Evolutionary Design of PMSM Machines

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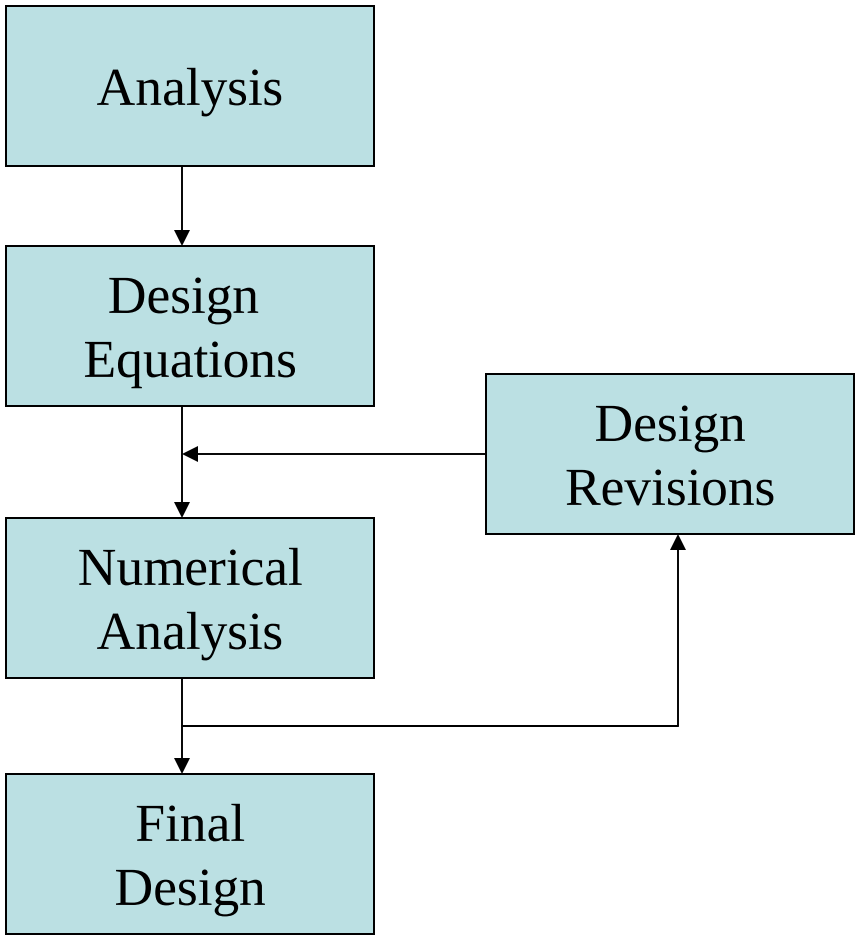
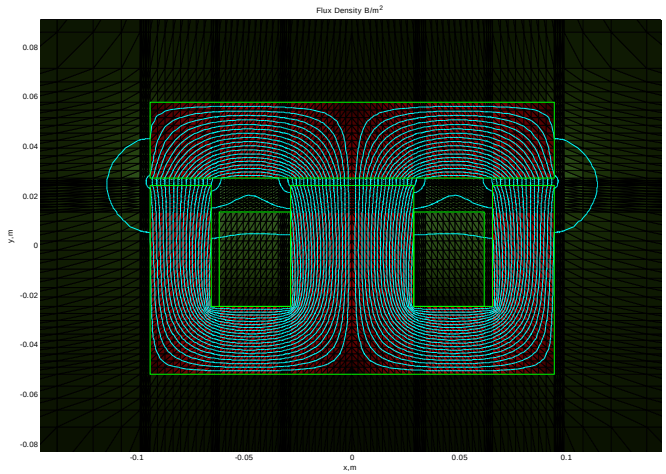
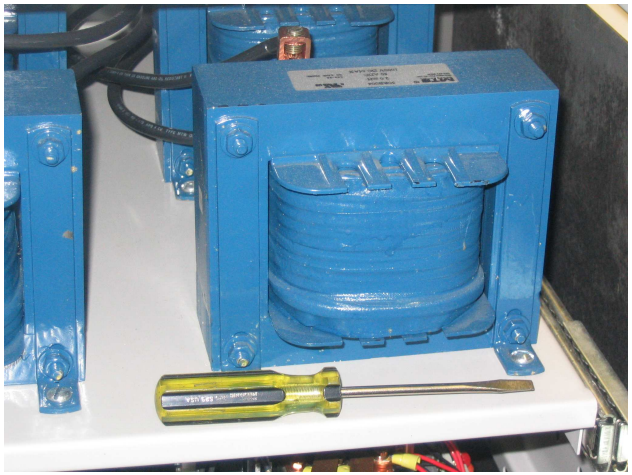
Manual Design Approach







Optimization Based Design and Analysis (Evolutionary or Otherwise)

- Pose Design Problem As An Optimization Problem
  - Can be single or multi-objective
  - Systematically encode design constraints and objectives into objective (fitness) function
- Reality Check: Problem Properties Not Always Friendly
  - Not differentiable
  - Not convex
  - Many local extrema
  - No unique global optimum

Optimization Methods

- Classic Methods
  - Gradient Methods
  - Newton's Method
  - Conjugate Direction Methods
  - Quasi-Newton Methods
  - Nedler-Mead Simplex Method
- Populations Based Methods
  - Population Based Classical Methods
  - Monte-Carlo
  - **Genetic Algorithms**
  - Particle Swarm Algorithms

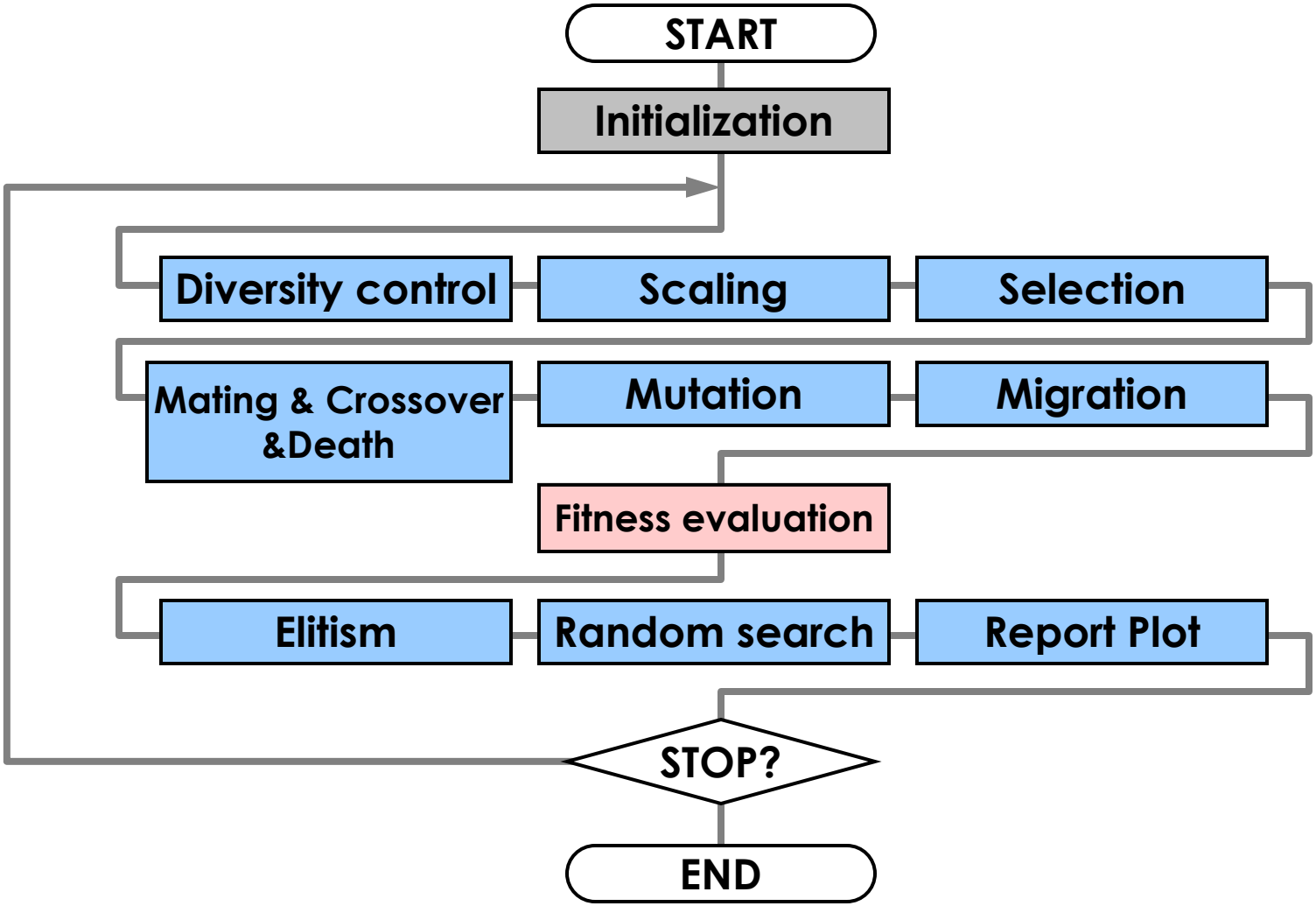
Evolutionary Design Approach

Evolutionary Environment

Detailed Analysis

Fitness Function

Modern (Real Coded) GA Execution



Facts of Life in Design Optimization

- On finding the global optimum ….

