**2D Hybrid Magnetic Field Model Performance Optimization for Linear Induction Motor**

By

**Michael Thamm**

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by

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May TBD, 2022

# DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I hereby declare that this thesis incorporates material thatis result of joint research, as follows:

This thesis contains the outcomes of publications which include the contributions of co-authors who were/are post-doctoral fellows, graduate students or associate professors under the supervision of Dr. Narayan C. Kar. In all cases, only my primary contributions towards these publications are included in this thesis. The contribution of co-authors was primarily with respect to refinement and editing process. In Chapter 2, I was the co-author in which I was actively part of experimental testing and assisted in data analysis. The model developed by the primary author, A. Fatima, in this publication is used by the proposed method and is therefore described in this chapter. Chapter 5, I was the co-author in which I applied the proposed method to predict dynamic performance characteristics. Only the sections with my personal contribution are included in this thesis to analyze the performance of the proposed method described in this thesis.

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|  |  |  |
| --- | --- | --- |
| Thesis Chapter | Publication title/full citation | Publication status |
| *Chapter 2* | A. Fatima, **T. Stachl**, M. S. Toulabi; W. Li, J. Tjong, G. Byczynski, and N. C. Kar, "Permeance–Based Equivalent Circuit Modeling of Induction Machines Considering Leakage Reactances and Non–Linearities for Steady–State Performance Prediction," *IECON 2021–47th Annual Conference of the IEEE Industrial Electronics Society*, 2021, pp. 1-6. | *Published* |
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# ABSTRACT

New electric vehicles demand higher performing, more cost-effective electric motors leading to the tractive induction motor (IM) being a promising choice for electric vehicles. Tractive IMs, however, have lower torque densities and slightly lower efficiency due to losses incurred in the rotor must be improved through rotor bar optimization to improve torque and reduced losses considering dynamic operating conditions. Numerous design factors, material limitations and performance characteristics must be considered during the design of tractive IMs prompting the use of optimization algorithms capable of systematically optimizing multiple design aspects. Unfortunately, conventional optimization algorithms are time consuming, limited objectives and input variables and susceptible to function bias resulting in undesirable traits for IM optimization. Therefore, a novel, robust non-dominated adaptive restart genetic algorithm capable of geometric rotor bar optimization considering dynamic operation is developed and proposed. To attain the desired optimization algorithm and optimal rotor bar geometry, this thesis: (1) Analyzes the challenges of IM design optimization, identifying optimization targets and design constraints. (2) Investigates and selects an optimization algorithm fit for IM design applications. (3) Proposes novel hyperbolic tangent based objective functions ensuring non-dominated solution. (4) A new adaptive restart genetic algorithm is developed with enhanced resistance to stalling minimizing run time. (5) The novel algorithm is implemented to optimize the torque and losses producing an optimal rotor bar which is validated and compared to a baseline IM. The proposed method is applicable to various IM topologies for multiple objective targets.

# DEDICATION

This thesis is dedicated to my other half, Miranda, and my family, Mara, Sonja, Chris and Tala. I love you all very much. Thank you for all your understanding, motivation, strength and support along the way. I would not have made it to where I am now without all of you.

To my friends who never failed to brighten my day, thank you gators. I appreciate and love you all. $20 to the first one of you to read it cover to cover!

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I would also like to thank all current and past members of the CHARGE Labs for your comradery throughout my time at the University of Windsor. I have learned from each of you. A special thank you to Dr. Aida Mollaeian for granting me access to the motor she designed and prototyped for use as the baseline motor in this thesis and to Dr. Shruthi Mukundan and Dr. Himavarsha Dhulipati for their warm welcome and patience when I entered the CHARGE Labs. Animesh Anik, Pengzhao Song, Areej Fatima and Buddhika G. Vidanalage, I greatly appreciate all your support and the friendship that was established. Lastly, I would like to thank a dear friend who I had the pleasure of sharing many laughs with, David Montgomery. Thanks, Buddy.

