

Multi-Objective Structural Optimization of PMSMs using Evolutionary Algorithms

Center for Hybrid Automotive Research and Green Energy
Department of Electrical and Computer Engineering, University of Windsor
Philip Korta, Himavarsha Dhulipati, Wenlong Li, and Narayan C. Kar

Abstract

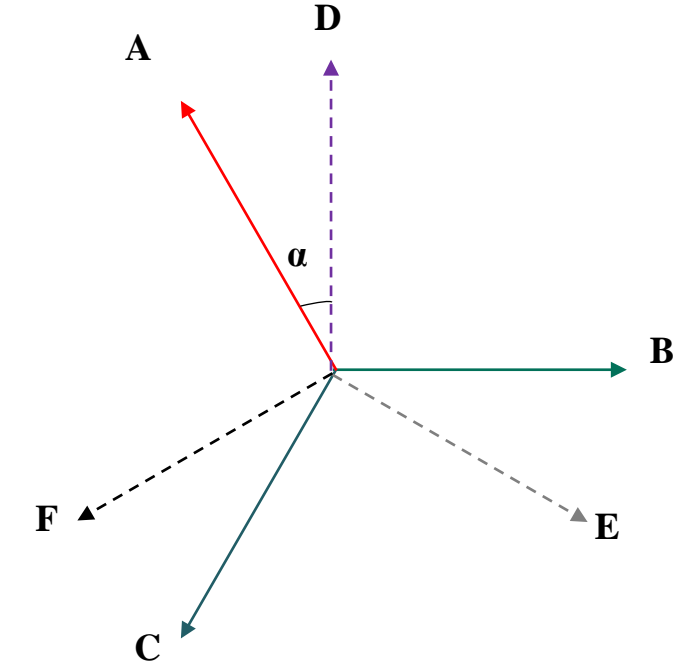
- A six phase fractional slot concentrated winding (FSCW) surface permanent magnet synchronous machine (SPMSM) is designed for a direct-drive EV application
- An analytical machine evaluation model in Matlab is used to assess the generated motor models
- Multi-objective dynamic differential evolution is implanted due to its superior convergence rate in comparison to other evolutionary algorithms
- Machines are optimized in terms of efficiency, average torque production, weight, and cost
- A comparative performance analysis of the baseline and optimized SPMSM is conducted