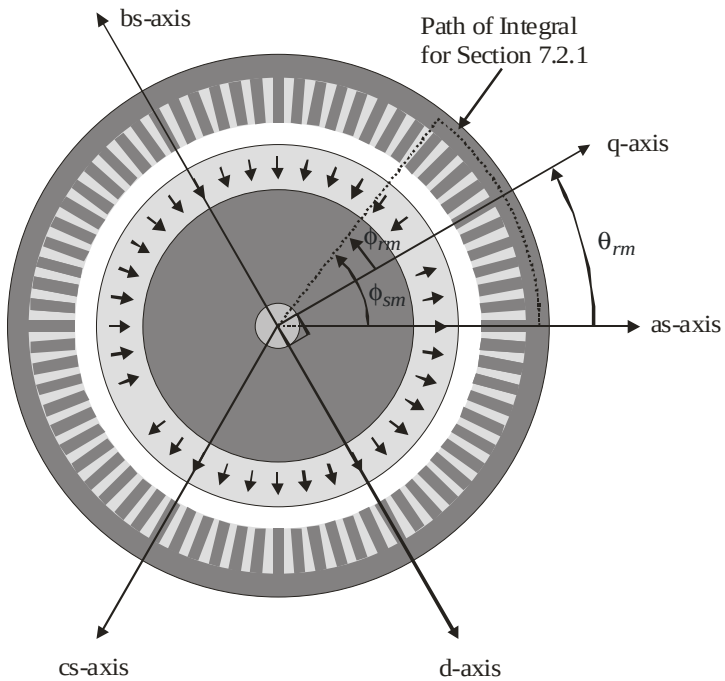
- On design repeatability ….

Analysis Options

- The hard part is predicting the magnetics (the incremental inductance).
- Options include
  - Analytical methods
  - Magnetic equivalent circuits
  - High fidelity magnetic equivalent circuits
  - 2-D Finite element analysis
  - 3-D Finite element analysis

Example: Design of a Permanent Magnet Synchronous Machine

- Specifications
  - 10 Nm at 2000 RPM with an RMS current of 10 A
  - The machine should be as torque dense as possible subject to a loss of 94 W



Parameter Encoding

Table II
Design Space – Direct Approach

	Parameter Number	Description (units)	Min	Max	Encoding
m_r	1	Rotor steel	1	5	Int
m_s	2	Stator steel	1	5	Int
m_p	3	Permanent magnet	1	4	Int
ϕ_i	4	Current phase advance (rad)	-1	1	Lin
α_{pm}	5	Permanent magnet faction	0	1	Lin
r_r	6	Rotor radius (m)	10^{-3}	10^{-1}	Log
d_m	7	Magnet depth (m)	10^{-3}	$5\cdot 10^{-2}$	Log
g	8	Air gap (m)	10^{-4}	10^{-2}	Log
d_s	9	Depth of slot (m)	10^{-3}	$5\cdot 10^{-2}$	Log
α_s	10	Fraction of slot region occupied by steel	0.05	0.95	Lin
d_b	11	Backiron depth (m)	10^{-3}	0.1	Log
l	12	Active length (m)	10^{-3}	0.2	Log
N_p^*	13	Desired peak conductor density (conductors/rad)	10	10^3	Log
α_3^*	14	Desired ratio of third harmonic to fundamental conductor density	-0.5	0.5	Lin
m_c	15	Conductor type	1	2	Int
α_c	16	Conductor area (m^2)	10^{-7}	10^{-4}	Log
a_f	17	Fillet fraction	0	1	Lin

- Direct Method

$$\boldsymbol{\theta} = \left[m_r \quad m_s \quad m_p \quad \phi_i \quad \alpha_{pm} \quad r_r \quad d_m \quad g \quad \cdots \right.$$
$$\left. d_s \quad \alpha_s \quad d_b \quad l \quad N_p^* \quad \alpha_3^* \quad m_c \quad a_c \quad a_f \right]^T$$

- Indirect Method

$$\boldsymbol{\theta} = \left[m_r \quad m_s \quad m_p \quad \phi_i \quad \alpha_{pm} \quad \alpha_{r_r} \quad \alpha_{d_m} \quad \alpha_g \cdots \right.$$
$$\left. \alpha_{d_s} \quad \alpha_s \quad \alpha_{d_b} \quad l \quad \alpha_{N_p} \quad \alpha_{\alpha_3} \quad m_c \quad \alpha_{a_c} \quad a_f \right]^T$$

Constraints

Table IV
Design Constraints

Constraint	Description
$c_1(\boldsymbol{\theta}) = \mathrm{ltn}(B_{t,max}, B^*_{si,max})$	Tooth flux density
$c_2(\boldsymbol{\theta}) = \mathrm{ltn}(B_{b,max}, B^*_{si,max})$	Backiron flux density
$c_3(\boldsymbol{\theta}) = \mathrm{ltn}(B_{tb,max}, B^*_{si,max})$	Tooth base flux density
$c_4(\boldsymbol{\theta}) = \mathrm{ltn}(B_{ri,max}, B^*_{ri,max})$	Rotor iron flux density
$c_5(\boldsymbol{\theta}) = \mathrm{gtn}(H_{m,min}, H^*_{m,min})$	Demagnetization
$c_6(\boldsymbol{\theta}) = \mathrm{ltn}(I_s / a_c, J^*_{c,max})$	Current density constraint
$c_7(\boldsymbol{\theta}) = \mathrm{ltn}(\alpha_{sf,max}, \alpha^*_{sf,max})$	Slot fill constraint
$c_8(\boldsymbol{\theta}) = \mathrm{gtn}(g, k_{gap} r_r)$	Air gap constraint
$c_9(\boldsymbol{\theta}) = \mathrm{gtn}(T_e, T_e^*)$	Torque constraint
$c_{10}(\boldsymbol{\theta}) = \mathrm{ltn}(P_{loss}, P_{max})$	Power loss constraint

Fitness Function Construction

- Our Objective

$$\hat{f}(\boldsymbol{\theta}) = \frac{T_e^*}{\pi(r_r + d_m + g + d_b)^2 l}$$

- Continuous Fitness Function

$$f_1(\boldsymbol{\theta}) = \hat{f}(\boldsymbol{\theta}) c(\boldsymbol{\theta}) \qquad c(\boldsymbol{\theta}) = \prod_{i=1}^{C} c_i(\boldsymbol{\theta})$$

- Discontinuous Fitness Function

$$f_2(\boldsymbol{\theta}) = \begin{cases} \left(\sum_{i=1}^{C} c_i\right) - C & c < 1 \\ \hat{f}(\boldsymbol{\theta}) & c \geq 1 \end{cases} \qquad c = \min(c_1, c_2, \ldots, c_C)$$

