2D Hybrid Magnetic Field Model Performance Optimization for Linear Induction Motors

Outline

- Objectives
- Performance Modelling Standards
- Research Contributions & Novelty
- Implementing GA on DSLIM
- Results
- Conclusion
- Future Work & Timeline

Objectives

Overall Objective

The objective of my research is to produce an **optimized LIM** design through a **general relationship** between performance variables and motor parameter inputs created by **GA**.

Defining Objectives

Relating Performance Variables to Slot and Poles

- Find the best slot-pole combination for a motor application
    - Trial and error through FEA simulations or trend data is tedious

- Create a metaheuristic algorithm can solve this as they introduce their own variables and modify weights to produce an equation.

- Requires:
    - A flexible model
    - Computational efficiency
    - Accuracy in results

[1]

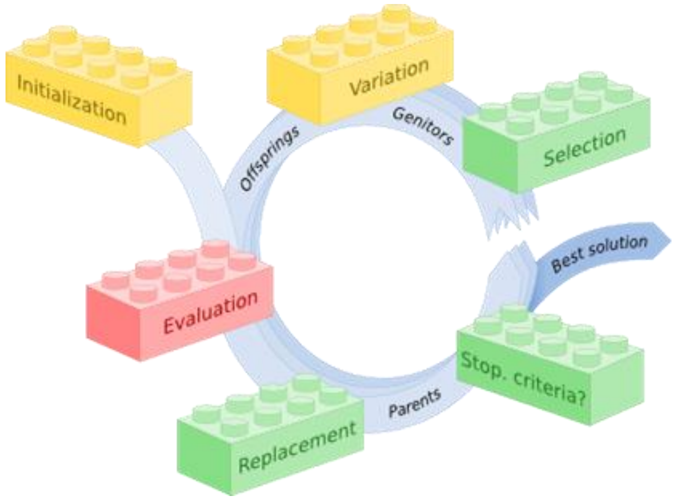


Figure 1: Algorithm Phases

Slot Optimization

Pros

- The field produced by the primary becomes more sinusoidal (efficient)
- End effect is a much lower percentage of the total power loss

Cons

- Thins the stator teeth causing higher flux densities, instability, and saturation
- Winding complexity

[2]

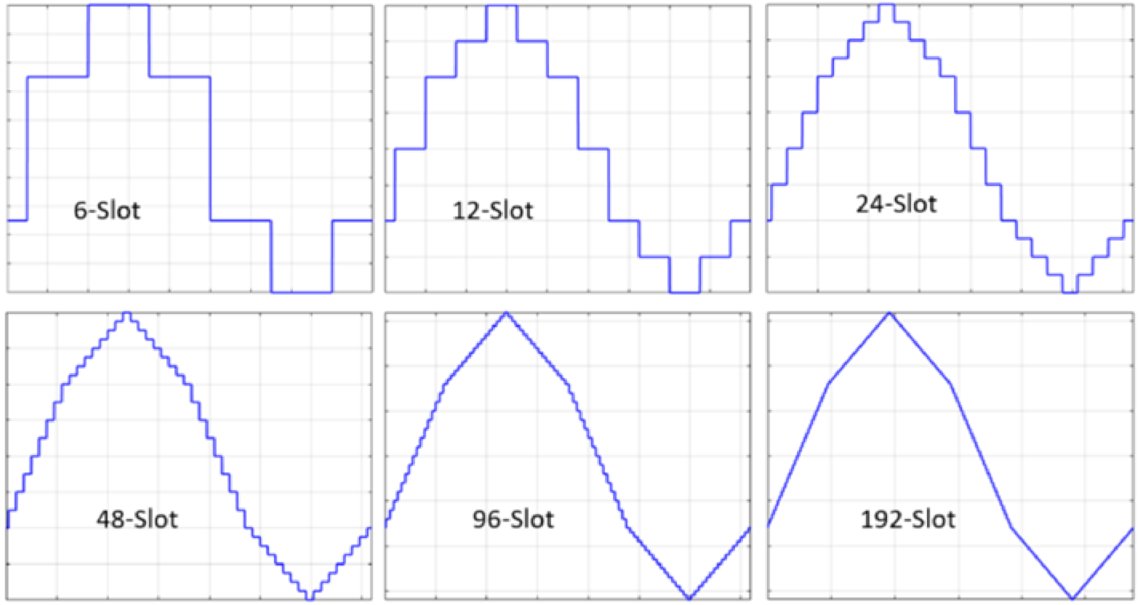


Figure 2: Slotting Effect On Primary Field Waveform

Pole Optimization

The number of poles greatly affects the performance of the motor through these equations:

- $V_s = 2f_sT_p$
  - Pole pitch changes with poles which means the poles directly affect **speed** and **frequency** of operation.

