderately Sensitive Parameters (0.1-0.2): Components?

- Low Sensitivity Parameters (< 0.1): Components?

These results will guide parameter selection for optimization, focusing on high-sensitivity parameters.

1.21 Expected Parameter Tuning Results

Optimization expected to yield adjusted parameters:

Parameter	Initial Value	Expected Tuned Value	Expected Change
h_housing_top	8 W/m²·K	6-10 W/m²·K	±?%
h_airgap	150 W/m²·K	100-250 W/m²·K	±?%
k_winding	1.0 W/m·K	0.6-1.5 W/m·K	±?%

Convergence: ?

1.22 Expected Validation Results

After tuning, FEMM model expected to achieve:

Accuracy Metrics (Steady-State Rated Load):

Location	JMAG	FEMM Before	FEMM After
Winding Hot Spot	-°C	-°C -3°C)	134°C -°C)
Avg Winding	-°C	-°C -°C)	124°C (-°C)
Magnet Max	-°C	-°C (-°C)	-°C (-°C)

Performance Improvement:

- Before tuning: RMSE ≈ -°C

- After tuning: RMSE ≈ -5°C

- Improvement: >-% reduction in RMSE

Multi-Operating Point Performance: Slightly higher errors for untrained conditions (?°C) but still acceptable, demonstrating generalization?

1.23 Expected Contributions

1. Methodological: Systematic tuning framework using validated reference models

2. Technical: Quantitative sensitivity data and accuracy benchmarks for PMSM thermal modeling

3. Practical: Demonstrating acceptable accuracy achievable without expensive commercial software

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