Machine Control

- Machine connected to a current controlled inverter

$$i_{as} = \sqrt{2} I_s \cos(\theta_r + \phi_i)$$

$$i_{bs} = \sqrt{2} I_s \cos(\theta_r + \phi_i - 2\pi/3)$$

$$i_{cs} = \sqrt{2} I_s \cos(\theta_r + \phi_i + 2\pi/3)$$

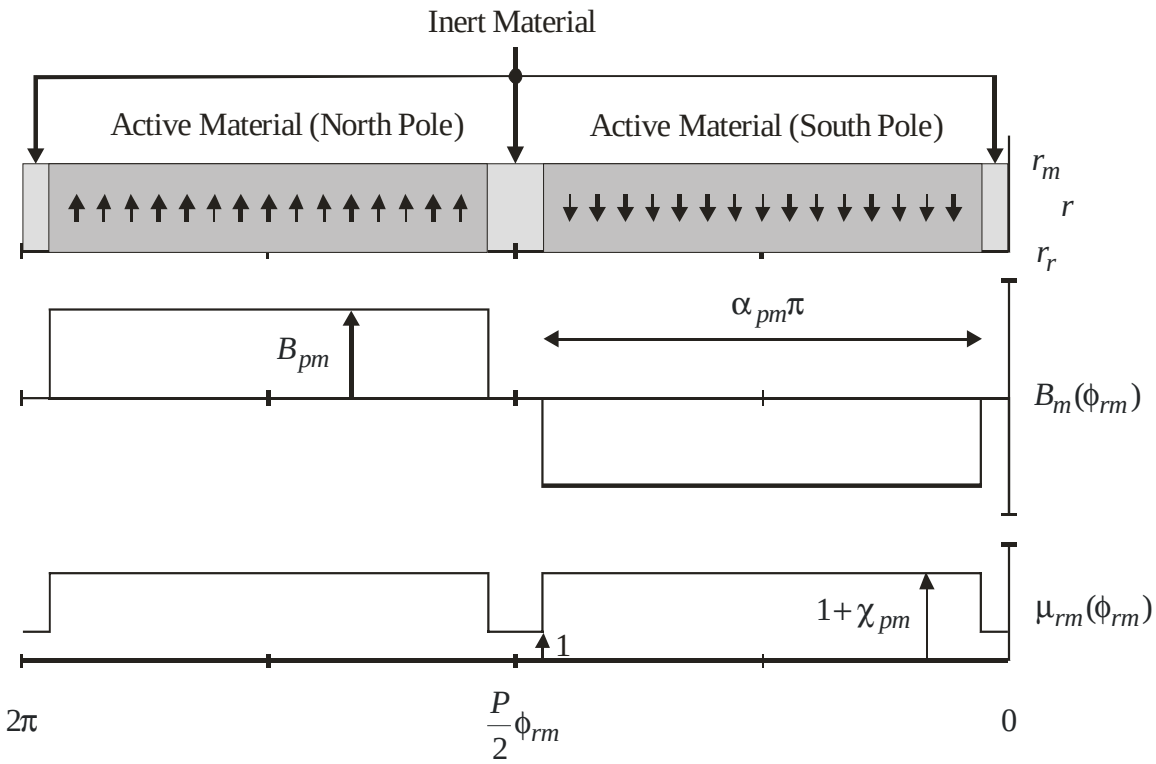
- Conductor distribution: sinusoidal

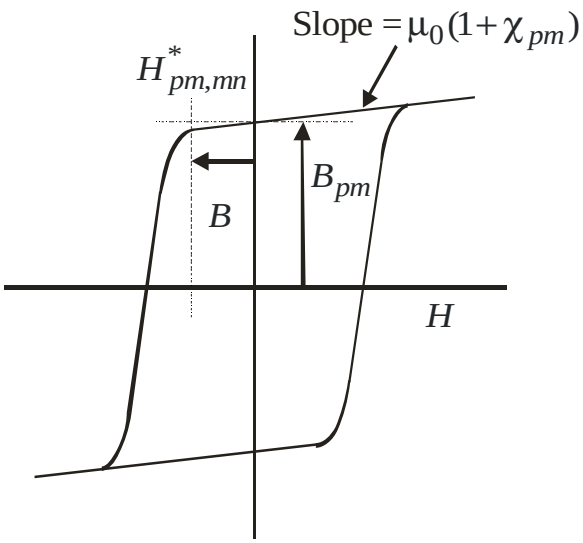
$$n_{as}(\phi_{sm}) = N_p \left(\sin\left(\frac{P}{2} \phi_{sm} \right) - \alpha_3 \sin\left(3 \frac{P}{2} \phi_{sm} \right) \right)$$

$$n_{bs}(\phi_{sm}) = N_p \left(\sin\left(\frac{P}{2} \phi_{sm} - \frac{2\pi}{3} \right) - \alpha_3 \sin\left(3 \frac{P}{2} \phi_{sm} \right) \right)$$

$$n_{cs}(\phi_{sm}) = N_p \left(\sin\left(\frac{P}{2} \phi_{sm} + \frac{2\pi}{3} \right) - \alpha_3 \sin\left(3 \frac{P}{2} \phi_{sm} \right) \right)$$

Flux Density in Permanent Magnet





Flux Density in Air Gap

$$B(r,\phi_{sm}) = \frac{r_r}{r}\frac{F_m(\phi_{sm}) - i_{enc}(\phi_{sm})}{R_p(\phi_{sm}) + R_g},\ r_r \le r \le r_s$$

$$i_{enc}(\phi_{sm}) = -\frac{3\sqrt{2}N_p I_s}{P}\cos\left(\frac{P}{2}\phi_{sm} - \theta_r - \phi_i\right)$$

$$R_p(\phi_{sm}) = \frac{r_r}{\mu_0\mu_{rm}(\phi_{sm} - \theta_{rm})}\ln\left(1 + \frac{d_m}{r_r}\right)$$

$$F_m(\phi_{sm}) = \frac{d_m}{\mu_0\mu_{rm}(\phi_{sm} - \theta_{rm})}B_m(\phi_{sm} - \theta_{rm})$$

$$R_g = \frac{r_r}{\mu_0}\ln\left(1 + \frac{g}{r_r + d_m}\right)$$

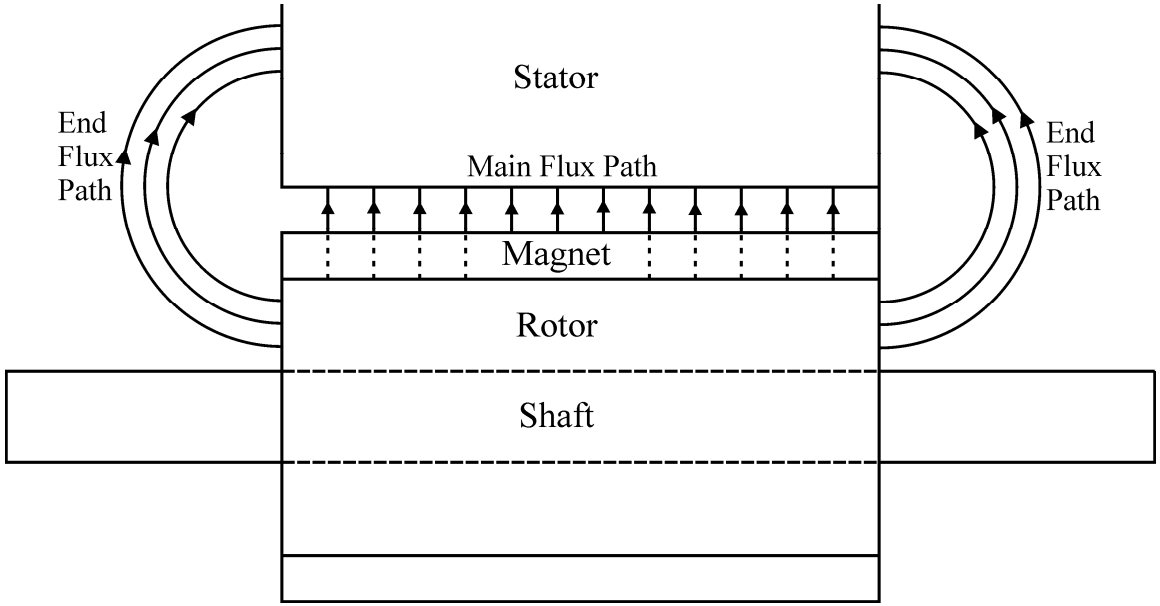
Key Lumped Parameters

$$L_{qm} = \frac{6 l_{eff} r_r N_p^2}{P^2} \left[\frac{\pi(1-\alpha_{pm}) + \sin(\pi\alpha_{pm})}{R_{sp} + R_g} + \frac{\pi\alpha_{pm} - \sin(\pi\alpha_{pm})}{R_{pm} + R_g} \right]$$

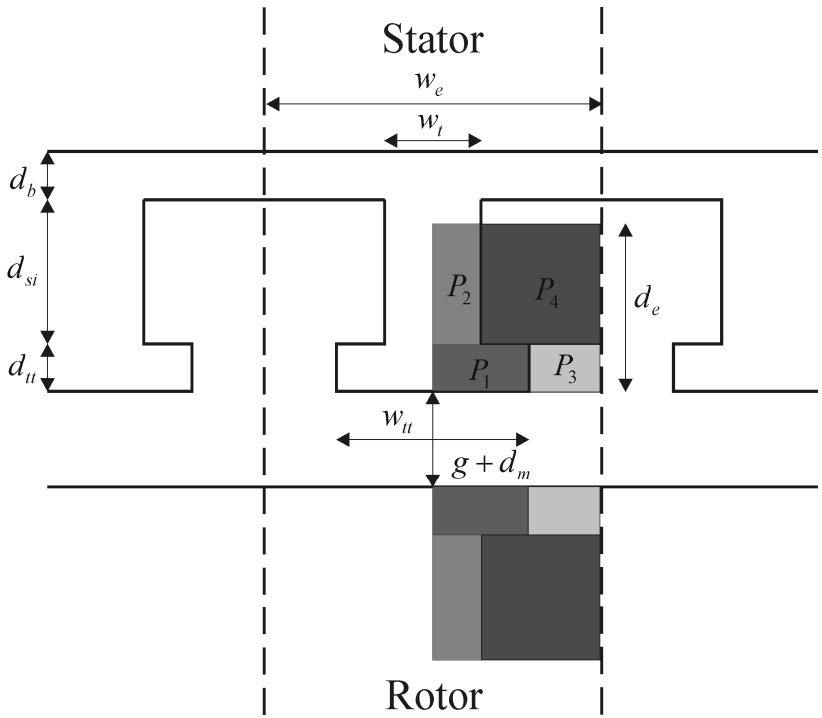
$$L_{dm} = \frac{6 l_{eff} r_r N_p^2}{P^2} \left[\frac{\pi(1-\alpha_{pm}) - \sin(\pi\alpha_{pm})}{R_{sp} + R_g} + \frac{\pi\alpha_{pm} + \sin(\pi\alpha_{pm})}{R_{pm} + R_g} \right]$$