- Q = slots/poles/phases
  - High Q value motors will operate at higher driving thrust but loses efficiency.
  - High Q values require lower operating frequencies (skin effect).

[2]

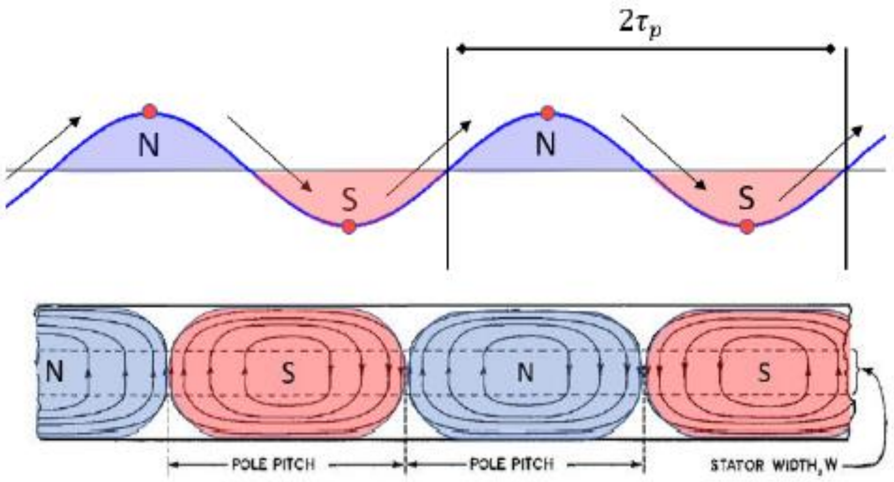


Figure 3: Magnetic Poles Related To Primary Field Waveform

Single-Sided LIM (SLIM) vs Double-Sided LIM (DLIM)[1]

- SLIM is less efficient due to the longer flux path through the air gap
  - Therefore, SLIMs use back iron to shorten this path length
- DLIM produces roughly twice the thrust for the same amount of rotor area used by the stator
- DLIM is only possible if both faces of the blade rotor are exposed
  - For example, an I-beam, otherwise a SLIM is required

[2]

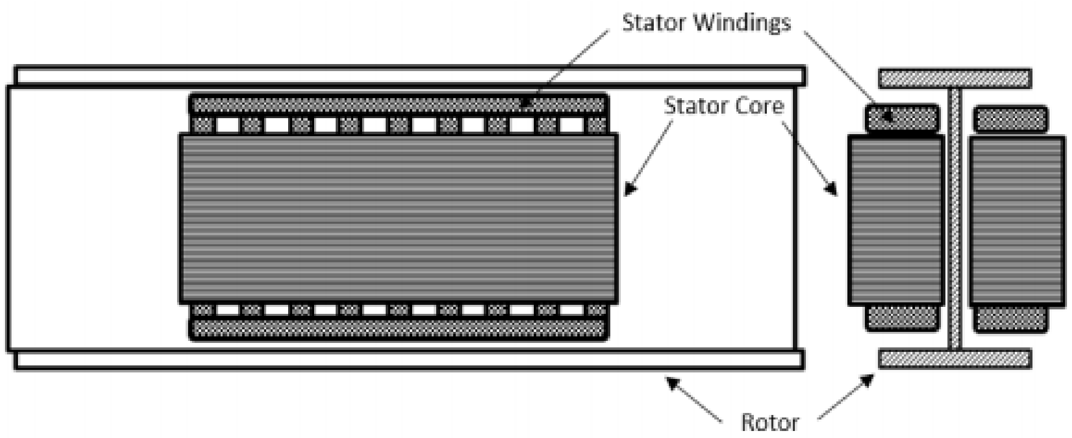
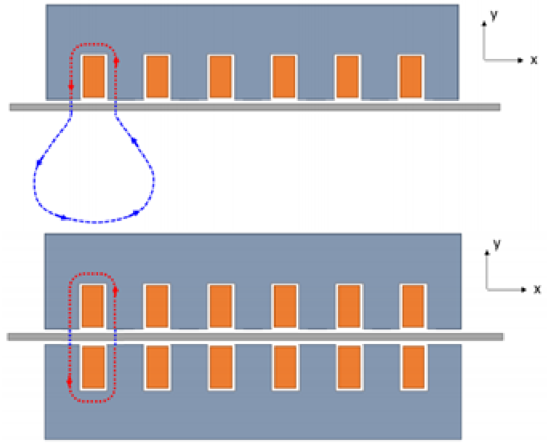