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# LIST OF ABBREVIATIONS

|  |  |
| --- | --- |
| **Abbreviation** | **Description** |
| LEM | Linear Electric Motor |
| REM | Rotary Electric Motor |
| LIM | Linear Induction Motor |
| LSM | Linear Synchronous Motor |
| HAM | Hybrid Analytical Model |
| HM | Harmonic Model |
| MEC | Magnetic Equivalent Circuit |
| ECM | Equivalent Circuit Model |
| FEA | Finite Element Analysis |
| OA | Optimization Algorithm |
| EA | Evolutionary Algorithm |
| NN | Neural Network |
| PSO | Particle Swarm Optimization |
| OMOPSO | Optimized Multi-Objective Particle Swarm Optimization |
| GA | Genetic Algorithm |
| NSGAII | Non-Dominated Sorting Genetic Algorithm II |
|  |  |
|  |  |
|  |  |
|  |  |

# NOMENCLATURE

|  |  |
| --- | --- |
| **Variable** | **Description** |
|  | Number of slots |
|  | Number of poles |
|  | Number of phases |
|  | Synchronous velocity |
|  | Electrical frequency |
|  | Pole pitch |
|  | Peak current |
|  | Phase current |
|  | Number of turns per coil |
|  | Magnetomotive force scaling factor |
|  | Number of nodes in the x-direction for a single coil |
|  | Slots/poles/phase |
|  | Conductivity |
|  | Vacuum permeability |
|  | Relative permeability |
|  | Slot height |
|  | Yoke height |
|  | Tooth width |
|  | Slot width |
|  | Slot pitch |
|  | Airgap |
|  | Aluminum thickness |
|  | Back iron thickness |
|  | Primary length |
|  | Primary height |
|  | Primary depth |
|  | Periodical length of model |
|  | Space harmonic |
|  | Spatial frequency for nth space harmonic |
| , | Complex harmonic analysis unknowns for nth space harmonic |
|  | Spatial position in the x-direction |
|  | Spatial position in the y-direction |
|  | Number of harmonic model regions in the model |
|  | Number of magnetic equivalent circuit regions in the model |
|  | y-index of a node in the magnetic equivalent circuit region |
|  | x-index of a node in the magnetic equivalent circuit region |
|  | Number of rows in a magnetic equivalent circuit region |
|  | Number of columns in a magnetic equivalent circuit region |
|  | Total nodes in a magnetic equivalent circuit region |
|  | Reluctance |
|  | Magnetomotive force |
|  | Flux |
|  | Complex scalar potential |
|  | Surface Area |
|  | Magnetic flux density |
|  | Magnetic field |

# Introduction

## Electric Vehicles–A Green Form of Personal Transportation

### A Surging Interest in Electric Vehicles

### Industry Leading Electric Drive System for Tractive Applications

## State of the Art Electric Motors for Tractive Applications

## Literature Survey on Traction Induction Motor Design and Geometry

### Stator Design and Geometry

### Rotor Design and Geometry

### Summary of the Effect of Geometry on Design Factors

## Tractive Induction Motor Optimization

### Tractive Induction Motor Analytical Modeling for Optimization

### Induction Motor Optimization Input Variables and Objective Targets

## Research Motivations

### Vehicle Level Motivations

### Motor Level Motivations

### Algorithm Level Motivations

## Research Objectives

## Research Contribution and Deliverables

## Organization of Thesis

This thesis proposes a novel method of metaheuristic optimization of LIMs to improve the thrust-to-weight ratio. The major sections of this thesis are as follows:

1. Chapter 1 provides an overview of EVs, LEMs and the use of OAs in induction machine optimization, demonstrating the motivations, challenges and objectives associated with the proposed method from a vehicle level to the motor level and the incorporation of the algorithm level.
2. The baseline LIM considered for optimization is introduced in chapter 2, outlining the base rotor bar shape and the baseline torque and loss performance is determined. The modified permeance based equivalent circuit model used in the proposed method is described and validated, and the optimization algorithm to be used is selected.
3. A novel OF modeling strategy is proposed and tested in chapter 3 to ensure all function bias is eliminated between the torque and loss objectives during optimization. The elimination of function bias ensures a balanced optimal solution across all objectives.
4. The development of a robust adaptive restart GA is detailed in chapter 4 to improve the algorithms ability to resist stalling and early convergence, increase the final solution quality and reduce the overall run time through intelligent search space reduction.
5. Chapter 5 incorporates the effects of various dynamic operating conditions required by tractive IMs into the optimization process. These dynamic operating points are determined over the WLTP -3 drive cycle and reduced using the energy center of gravity method ensuring operating conditions of the highest energy consumption are represented.
6. Chapter 6 analyzes the optimized rotor bar shape and performance against the baseline motor and validates using FEA. The algorithm performance of the novel non-dominated adaptive restart GA is analyzed and discussed.
7. Chapter 7 summarizes the results generated through the proposed method and identifies the future scope of the proposed research and developed method in the area of IMs and algorithm-based IM optimization.