Baseline Machine

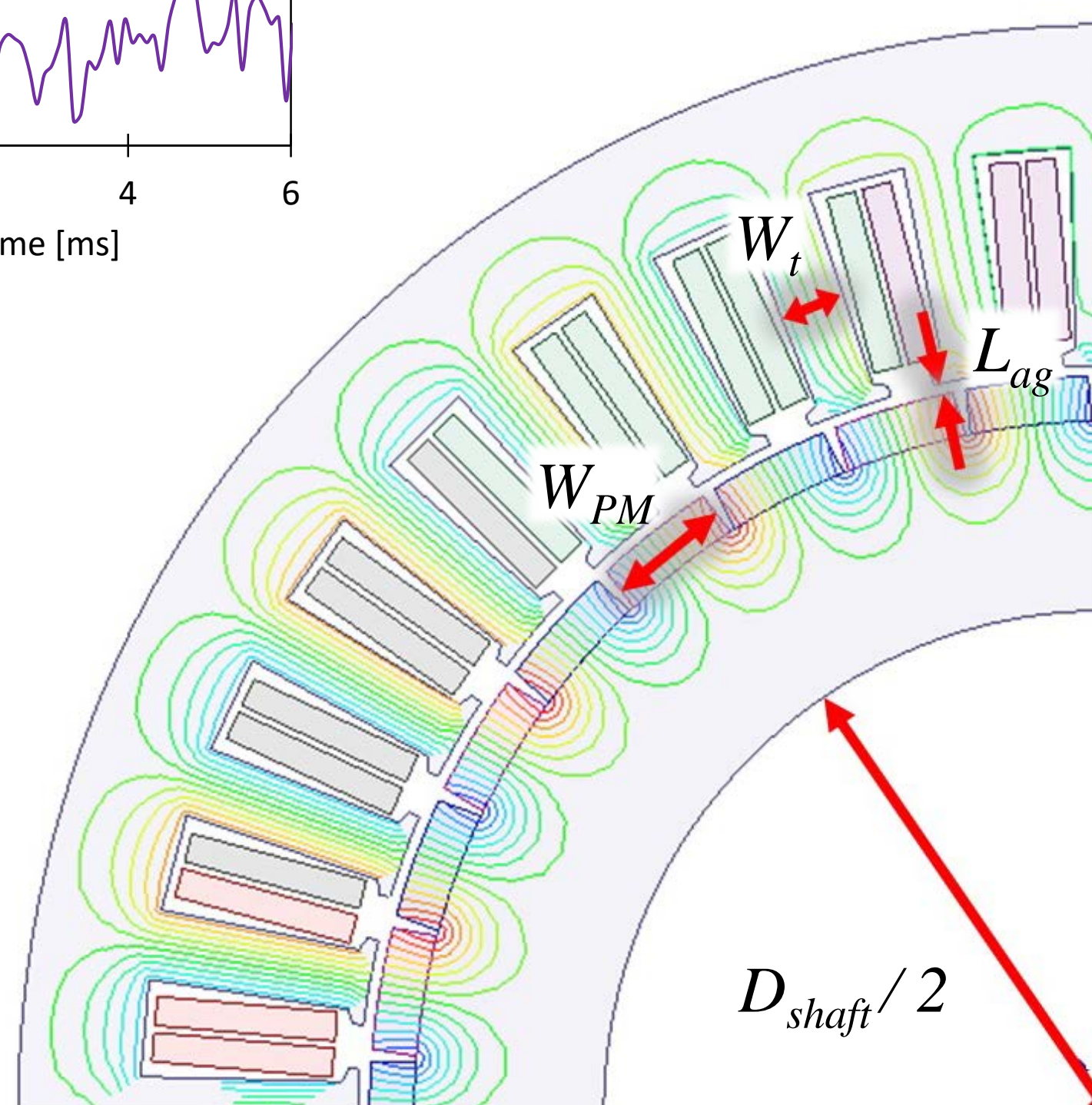
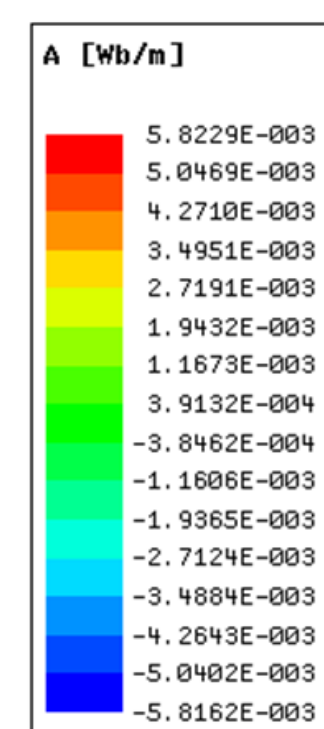
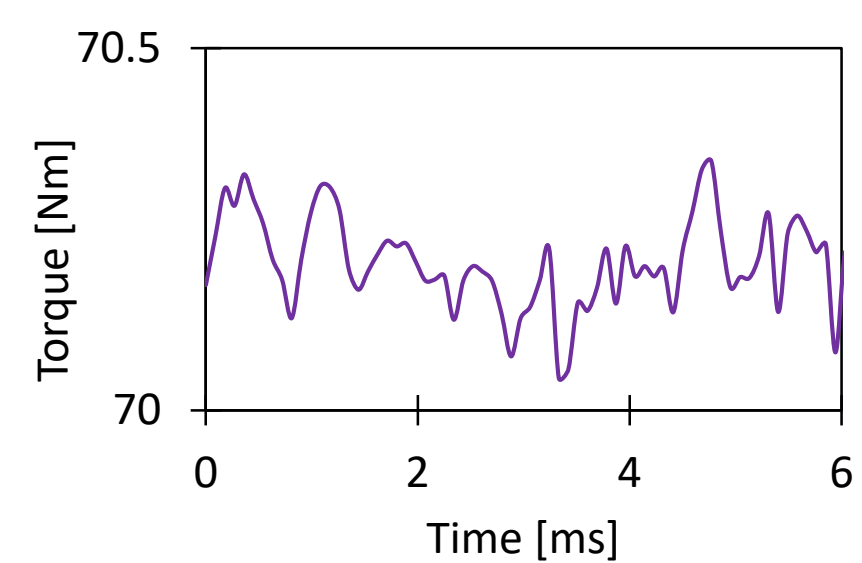
Design Parameters