Figure 4: DLIM with I-beam Blade Rotor



[2]

Figure 5: SLIM vs. DSLIM Flux Paths

Performance Modelling Standards

Literature Survey

<u>Fourier Based Harmonic Modelling (HM)</u> [2]

- Computationally efficient
- Modelling accuracy depends on harmonics considered
- Limited modelling geometries

<u>Magnetic Equivalent Circuit Modelling (MEC)</u> [3]

- Accurate modelling of flux paths
- Ability to model complex geometries
- Modelling accuracy depends on mesh density
- Computationally intensive

<u>Hybrid Analytical Modelling (HAM)</u> [1], [3]

- Computationally efficient
- Modelling accuracy depends on harmonics and meshing density considered
- Flexible for all geometries
- Little error compared to FEA at sufficient parameters

Background Study

- At the boundary between MEC and Fourier regions the **continuity** of **By** and **Hx** must hold through these equations:

$$\varphi_{yn}^{HM}(l,k,t) = L_s \int_{x_l(l,k)-vt}^{x_r(l,k)-vt} B_y^{HM}(x, y_{BC})\,dx \quad , \quad \frac{1}{\mu_0 \mu_r^{HM}} B_x^{HM}(x, y_{BC}, t) = \sum_{k=1}^{K} \frac{1}{\mu_0 \mu_r^{MEC}(l,k)} B_x^{MEC}(x, y_{BC}, t)$$

- These equations include unknown variables ($\boldsymbol{a_n},\ \boldsymbol{b_n},\ \boldsymbol{\psi(l,k,t)}$) from both the MEC and Fourier regions
- HM unknowns scale with number of **harmonics**
- MEC unknowns scale with number of **nodes in the mesh**

[3]