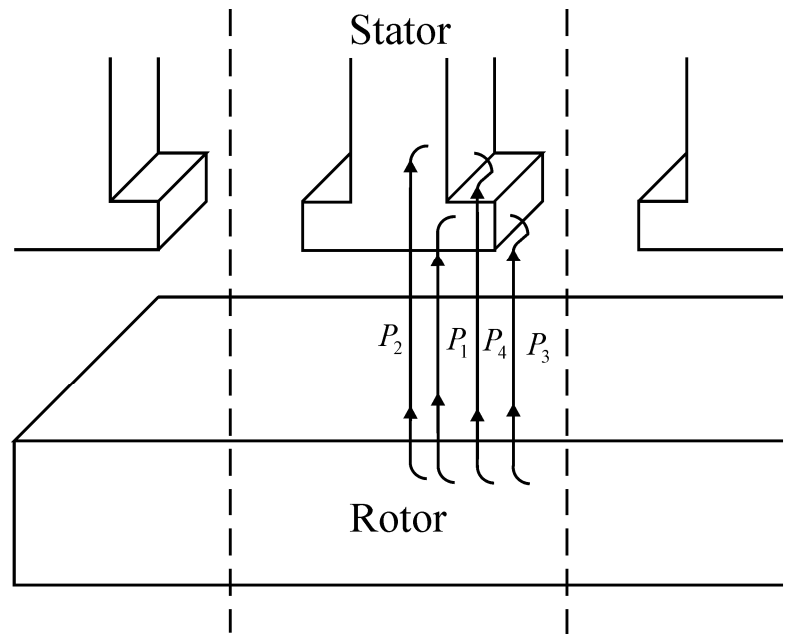
$$\lambda_m = \frac{8 r_r l N_p}{P(R_{pm} + R_g)} \frac{d_m}{\mu_0 \mu_{rm}} B_{pm} \sin\left(\frac{\pi\alpha_{pm}}{2} \right)$$

End Effects on Magnetizing Inductance



Axially Compensated Length





$$P_{end} = 2(P_1 + P_2 + P_3 + P_4)$$

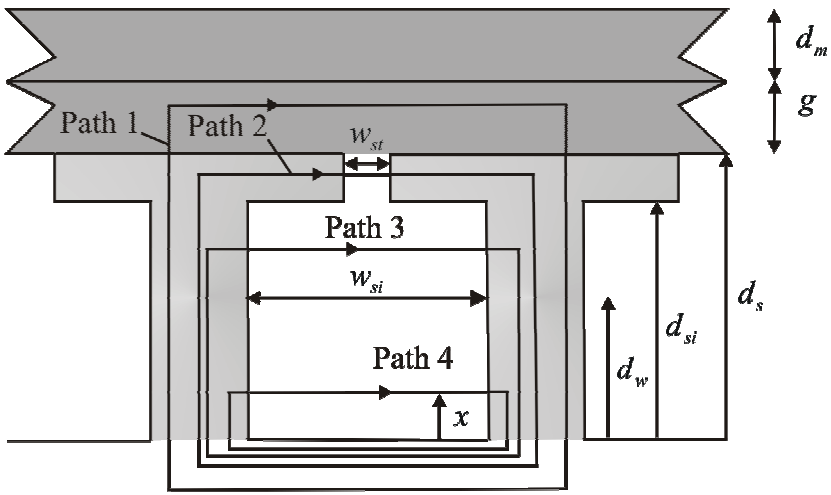
$$P_1 = \frac{\mu_0 w_1}{\pi} \ln\left(1 + \frac{\pi d_1}{g_1}\right)$$

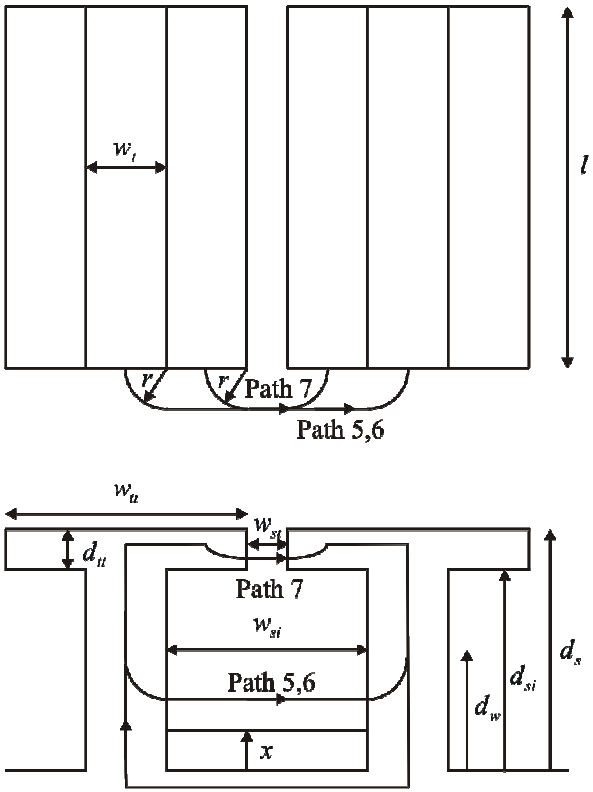
$$P_2 = \frac{\mu_0 w_2}{\pi} \ln\left(1 + \frac{\pi d_2}{g_2}\right)$$

$$P_3 = \frac{\mu_0}{\pi^2}\left[\begin{array}{l} 2\pi d_3 \ln\left(1 + \dfrac{\pi w_3}{2g_3 + 2\pi d_3}\right) \\ + (\pi w_3 + 2g_3)\ln\left(1 + \dfrac{2\pi d_3}{\pi w_3 + 2g_3}\right) \\ - 2g_3 \ln\left(1 + \dfrac{\pi d_3}{g_3}\right) \end{array}\right]$$

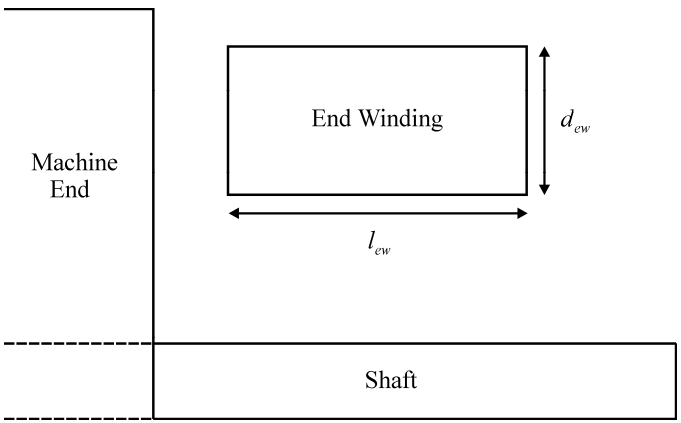
$$P_4 = \frac{\mu_0}{\pi^2}\left[\begin{array}{l} 2\pi d_4 \ln\left(1 + \dfrac{\pi w_4}{2g_4 + 2\pi d_4}\right) \\ + (\pi w_4 + 2g_4)\ln\left(1 + \dfrac{2\pi d_4}{\pi w_4 + 2g_4}\right) \\ - 2g_4 \ln\left(1 + \dfrac{\pi d_4}{g_4}\right) \end{array}\right]$$