Output power (P_{out})	3 kW
Phase voltage ($V_{ph\ rms}$)	60 V
Rated speed (N_{rated})	405 rpm
Maximum speed (N_{max})	1,500 rpm
Per phase current ($I_{ph\ rms}$)	11 A
Number of slots (S)	36
Number of poles (P)	34

Angle between phase sets



Electromagnetic Torque



Analytical Machine Evaluation

Constraints

Tooth Flux Density:

$$B_t = \frac{P\phi_g}{0.92 L_{st} W_t S}$$

Yoke Flux Density:

$$B_Y = \frac{\phi_g}{0.92 L_{st} W_Y}$$

Objectives

Efficiency:

$$P_{out} = \frac{2\pi n T_{avg}}{60}$$

$$P_{Cu} = 6 \left(\frac{I_m}{\sqrt{2}} \right)^2 R_{ph}$$

$$\begin{cases} \omega_h = k_h f B^2 \\ \omega_e = k_e (fB)^2 \end{cases}$$

$$P_{Fe} = (\omega_h + \omega_e) M_{Fe}$$

$$P_{Mech} = k_c n^2$$

$$P_{in} = P_{Cu} + P_{Fe} + P_{Mech} + P_{out}$$

$$Efficiency = \frac{P_{out}}{P_{in}}$$

Average Torque:

$$\lambda_{PM} = \frac{2}{P} k_w T_{ph} k_f B_{av} D_{in} L_{st}$$

$$T_{avg} = \frac{6P}{4} \lambda_{PM} I_q$$

Mass:

$$Mass = M_{Mag} + M_{Cu} + M_{Fe}$$

Cost Index:

$$Cost = 24M_{Mag} + 3M_{Cu} + M_{Fe}$$

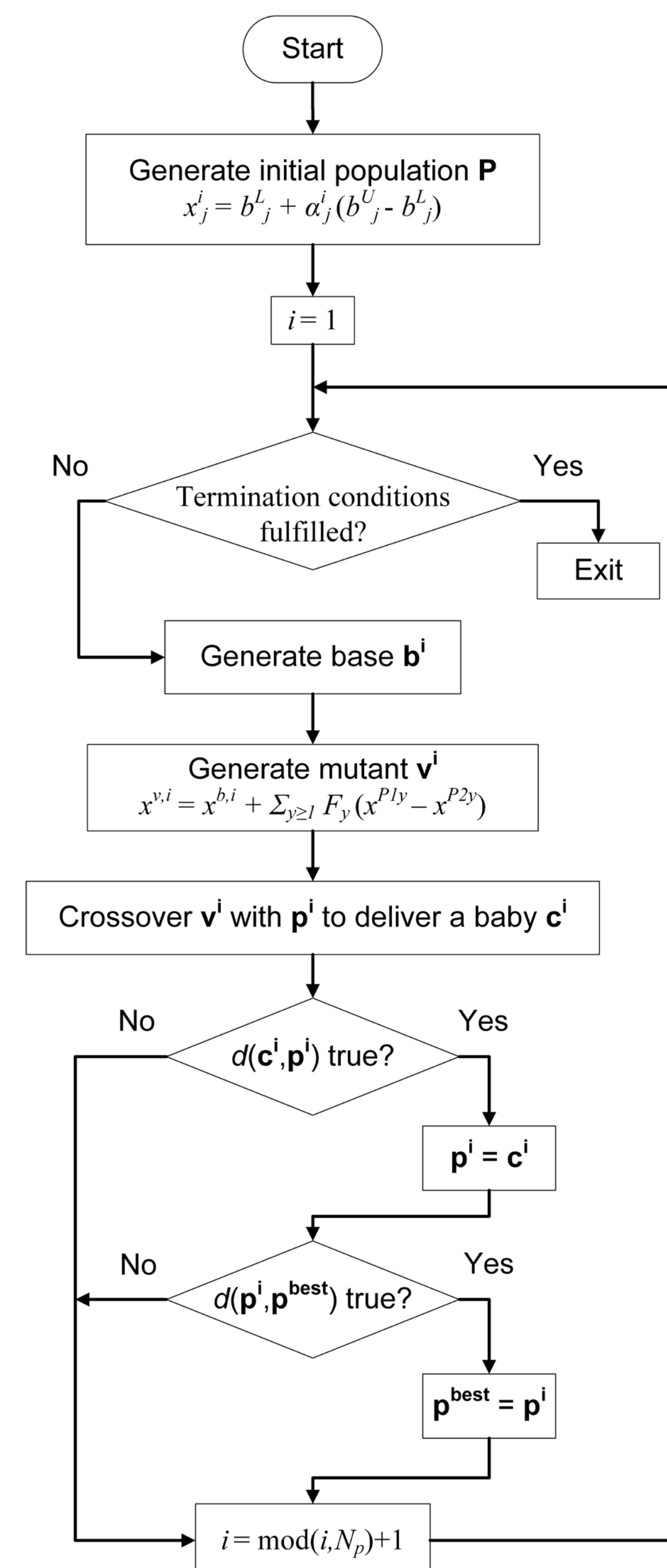
B_t = Tooth flux density
 B_Y = Yoke flux density
 ϕ_g = Air gap flux
 L_{st} = Stack length
 W_t = Tooth width
 W_Y = Yoke width