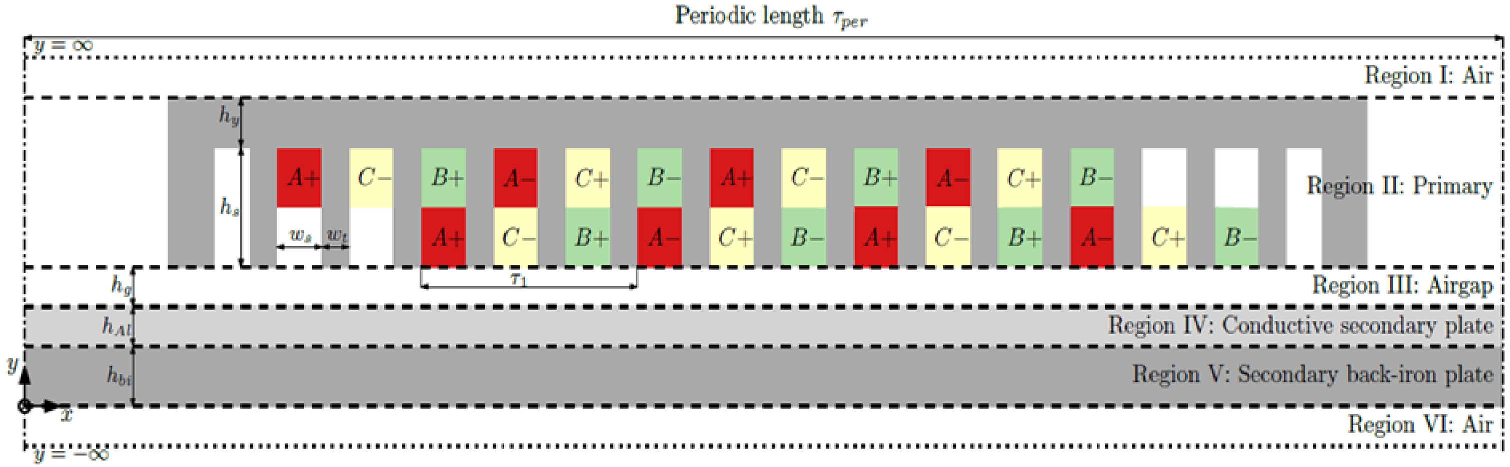


Figure 6: SLIM Modelled in Regions

Research Contributions & Novelty

Research Contributions

The proposed extended hybrid model considers the following:

- Incorporates **MEC & Fourier** modelling
    - Stator modelled as MEC for **complex winding** configurations and **stator designs**
- Incorporates **time & velocity** of the stator operation
- **Averaging** of the staircase-shaped magnetic flux density function
- **DLIM** modelling
- **Flexible motor input parameters** that produces a new model
- **Metaheuristic optimization** on a range of motors
    - Test **input range** of motor parameters for **performance trends**
    - Converge on **optimal** motor design

Novelty

- Producing an **innovative** motor design application that is competitive with industry motor simulation software
  - **Optimize** over a range of motors
  - ANSYS has optimization algorithms, single variable optimization

- Contributions towards DSLIM **design theory**
  - Produce a novel, general relationship between **slot-pole** combination and motor **performance**
  - GA creates its own equation through **weights and biases**

Constrain Motor Parameters

It is important to constrain well defined parameters for computational efficiency and feasibility

- Constants – if the value is known
- Defined range – if the upper and lower limits are known
- Ratio – if there is a linear relationship between 2 variables (introduces manageable error)

Constant		Range	Ratio
Stator Length	Back Iron Height	Slots	Slot Width
Stator Height	Input Current	Poles	Tooth Width
Stator Depth	Velocity		Fill Factor
Yoke Height	Winding Turns		
Slot Height	Frequency		
Air Gap	Time		
Rotor Height			

Table 1: Variable Constraints for Proposed Algorithm

Implementing GA on DSLIM

GA Framework

- The state diagram takes in an original slot-pole combination guess
- **Build Motor** calculates the remaining motor parameters and builds the model mesh
- **Compute HAM** builds the matrix equation Ex=Y to solve for the unknown variables.
- **Compute Fitness** takes the performance parameters and calculates the fitness value of that given slot-pole combination

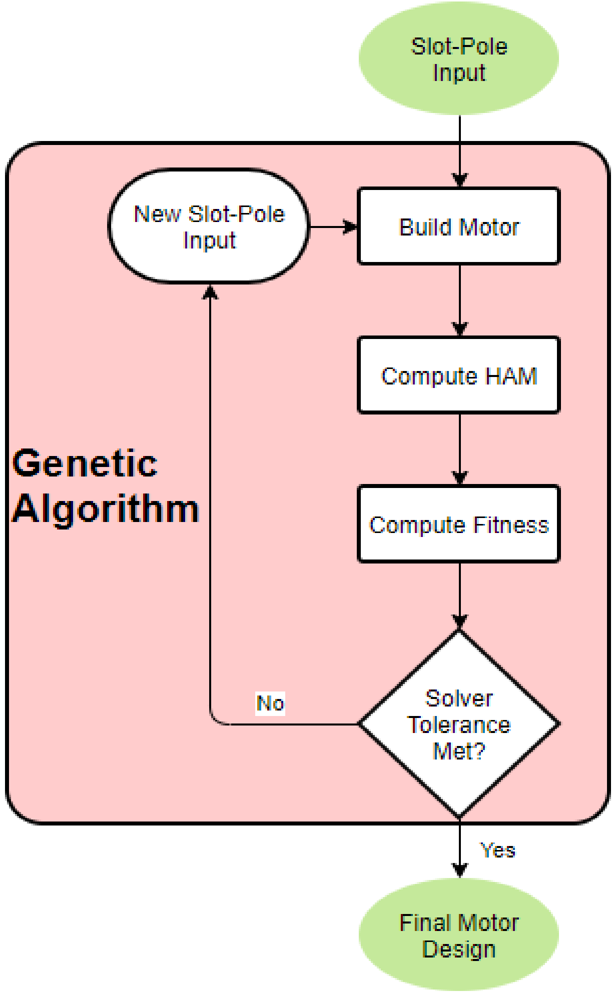


Figure 7: State Diagram of Model Algorithm

Flexible Computing

- The metaheuristic algorithm requires a flexible model to quantify the performance of a wide range of motors
- Stator & rotor geometries, air gap, winding configuration, power requirements, velocity, time and mesh density are configurable!
- The motor designs below are made from the same model but have drastically different motor parameters