# Permeance Based Equivalent Circuit Modeling of Induction Motors and Optimization Algorithm Selection

## Baseline Tractive Electric Motors

## Permeance Base Equivalent Circuit Modeling of Induction Motors

### Incorporation of Leakage Effects

### Incorporation of Non-Linearities

### Permeance Based Model Validation

## Optimization Algorithms

### Particle Swarm Optimization

### Genetic Algorithms

### Schwefel Function Minimization Case Study

While the modelling methods are important for quantifying motor performance, the model optimization algorithm must also be chosen methodically and implemented effectively. To categorize the field of optimization algorithms, some classifications were provided to simplify the choice. There are 3 main types of optimization algorithms shown in Figure X which serve a similar purpose in the optimization process. The evolutionary algorithm [EA] and the neural network [NN] are both metaheuristics while gradient based algorithms [GBA] require function evaluations to determine search directions. Due to the limitations in complexity and flexibility, GBAs are used for small-scale or local optimizations. Since the model mesh evaluations require metaheuristics, therefore the choice is limited to EAs and NNs. Although NNs are very effective at solving and predicting solutions to complex problems, such as classification, they are computationally intensive. As a result, EAs were chosen as the appropriate optimization algorithm category which includes the genetic algorithm [GA] and particle swarm optimization [PSO], to name a few. These algorithms find a balance between flexibility and efficiency while maintaining robustness.

A case study was conducted to determine the optimal optimization algorithm among the subset of EAs through the Schwefel test function. A test function is used to test the ability of an optimization algorithm to converge on a solution that is the global maximum or minimum rather than the function’s local maxima or minima. The Schwefel function was chosen since it has a plethora of local maxima and minima which can stall solvers prior to converging on the solution. The function is defined as:

where is the number of input dimensions and is the function input per dimension . The global minimum is located at inside of the hypercube for all

Chart, surface chart

Description automatically generated

To couple a solver to this test function, a new input is generated by the solver per iteration. These inputs are used to calculate and minimize the objective value through the Schwefel function until convergence on a solution. To ensure that each optimization algorithm is fairly compared in this case study, common solver parameters are used to configure each algorithm. Every algorithm will execute 30 iterations over its population with the only solver termination criteria being the max number of executions reached. Other solver termination criteria like reaching objective tolerance or stalling were omitted in this case study to determine the speed of each algorithm and the ability to converge on the correct solution with a fixed number of iterations. Additionally, the optimization process is conducted 5 times to determine the average performance to ensure that an outlier does not significantly impact the decision making. Table X compares the EAs: PSO and GA through performance parameters like execution time and error. The solver accuracy is the principal performance parameter, while the solver time holds less value as a performance parameter. From these criteria, the PSO algorithm outperforms the GA in both solution accuracy and solver speed.

Table X – Optimization Algorithm Comparison

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Algorithm** | **PSO** | **OMOPSO** | **GA** | **NSGAII** |
| **Population/Swarm Size** | 1000 | | | |
| **Offspring/Leader Size** | 200 | | | |
| **Algorithm Iterations** | 30 | | | |
| **Average Time (s)** | 1.68 | 2.45 | 2.03 | 2.95 |
| **Average Error In X** | 0.0000 | 0.0000 | 0.0041 | 0.0039 |
| **Average Error In Y** | 0.0000 | 0.0000 | 0.0216 | 0.0009 |
| **Average Error in Objective** | 0.0000 | 0.0000 | 0.0001 | 0.0000 |

I should do another test similar to above but with function tolerance to expand on the robustness between models. This will give me at least another page of content