P_{out} = Output power
 T_{avg} = Average torque
 n = Speed
 P_{Cu} = Copper loss
 I_m = Peak current
 R_{ph} = Phase resistance
 ω_h = Hysteresis component of core loss
 ω_e = Eddy-current component of core loss
 k_h = Hysteresis coefficient
 k_e = Eddy-current coefficient
 f = Frequency
 B = Flux density
 P_{Fe} = Core loss
 M_{Fe} = Core Mass
 P_{Mech} = Mechanical loss
 k_c = Carter's coefficient
 P_{in} = Input power
 λ_{PM} = PM flux linkage
 k_w = Winding factor
 T_{ph} = Turns per phase
 k_f = Form factor
 B_{av} = Average magnetic loading
 D_{in} = Stator inner diameter
 I_q = q-axis current
 M_{Mag} = Magnet mass
 M_{Cu} = Copper mass

Machine Parameter	Lower Limit (mm)	Upper Limit (mm)
Magnet Width (W_{PM})	9.7	11.2
Airgap Length (L_{ag})	0.6	1
Shaft Diameter (D_{shaft})	80	100
Tooth Width (W_t)	6.3	9.7

Optimization Procedure

- Multi-objective Dynamic Differential evolution
- Best candidate is used as the base vector during the creation of the mutant vector
- Utilizes binomial crossover and includes a regularization of infeasible mutants