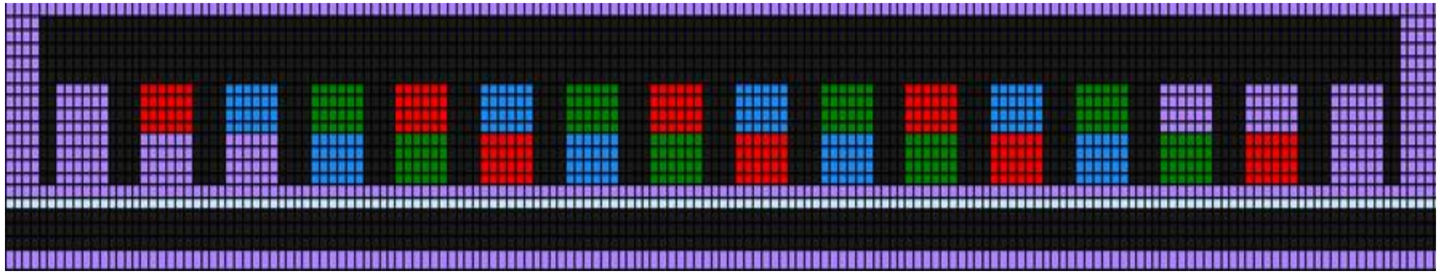


Figure 8: SLIM with Unique Motor Design Parameters

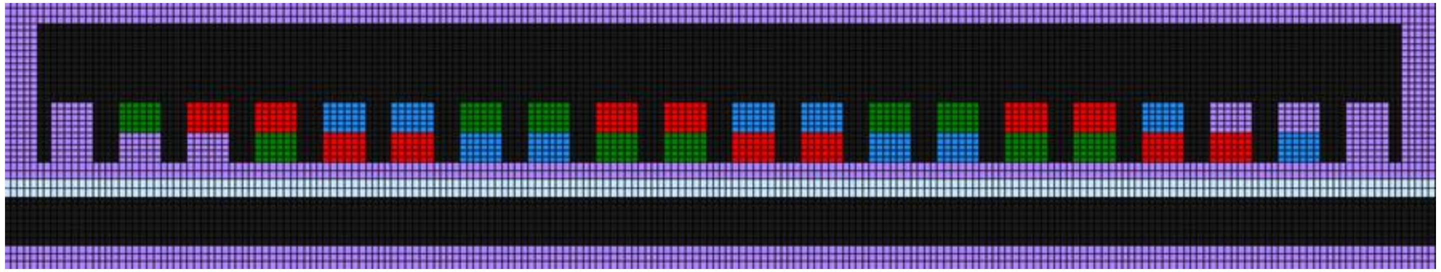


Figure 9: SLIM with Flexible, Modified Motor Design Parameters

Inputs & Outputs

- Choose useful motor inputs and outputs which will produce the most **improvement** on the motor performance
- Inputs for **parametric** and **correlation** testing
  - Slots, Poles, Length, Width, Air gap, ...
- Outputs of important **performance parameters**
  - Thrust, Max frequency, B field, Loss, ...