The EA chosen from this case study will be implemented to optimize the HAM which will require multi-objective optimization. Without modification, PSO and GA cannot optimize multi-objective problems and require a modified implementation that produces non-dominated solutions. The non-dominated sorting genetic algorithm II [NSGAII] is a modified implementation of the GA, while the optimized multi-objective particle swarm optimization [OMOPSO] is a modified implementation of the PSO. These algorithms were included in the comparison of Table X. The data is not in favor of the NSGAII algorithm, solidifying the decision to use OMOPSO as the multi-objective optimization algorithm for the HAM. This decision is further enforced through a comparative study between NSGAII and OMOPSO [Reference that OMOPSO is better than NSGAII](https://www.researchgate.net/publication/224212508_An_Experimental_Comparison_of_Multiobjective_Algorithms_NSGA-II_and_OMOPSO) which concludes that “The binary values of the metrics indicate that OMOPSO is relatively better than the NSGAII in two test functions and better in one test function”. As a result, all future optimization of HAM will be conducted using OMOPSO to gather non-dominated solutions for the motor optimization objective.

Table 2.4

Optimization Algorithm Parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| PS Optimization | | PSO | | GA Optimization | |
| Parameter | **Value** | **Parameter** | **Value** | **Parameter** | **Value** |
| Maximum Iterations | 25 | **Maximum Iterations** | 500 | **Maximum Iterations** | 500 |
| Max Stall Iterations | 5 | **Max Stall Iterations** | 25 | **Max Stall Iterations** | 25 |
| Function Tolerance | 10-6 | **Function Tolerance** | 10-6 | **Function Tolerance** | 10-6 |
| Global Upper Bound | [500, 500] | **Global Upper Bound** | [500, 500] | **Global Upper Bound** | [500, 500] |
| Global Lower Bound | [-500, -500] | **Global Lower Bound** | [-500, -500] | **Global Lower Bound** | [-500, -500] |
| Reduction Factor | 25% | **Swarm Size** | 200 | **Population Size** | 200 |
| Resolution | 100 | **Global Vector Constant** | 40% | **Crossover Fraction** | 30% |
| Resolution Factor | 15% | **Local Vector Constant** | 25% | **Mutation Fraction** | 10% |

Table 2.5

Optimization Algorithm Performance

|  |  |  |  |
| --- | --- | --- | --- |
| Optimization Algorithm | PS | PSO | GA |
| Total Iterations | 13 | 52 | 39 |
| Algorithm Run Time | 1.4560s | 9.3813s | 7.4137s |
| X1 Solution | 420.9706 | 420.9687 | 420.9687 |
| X2 Solution | 420.9706 | 420.9687 | 420.9687 |
| Function Value at Solution | 2.633 x10-5 | 2.5455 x10-5 | 2.5455 x10-5 |
| Error In Solution | 0.002633% | 0.0025455% | 0.0025455% |

by the PS, while Fig. 2.14 demonstrates the population of particles and individuals at Chart, surface chart

Description automatically generated

Fig. 2.13. Depicts the migration of the best-known solution of the PS algorithm over the 13 limit reduction iterations the PS algorithm performed.

