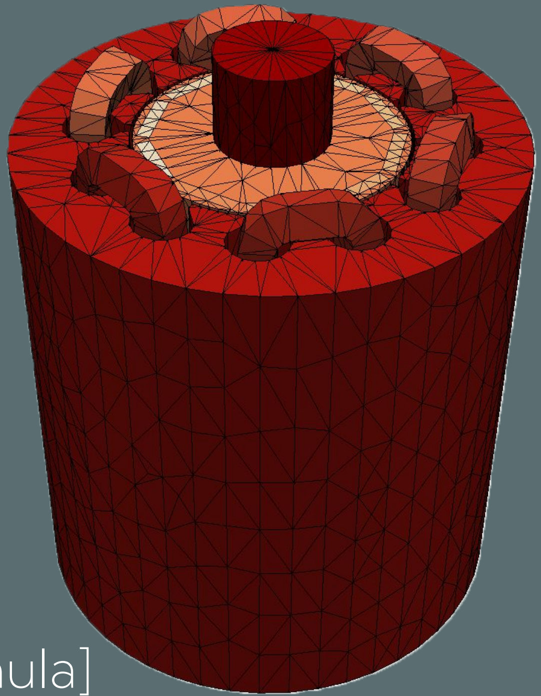
MA5960: Project Proposal and Progress

Modelling a Permanent Magnet Synchronous Motor (PMSM) using Finite Element Method in FEniCS



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Agenda

- Objective
- Introduction
- Timeline
- TEAM 30 Problem - Induction Motor Analysis
- The Maxwell's Equations
- Weak formulation of induction motor problem
- Mesh Generation using GMSH
- Outputs of Induction motor problem
- Future work
- Link References

Objective

Efficient PMSM Modelling using FEM in FEniCSx

- Literature insights from TEAM 30 - Induction Motor problem
- Weak formulation using Dolfinx
- Analyze magnetic flux density
- Shift from 2D to 3D mathematical representation
- Contribute to transportation electrification
- Direct collaboration and mentorship from developer of FEniCS, Jørgen Dokken (Simula)

FEniCS

Introduction

- Electrifying heavy-duty vehicles and aviation lags due to the need for **more efficient, power-dense, and lightweight motors.**
- **Permanent Magnet Synchronous Motors (PMSM)** offer high efficiency and torque density for electric heavy vehicles and aviation.
- **Finite Element Method (FEM)** is used extensively for analyzing and improving performance of these electric machines.
- **FEniCS**: open-source computing platform for solving PDEs with FEM enables scalable, efficient simulations.
- **This project focuses on implementing a 2D computational model and understanding the 3D implementation for simulating the electromagnetic behavior of PMSMs using FEM in FEniCSx.**

Timeline

Aug

- Python
- Finite Element Method

Sep

- FEniCS
- PDE solving using Dolfinx
- Codes link

Oct

- TEAM 30 - induction motor problem
- Maxwell's Equations

Nov

- Mesh generation using GMSH
- Solving 2D induction motor problem

Dec

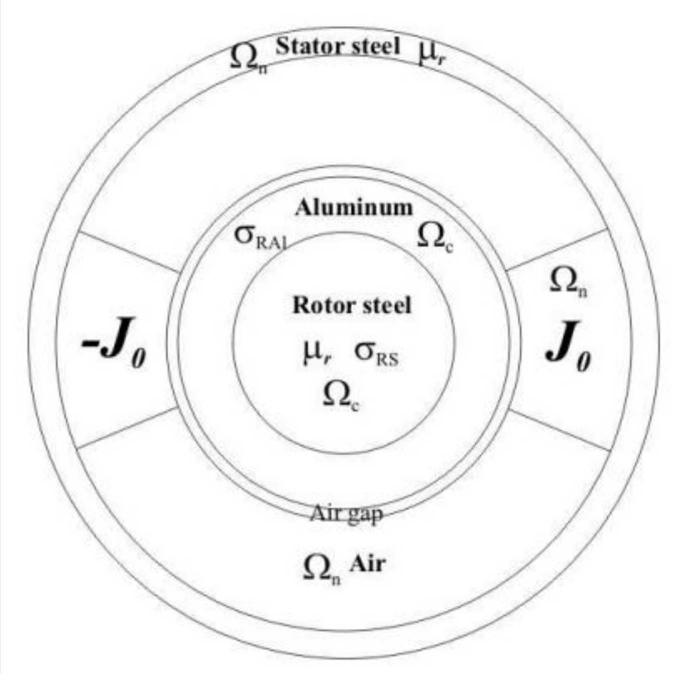
- 2D Mesh generation of PMSM
- Weak formulation and implementation using Dolfinx

Next Steps

- Deliver a validated and efficient FEM-based 2D model for PMSM.
- Shifting from 2D to 3D mathematical representation

Induction Motor Analysis

TEAM 30 Problem



The structure of the eddy current field problem

- Given
  - angular velocity of rotor and stator (ω)
  - source current density (Jo)
  - conductivity (σ) &
  - relative permeability of each material (μr)
- To compute:
  - Electromagnetic torque
  - Induced voltage in the phase coil A
  - Average power dissipation (eddy current - Rotor Loss and Steel Loss)