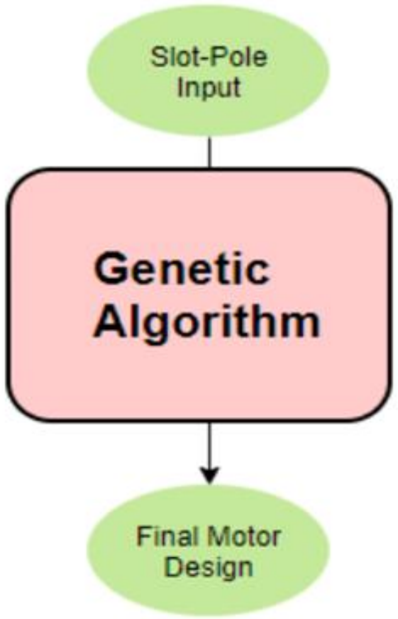


Figure 10: Black-Boxed Algorithm

Model Methodology

- Define all boundary conditions and solve the matrix equation **Ex=Y**
- **E** - 2D matrix of unknown coefficients
- **Q** - 1D matrix of unknown variables
- **Y** – 1D matrix of resulting constants
- Substitute solution back into the equations for magnetic flux density to produce a plot on the entire model

[4]

$$\underbrace{\begin{bmatrix} E_b^1 \\ E_t^1 \\ E_b^2 \\ \vdots \\ E_b^{m-1} \\ E_{\mathrm{MEC}}^{m-1} \\ E_{KCL} \\ E_{\mathrm{MEC}}^{m+1} \\ E_t^{m+1} \\ E_b^{m+2} \\ \vdots \\ E_t^I \end{bmatrix}}_{E_{tot}} \underbrace{\begin{bmatrix} Q^1 \\ Q^2 \\ \vdots \\ Q^{m-1} \\ \Psi \\ Q^{m+1} \\ Q^{m+2} \\ \vdots \\ Q^I \end{bmatrix}}_{X} = \underbrace{\begin{bmatrix} Y_b^1 \\ Y_t^1 \\ Y_b^2 \\ \vdots \\ Y_b^{m-1} \\ Y_{\mathrm{MEC}}^{m-1} \\ Y_{KCL} \\ Y_{\mathrm{MEC}}^{m+1} \\ Y_t^{m+1} \\ Y_b^{m+2} \\ \vdots \\ Y_t^I \end{bmatrix}}_{Y_{tot}}$$

Figure 11: Matrix Equation Solving for Unknown Variables

[4]

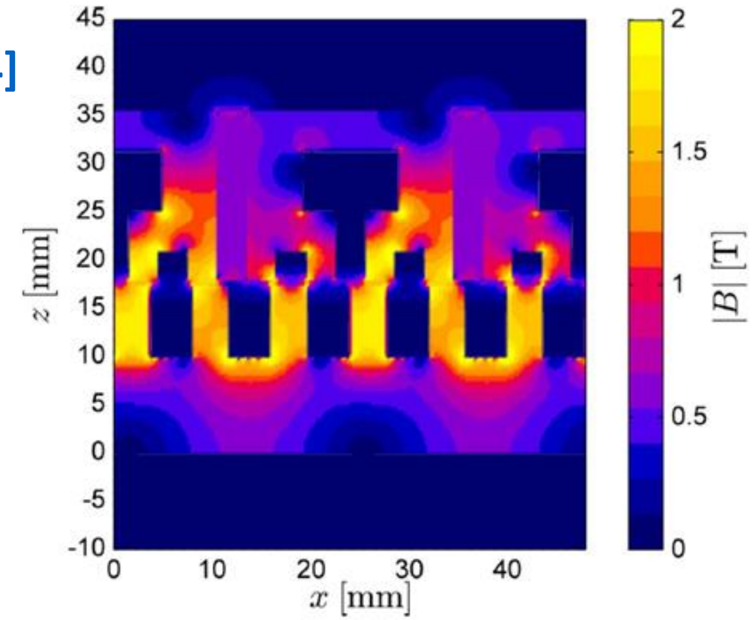


Figure 12: B Field Plot of a PMSM Using HAM

Results

Results

- The resulting B field in the air gap is used to calculate the **motor's performance**
- The plot on the right compares the HAM solution to FEA analysis
- The plot on the left is the proposed algorithm's solution reproduced for this model
- This is the basis of producing **ground truth data**