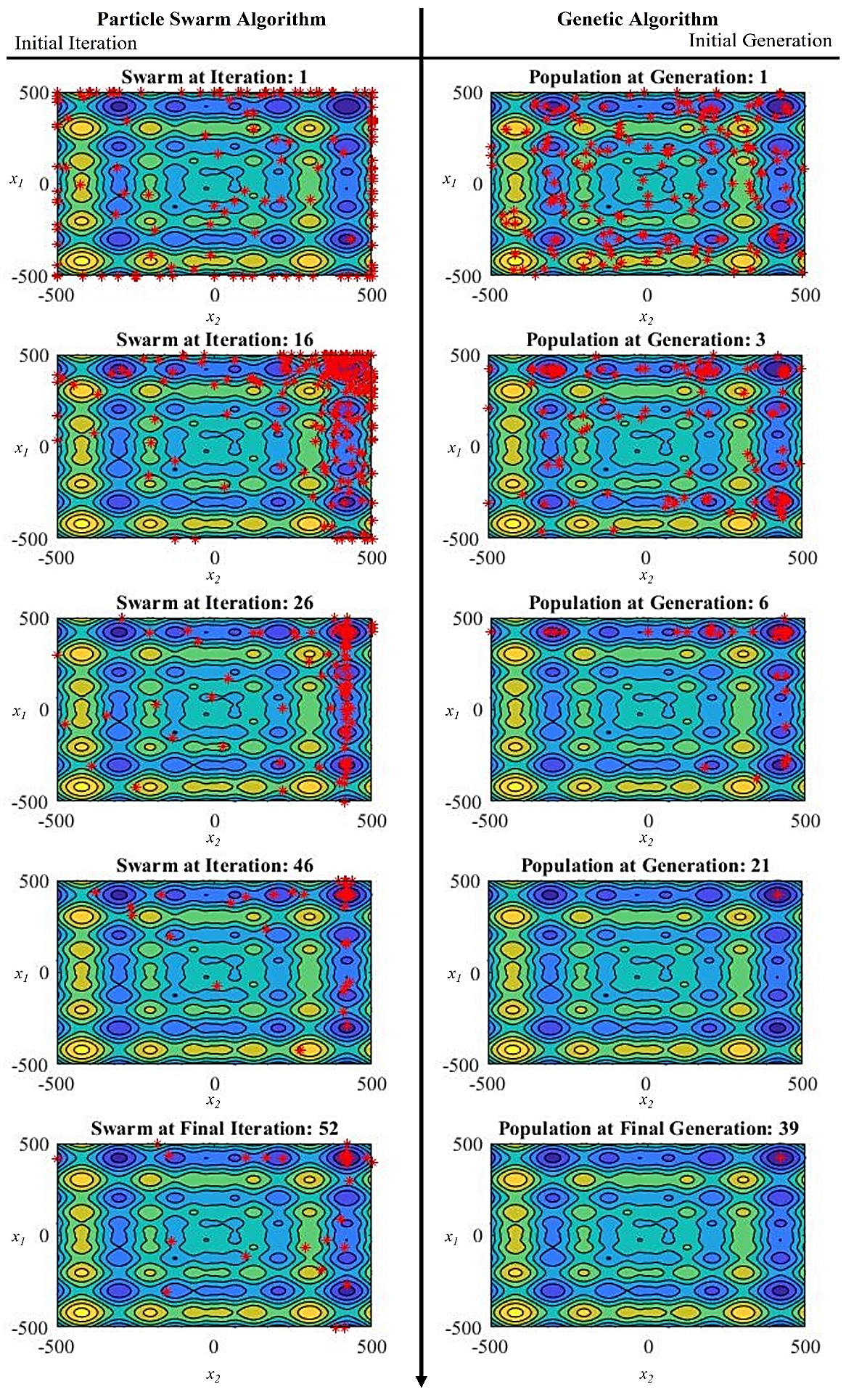


Fig. 2.14. Visualizes different stages of the particle swarm and GA optimization.

# Eliminating Function Bias in Multi-Objective Rotor Bar Optimization Through Novel Objective Function Modeling

## Significance of Objective Function Modeling

## Conventional Objective Function Modeling

## Novel Hyperbolic Tangent Based Objective Functions

# Enhanced Solution Quality Multi-Objective Rotor Bar Optimization Through Adaptive Restart Capabilities

# Rotor Bar Optimization Considering Dynamic Operating Conditions Through Energy Center of Gravity Clustering

## Significance of Considering Dynamic Operating Conditions

## Core Loss Prediction Under Dynamic Operating Conditions

### Core Loss Prediction Using Adaptive Restart Genetic Algorithm

### Adaptive Restart Genetic Algorithm Performance

## Considering Dynamic Operation Through Drive Cycle Based Testing

### Electric Vehicle Dynamics Modeling

### Simulated Dynamic Operating Points Over WLTC Class 3 Drive Cycle

## Operating Point Reduction Through Energy Center of Gravity Method

## Optimization Considering Multiple Operating Points

# Tractive Induction Motor Rotor Bar Optimization Using a Novel Non-dominated Adaptive Restart Genetic Algorithm Considering Dynamic Operating Conditions

## Novel Adaptive Restart Genetic Algorithm Performance

## Comparison of Optimal Rotor Bar Geometry and Validation

# Research Summary

## Conclusions

## Future Research on Rotor Bar Optimization of Tractive IMs

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