The Maxwell's Equations

$$\nabla \times \vec{H} = \vec{J}_0, \quad \text{in } \Omega_n,$$

$$\nabla \cdot \vec{B} = 0, \quad \text{in } \Omega_n,$$

$$\nabla \times \vec{H} = \vec{J}, \quad \text{in } \Omega_c,$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \text{in } \Omega_c,$$

$$\nabla \cdot \vec{B} = 0, \quad \text{in } \Omega_c,$$

$$\nabla \cdot \vec{J} = 0, \quad \text{in } \Omega_c,$$

$$\vec{B} = \begin{cases} \mu_0 \vec{H}, & \text{in air, } \Omega_n, \\ \mu_0 \mu_r \vec{H}, & \text{in magnetically linear material, } \Omega_c, \end{cases}$$

$$\vec{J} = \sigma \vec{E}, \quad \text{in } \Omega_c.$$

$$\vec{H} = \begin{cases} \nu_0 \vec{B}, & \text{in air, } \Omega_n, \\ \nu_0 \nu_r \vec{B}, & \text{in magnetically linear material, } \Omega_c. \end{cases}$$

$$\vec{E} = \rho \vec{J}, \quad \text{in } \Omega_c.$$

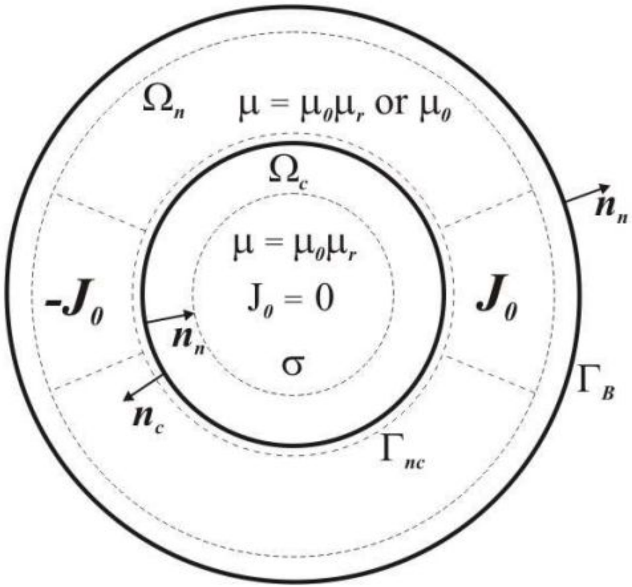
Boundary conditions

$$\vec{B} \cdot \vec{n} = 0, \quad \text{on } \Gamma_B,$$

$$\vec{H}_c \times \vec{n}_c + \vec{H}_n \times \vec{n}_n = \vec{0}, \quad \text{on } \Gamma_{nc},$$

$$\vec{B}_c \cdot \vec{n}_c + \vec{B}_n \cdot \vec{n}_n = 0, \quad \text{on } \Gamma_{nc},$$