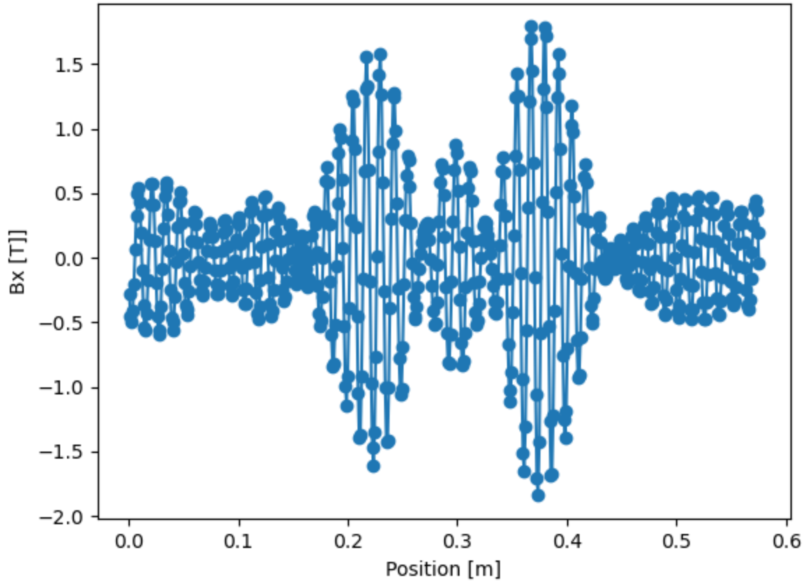


Figure 13: Bx Field Plot of Proposed Model Algorithm

[3]

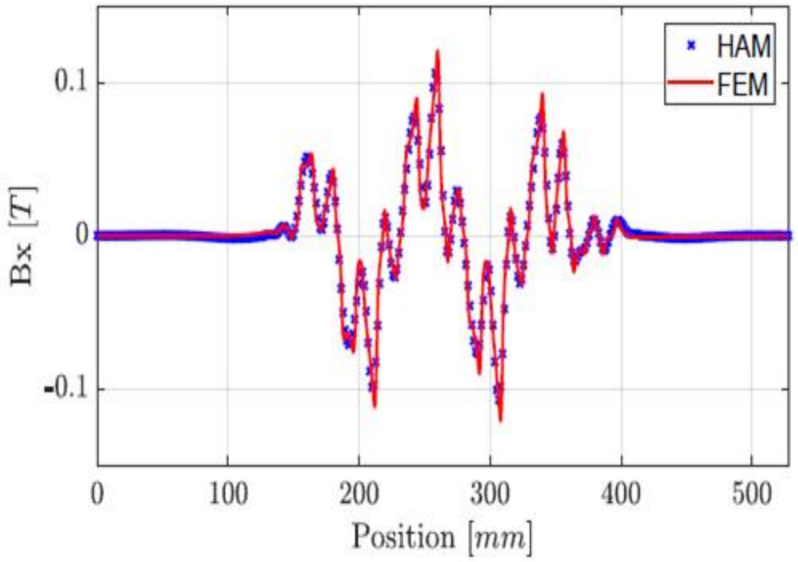


Figure 14: Bx Field Plot of SLIM Reference Paper

Results

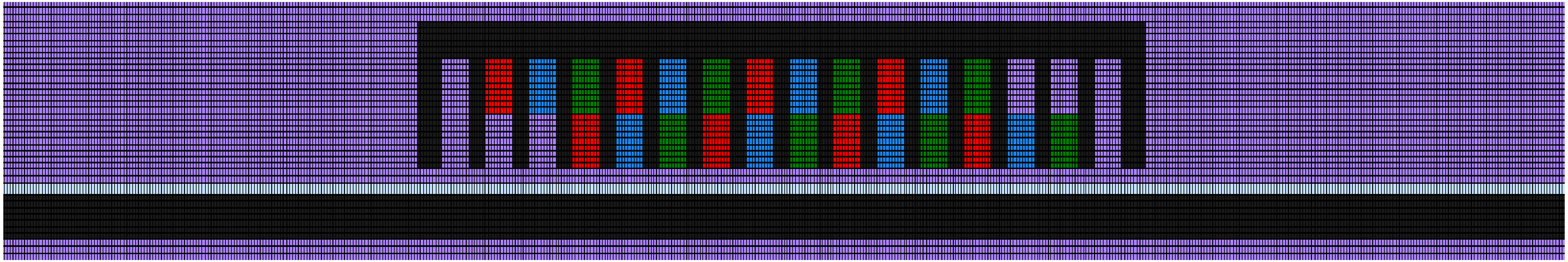
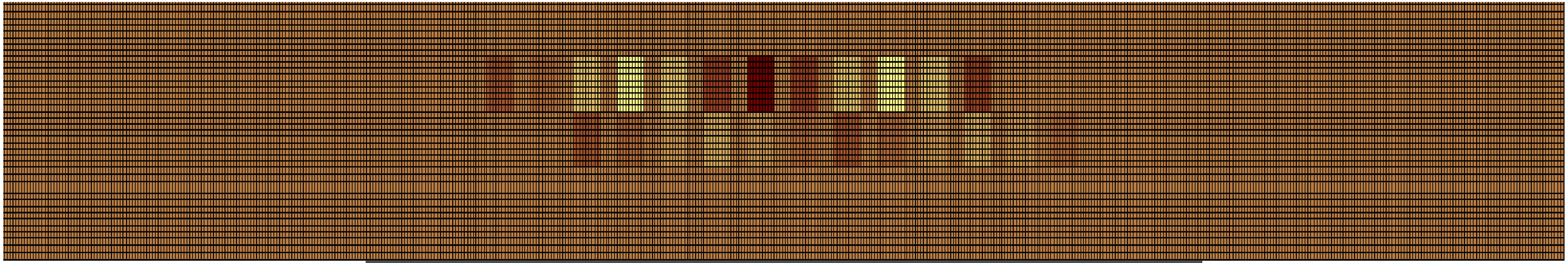