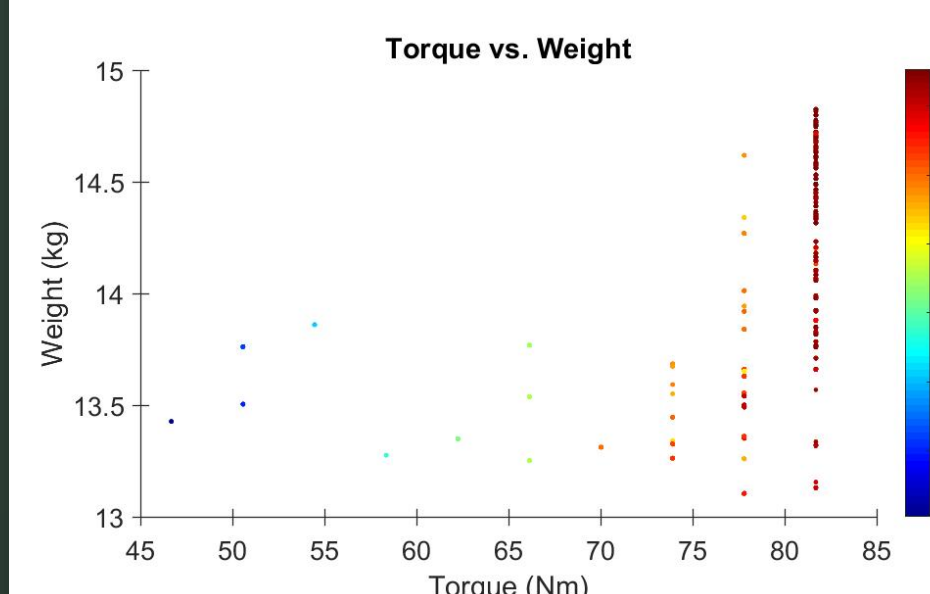
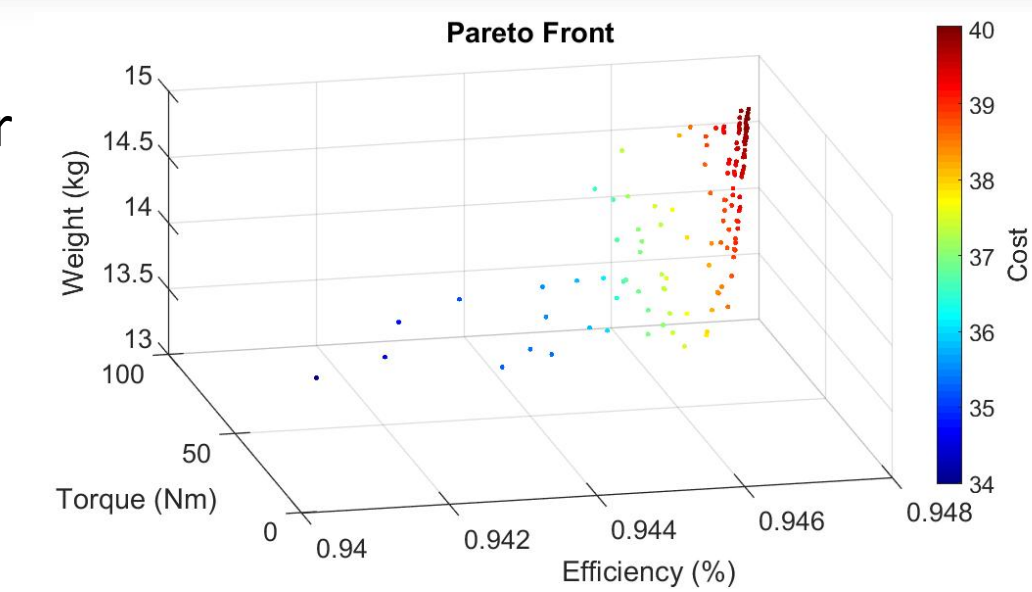


The logical dominance function is based on:

- If both c and p are infeasible, but c violates fewer constraints
- If c is feasible while p is infeasible
- Both c and p are feasible, but c is better than p in terms of objective function values

Results

- 100 generations with a population size of 100 motor models is used for the optimization
- Results plotted as a Pareto front of optimized solutions



- Objectives:
- Maximize efficiency
 - Maximize average torque
 - Minimize weight
 - Minimize cost
- Constraints:
- Tooth flux density < 1.7 T
 - Yoke flux density < 0.7 T

Machine Parameter	Baseline Machine	Optimized Machine
Magnet Width (W_{PM})	11.2	11
Airgap Length (L_{ag})	1	1
Shaft Diameter (D_{shaft})	90	100
Tooth Width (W_t)	6.3	6.3

Conclusion

- A multi-objective structural optimization has been conducted for the baseline machine
- This optimization searches through thousands of machine structures in the design space to offer optimal solutions in terms of efficiency, torque, weight, and cost
- The optimization converged to a result that has a significant reduction in terms cost and weight while maintaining torque and efficiency

Objective	Baseline Machine	Optimized Machine
Efficiency	94.73 %	94.70 %
Torque	70.20 Nm	70.20 Nm
Weight	13.98 kg	13.13 kg
Cost Index	39.06	37.84