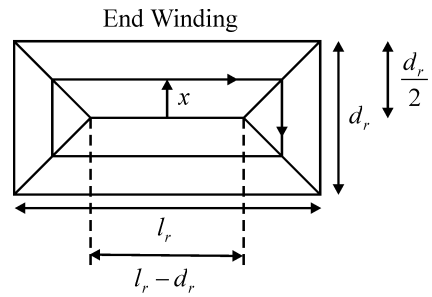
Slot Leakage Permeance





End Leakage Permeance

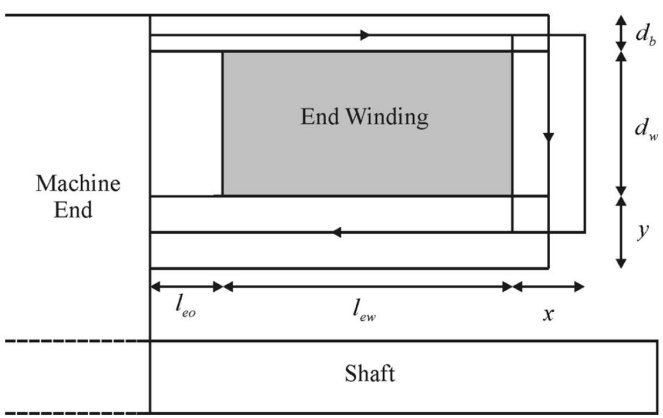




$$l_r = \max(l_{ew}, d_{ew})$$

$$d_r = \min(l_{ew}, d_{ew})$$

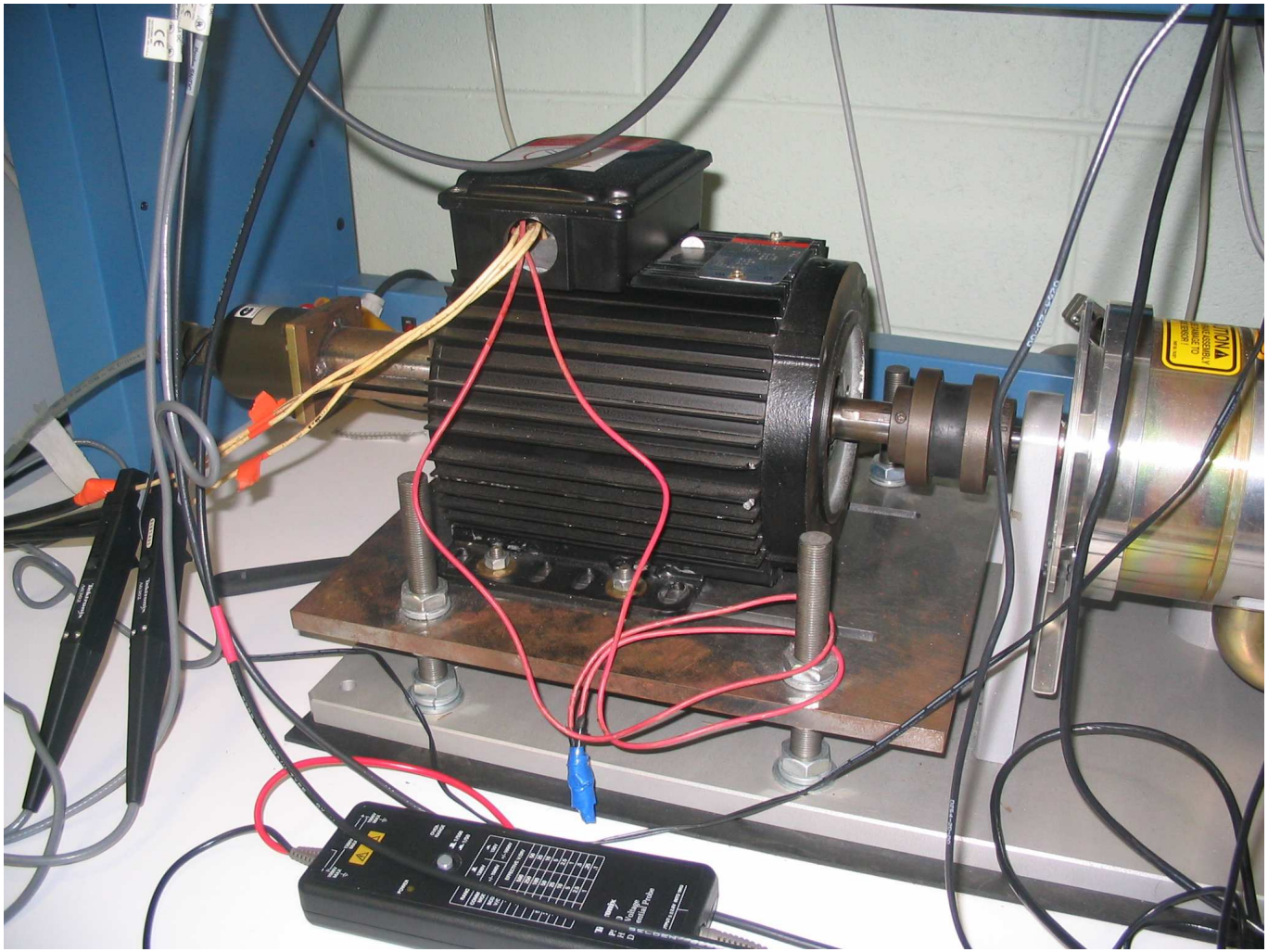
$$P_{el,1} = \frac{\mu_0 L_{seg}}{d_r^2 l_r^2}\left[\begin{array}{l}\frac{d_r^4}{32} + \frac{d_r^3}{16}(l_r - d_r) + \frac{d_r^2}{64}(l_r - d_r)^2 \\ -\frac{d_r}{64}(l_r - d_r)^3 + \frac{1}{128}(l_r - d_r)^4 \ln\left(1 + \frac{2d_r}{l_r - d_r}\right)\end{array}\right]$$



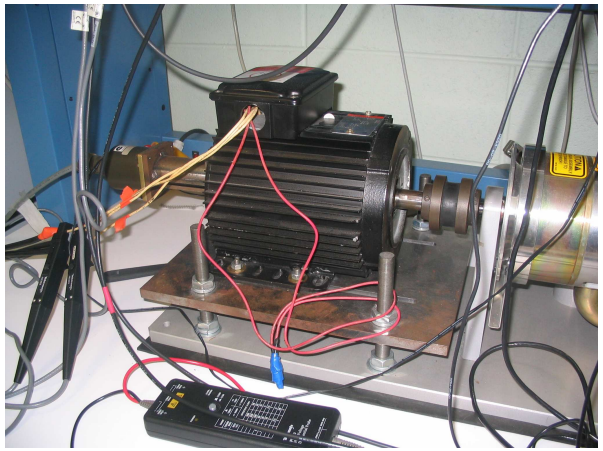
$$R = \frac{(l_{eo} + l_{ew} + x)}{d_b L_{seg} \mu_0} + \frac{\left(d_w + \frac{d_b}{2} + y\right)}{2x L_{seg} \mu_0} + \frac{(l_{eo} + l_{ew} + x)}{2y L_{seg} \mu_0}$$

$$P_{el,2} = \frac{1}{R_{\min}}$$

Hardware Validation

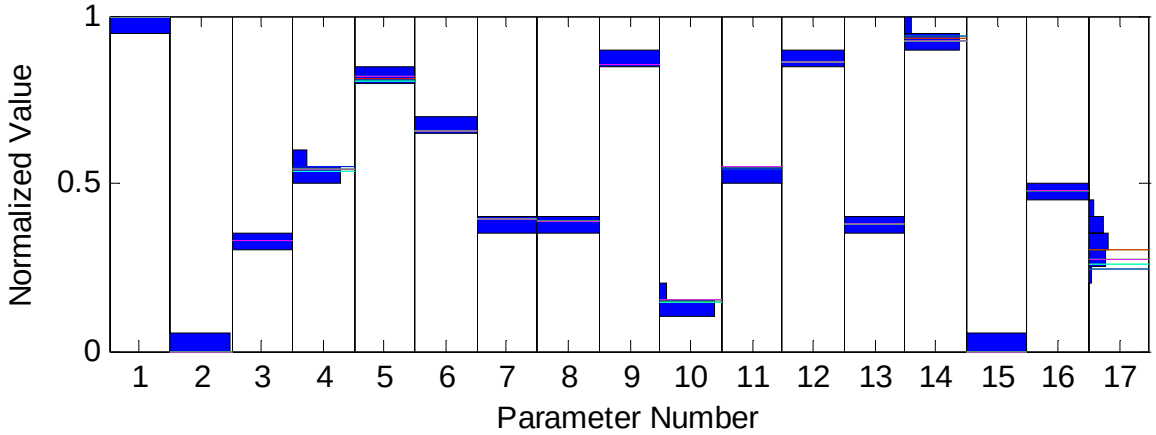


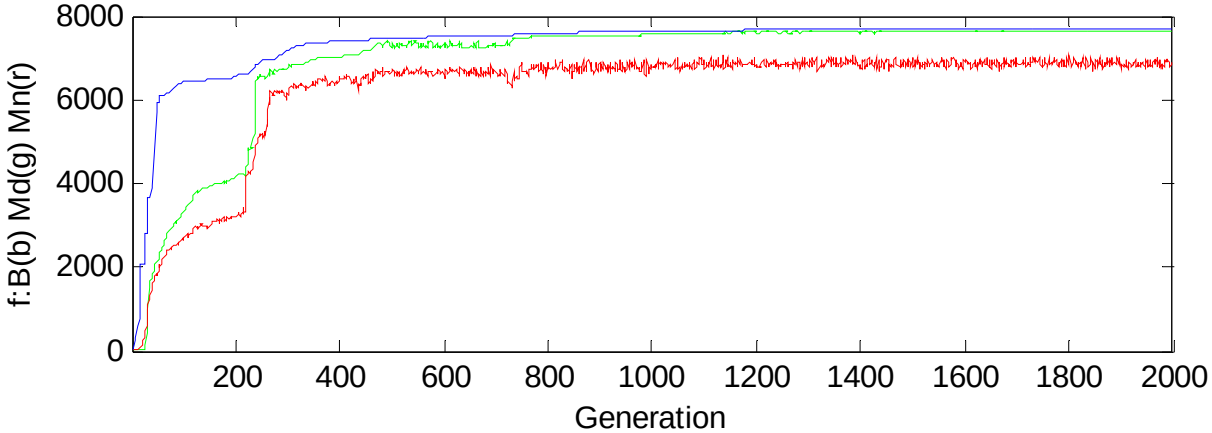
Hardware Validation



Par.	Machine A	Machine B	Machine C	Machine D	Machine E	Calc. Value	Percent Error
R_s	2.22 Ω	2.22 Ω	2.22 Ω	2.22 Ω	2.22 Ω	2.29 Ω	3.1%
λ_m	.295 Vs	.295 Vs	.295 Vs	.293 Vs	.295 Vs	.308 Vs	4.2%
L_q	16.45 mH	15.88 mH	15.69 mH	16.20 mH	16.06 mH	15.19 mH	5.4 %
L_d	14.38 mH	14.87 mH	15.19 mH	14.48 mH	14.73 mH	15.26 mH	3.6 %

Sample Design
(Direct Encoding; Discontinuous Fitness)