$$\vec{J} \cdot \vec{n}_c = 0, \quad \text{on } \Gamma_{nc},$$



Weak formulation of induction motor problem

2D weak formulation of potential formulation in the time domain

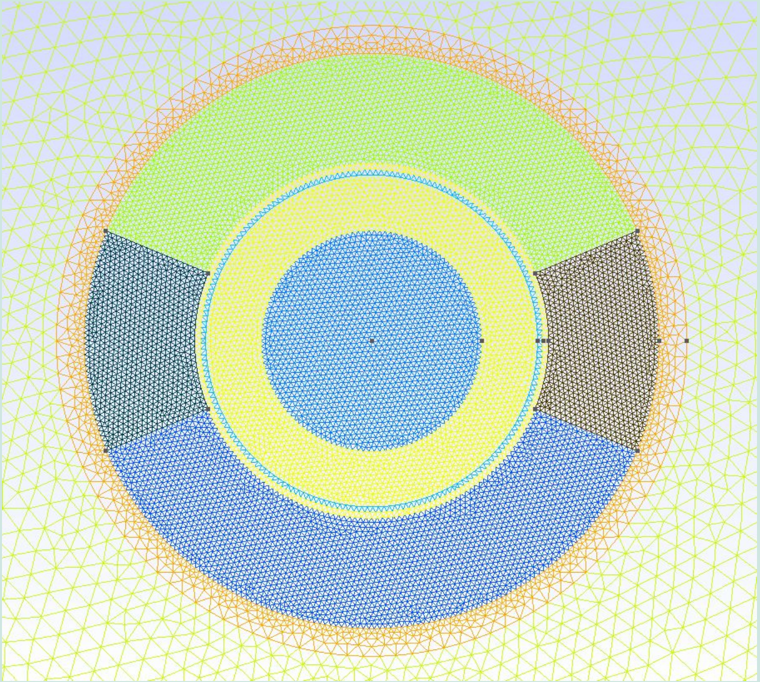
$$\vec{B} = \nabla \times \vec{A}$$

$$\vec{E} + \frac{\partial \vec{A}}{\partial t} = -\nabla V,$$

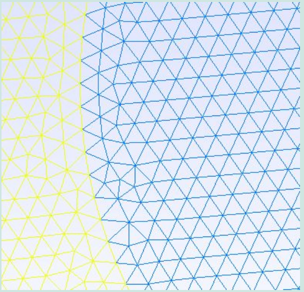
$$\int_{\Omega_c \cup \Omega_n} \nu (\nabla \times \vec{W}_k) \cdot (\nabla \times \vec{A}^{\kappa}) \,\mathrm{d}\Omega$$
$$+ \int_{\Omega_c} \vec{W}_k \cdot \sigma \left(\frac{\partial \vec{A}^{\kappa}}{\partial t} - \vec{v} \times \nabla \times \vec{A}^{\kappa} \right) \mathrm{d}\Omega$$
$$= \int_{\Omega_n} \vec{W}_k \cdot \vec{J}_0^{\kappa} \,\mathrm{d}\Omega.$$

Steps in weak formulation: Weak_formulation_derivation

Mesh Generation using GMSH



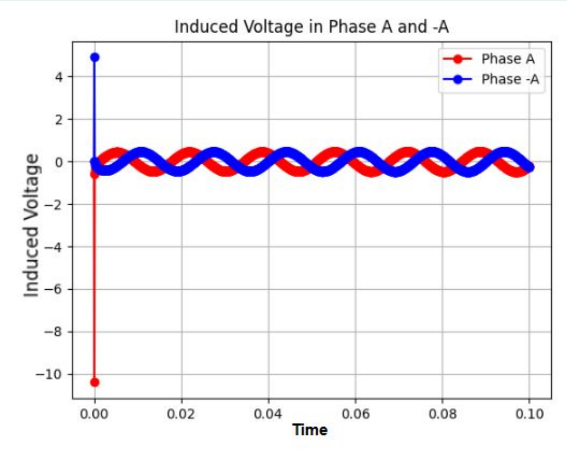
2D mesh

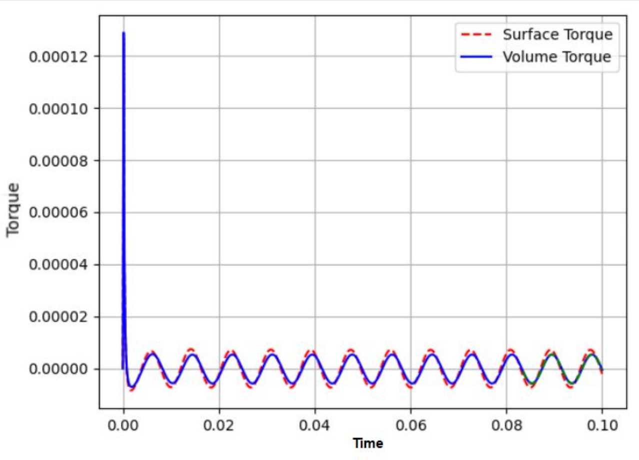


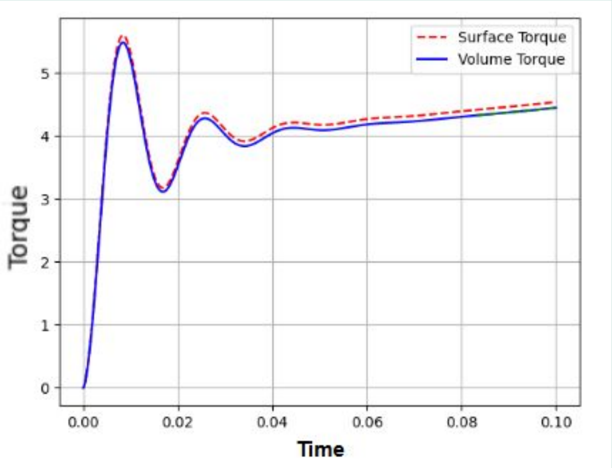
zoomed view

- 2D finite element mesh – discretized by triangular elements.
- Generated using GMSH, an open-source mesh generator.

Outputs of existing Dolfinx code







Solve the Single-Phase Problem

Solve the Three-Phase Problem with Applied Torque

Future work

- Mesh generation of PMSM using GMSH.
- Applying the methodology of induction motor problem for the simulation of PMSM model.
- Deliver a validated and efficient FEM-based model for PMSMs.
- Shifting from 2D to 3D mathematical representation of the model.

Link References

- Modelling a permanent magnet synchronous motor in FEniCSx for parallel high-performance simulations - James McDonagh, et al.
- Documentation | FEniCS Project
- GitHub - Wells-Group/TEAM30: A repository for the TEAM-30 benchmark using DOLFINx
- Using the GMSH Python API to generate complex meshes | Jørgen S. Dokken
- Computational Electromagnetics - YouTube
- Performance Comparison of High-Speed Motors for Electric Vehicle

FEniCS

Thank you