Figure 15: Model Without Field Plot

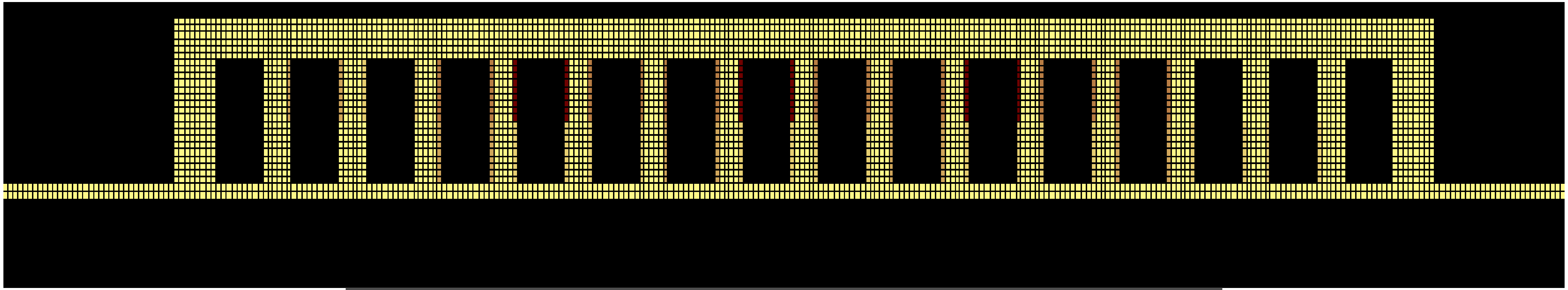


(Max, Min): (195882.7205242974, -195882.7205242974) colour: (#700000, #fff888) Type: MMF

Figure 16: MMF Field Plot of Entire Model

Results

- The field plot can be filtered on any region to highlight any parameter
- Stator core B field highlights **magnetic saturation**
- B field in the **air gap** defines **performance**



(Max, Min): (221.33694237660472, 2.363910969546775e-20) colour: (#700000, #fff888) Type: B

Figure 17: B Field Plot of Core and Airgap

Conclusion

Conclusions

HAM vs FEA

Within 5% error compared to FEA

GA Convergence

Convergence within 1000 iterations

Flexible Modelling

Handles all linear IM motor types

Slot-Pole Ratio Equation

Relating performance to slot-pole ratio

Airgap Waveform & Amplitude

Difficulty achieving the correct result

Computation Time

Estimated 1 min per simulation

Future Work & Timeline

Future Work

Objective 1: 2D Hybrid Steady-State Magnetic Field Model for SLIM

- Solve for the B field in the air gap and validate against the results of the paper for ground truth
- Modify the model to account for DLIM motor designs
- Create an FEA equivalent to compare against since no paper results exist for this model and design

Objective 2: GA Optimization on the Performance Characteristics of the DLIM

- Pass the HAM model results to GA to validate convergence
- Solution shall be feasible and the optimized solution

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