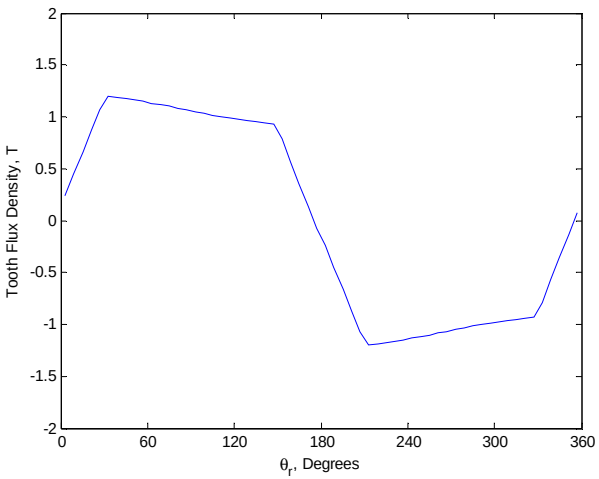


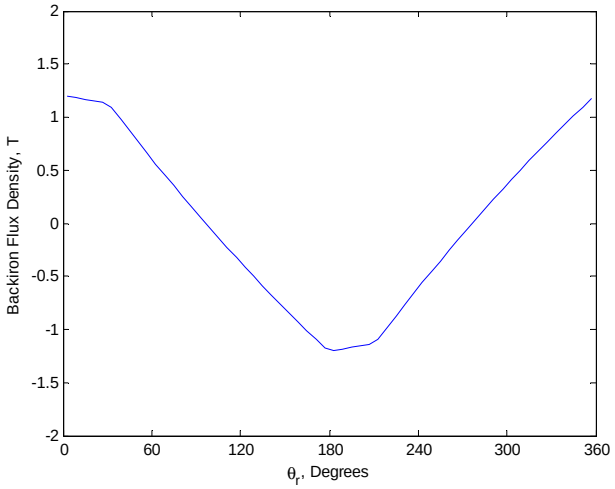


Sample Design

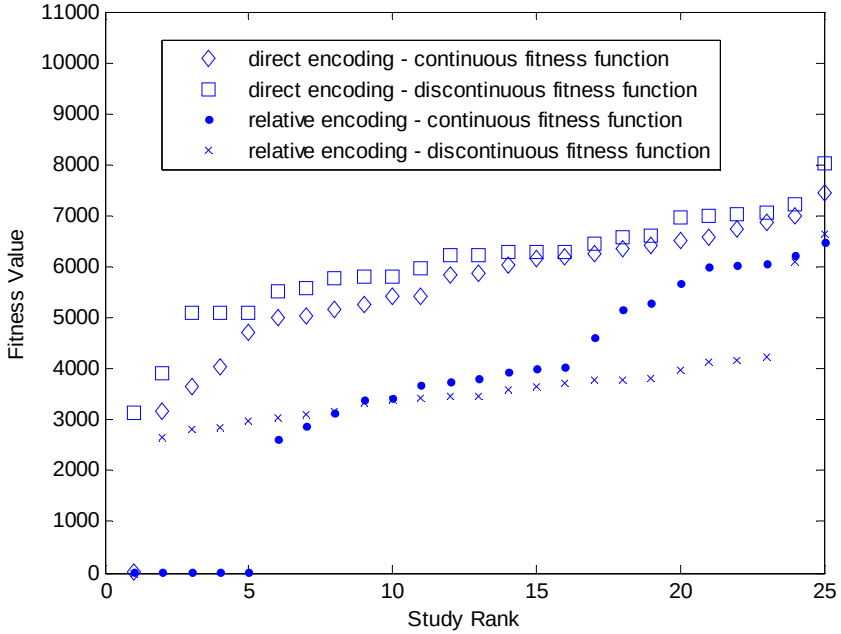
Table IV
Design Parameters

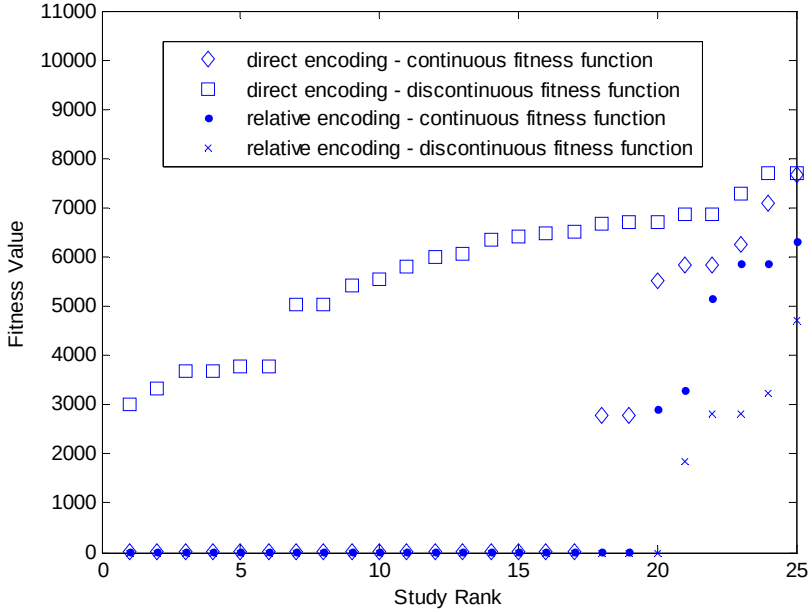
Rotor Material Type	M47	Slot Depth (cm)	2.80
Stator Material Type	M19	Depth of Backiron (cm)	1.24
Permanent Magnet Type	NdFeB-30	Active Length (cm)	9.49
Current Phase Advance (Degress)	4.16	Fundamental Conductor Density (conductors/rad)	57.5
Permanent Magnet Fraction (Percent)	82.5	3rd Harmonic Turns Density	40.7
Slot Fraction (Percent)	18.2	Conductor Type	Copper
Rotor Iron Radius (cm)	2.05	Conductor Area (mm^2)	2.67
Permanent Magnet Depth (cm)	0.46	Fillet Fraction	0.26
Air Gap (mm)	0.59		





Algorithm Comparisons
One Region / Neighborhood

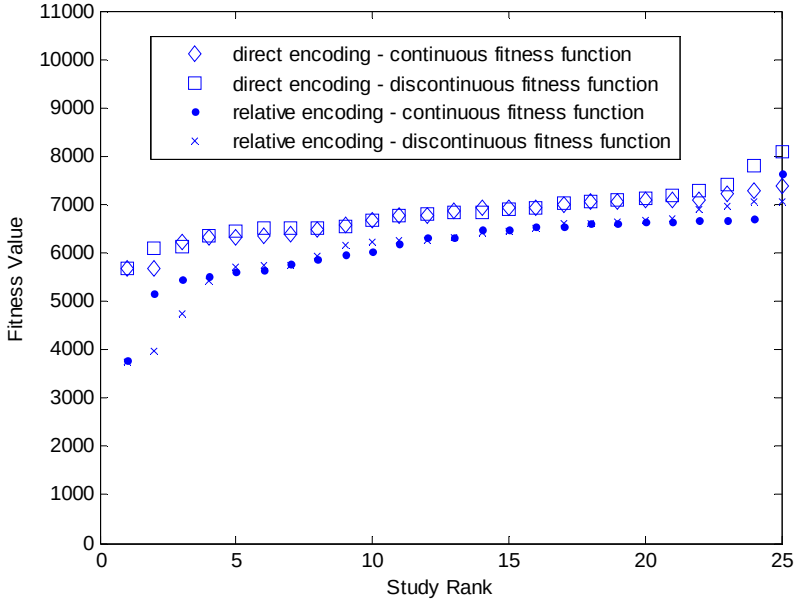


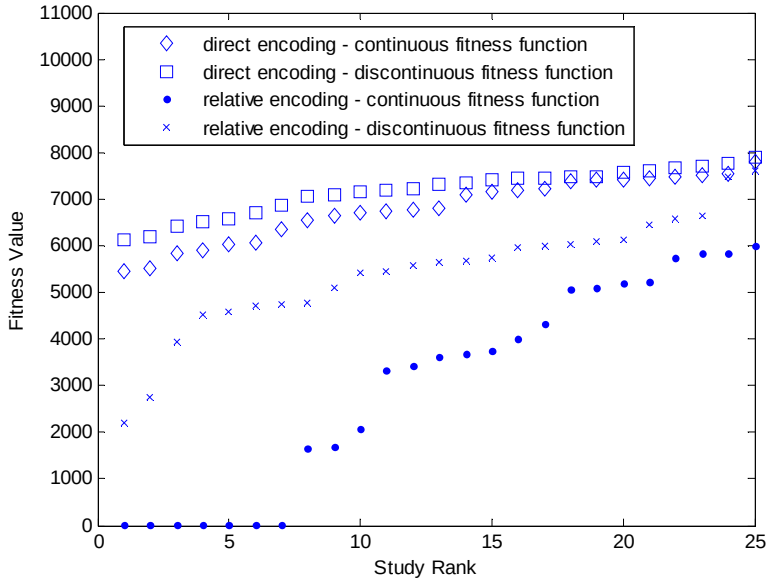


GA
Population Size: 2000
Generations: 2000
Evaluations: 2,400,000

PSO
Swarm Size: 1549
Iterations: 1549
Evaluations: 2,400,000

Algorithm Comparisons
Thirty Regions / Neighborhoods

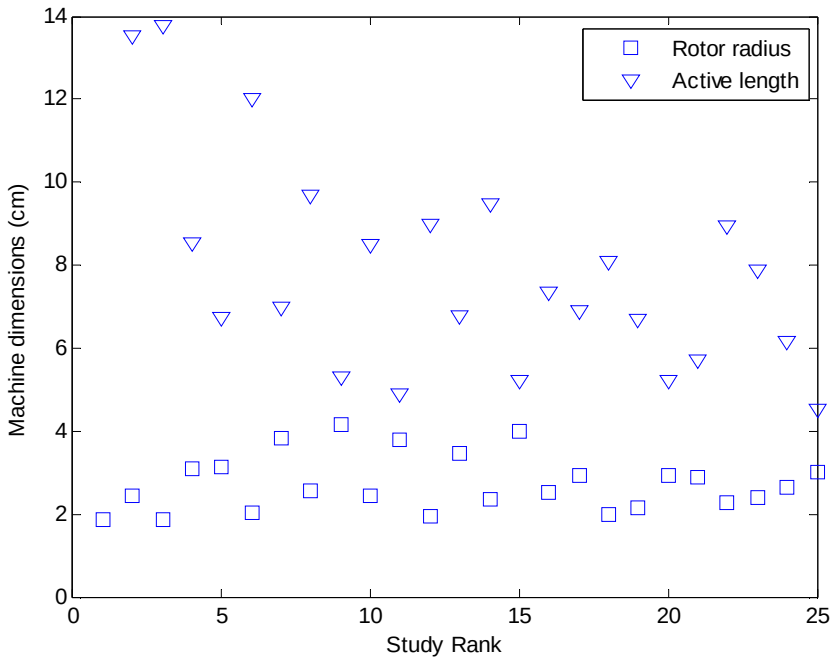


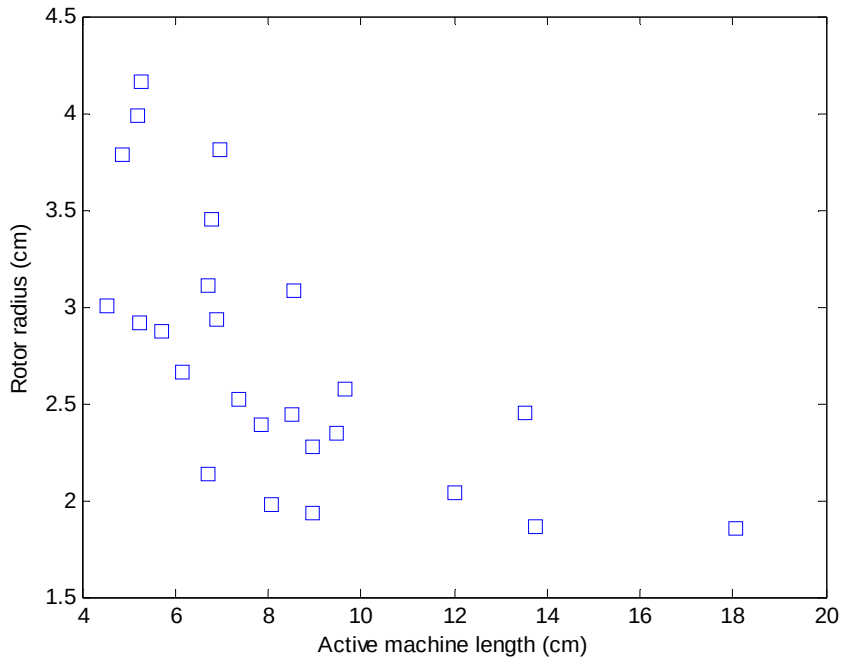


GA
Population Size: 2000
Generations: 2000
Evaluations: 2,400,000

PSO
Swarm Size: 1549
Iterations: 1549
Evaluations: 2,400,000

Design Uniqueness
(GA, Direct Enc., Disc. Fitness)

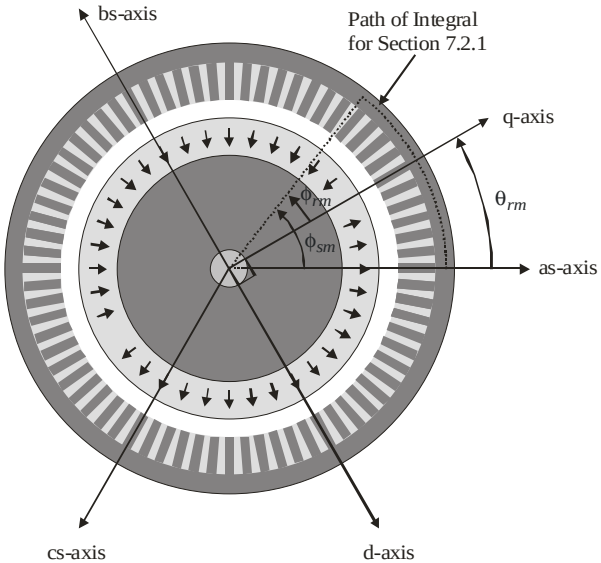


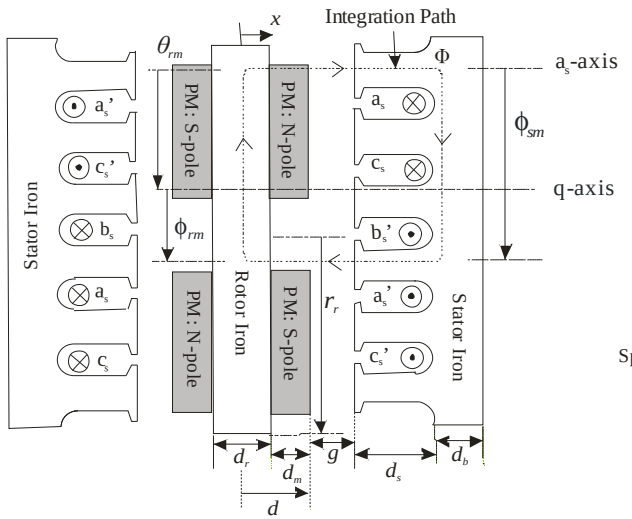


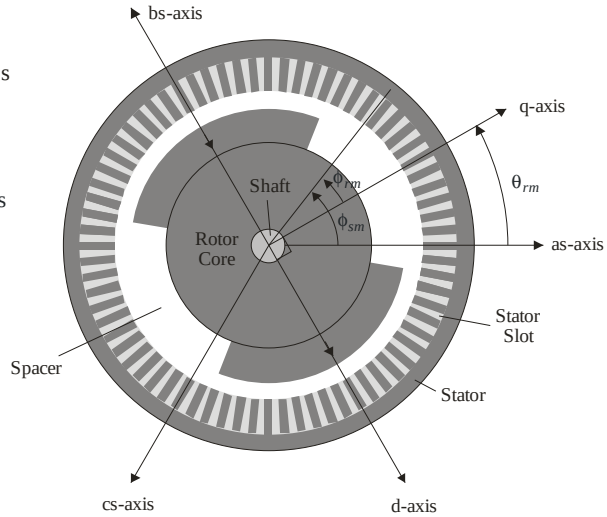
Design a Soldier Portable Generator

- Specifications
  - 400 V dc Bus
  - 3 kW Electrical Output Power

Candidate Designs



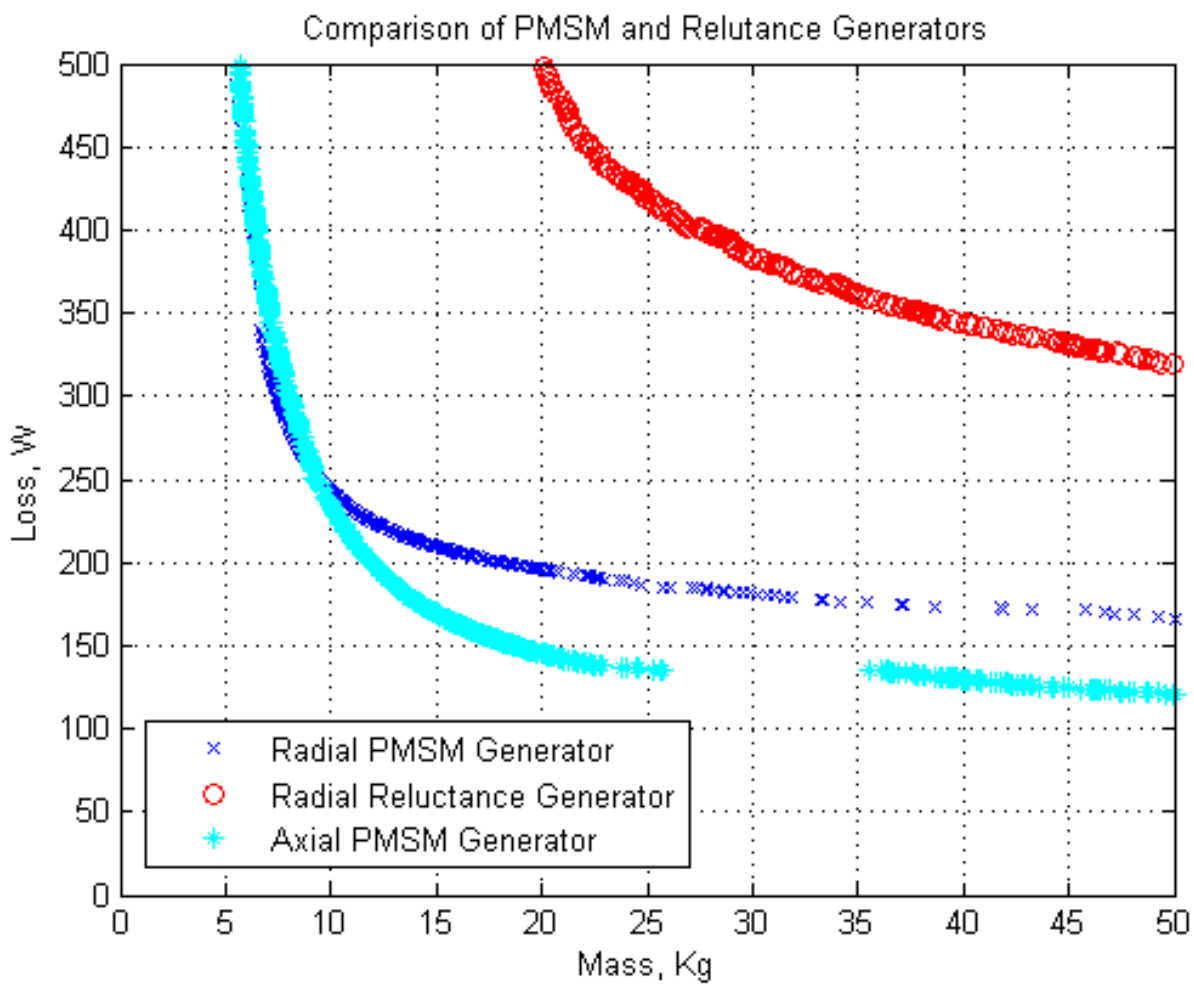




Machine Comparison

$$\bar{c} = \frac{1}{N}\sum_{n=1}^{N} c_n$$

$$f = \begin{cases} \varepsilon(\bar{c}-1)\begin{bmatrix}1\\1\end{bmatrix} & \bar{c} < 1 \\ \begin{bmatrix}\frac{1}{m}\\ \frac{1}{P_{loss}}\end{bmatrix} & \bar{c} \geq 1 \end{cases}$$



Selecting a Specific Design

- Approach 1: Pick one
  - Advantage: easy
  - Disadvantage: may not be on the front
- Approach 2: Run a single objective optimization with added constraint on loss

Single Objective Optimization

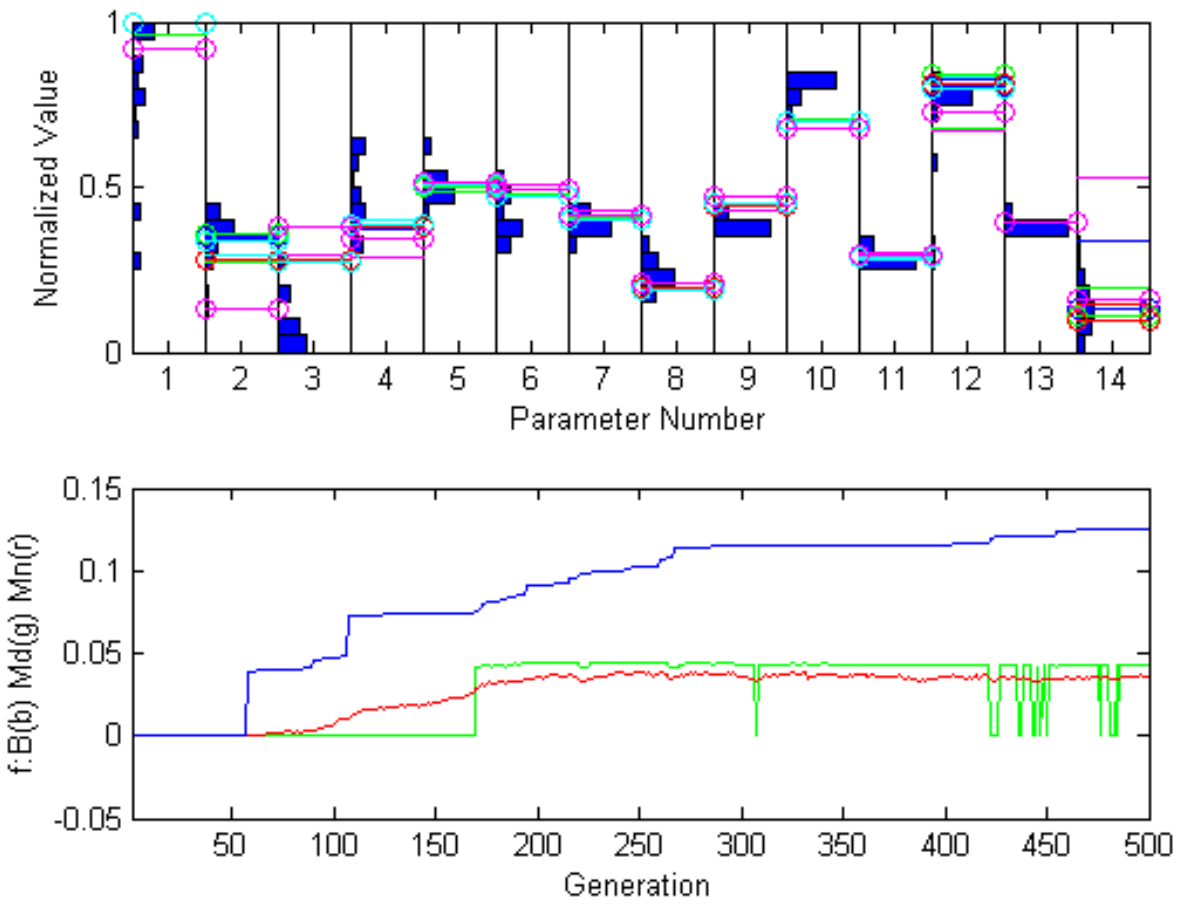
- For 2 kW design

-Added constraint of loss of 257 W
-90% efficiency for generator / rectifier

$$\bar{c} = \frac{1}{N}\sum_{n=1}^{N} c_n$$

$$f = \begin{cases} \varepsilon(\bar{c} - 1) & \bar{c} < 1 \\ \frac{1}{m} e^{\left(\frac{P_{req} - P_{out}}{P_{req}}\right)} & \bar{c} \geq 1 \end{cases}$$

Design Evolution

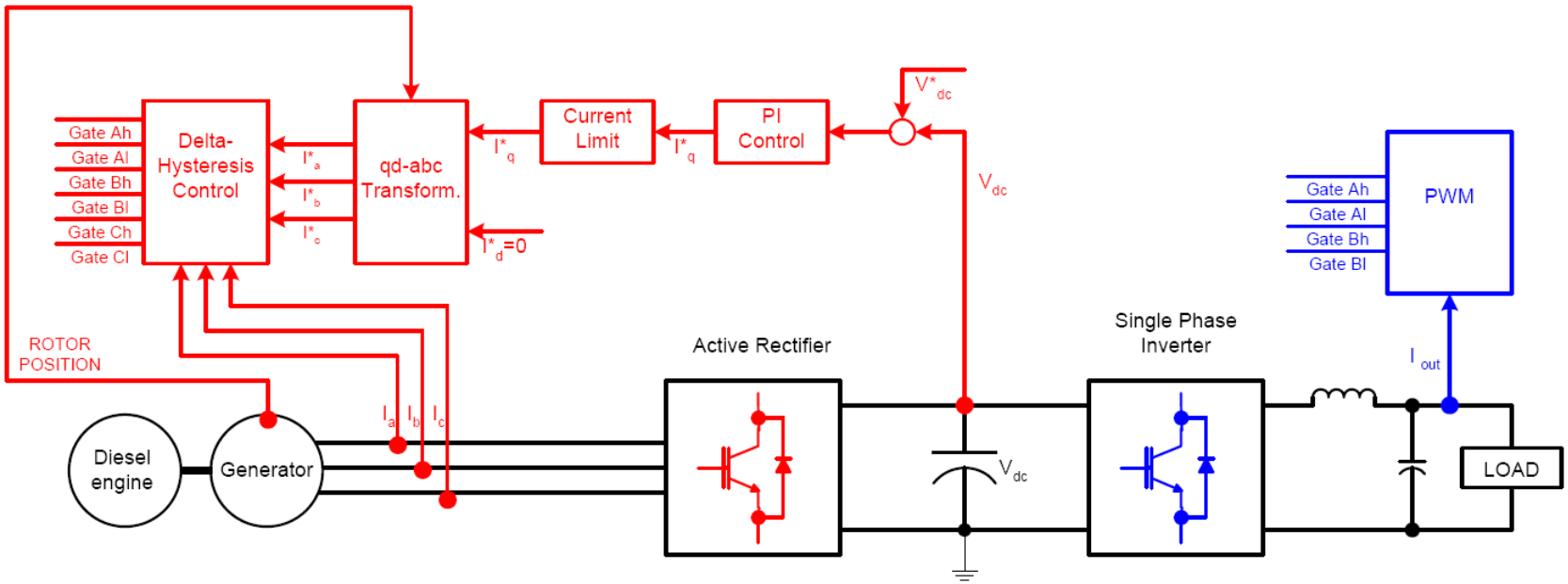


Design Report

- Mass: (kg)7.9715
- Rotor Steel Mass (less shaft) (kg): 1.2523
- Stator Iron Mass (kg): 4.8969
- Stator Copper Mass (kg): 1.4794
- Magnet Mass (kg): 0.34289
- Rotor Material Type: M19
- Stator Material Type: M19
- Permanent Magnet Type: NdFeB-30
- RMS Line Current (A): 13.5153
- Current Phase Advance (Degrees): 171.332
- Permanent Magnet Fraction (Percent): 36.5488
- Slot Fraction (Percent): 24.0531
- Rotor Iron Radius (cm): 3.1633
- Permanent Magnet Depth (cm): 0.73316
- Air Gap (mm): 1.0185
- Slot Depth (cm): 2.1585
- Depth of Backiron (cm): 0.96692
- Active Length (cm): 7.8083
- Minimum Total Length (cm)12.4086
- Outside Diameter(cm): 14.2473
- Number of Slots: 24
- Fundamental Turns Density (turns/rad): 40.9794
- 3rd Harmonic Turns Density (percent): 21.97
- Conductor Type: Copper
- Conductor Area (mm^2): 2.0816
- Slot Opening: 2.5173 mm
- American Wire Gauge: 14

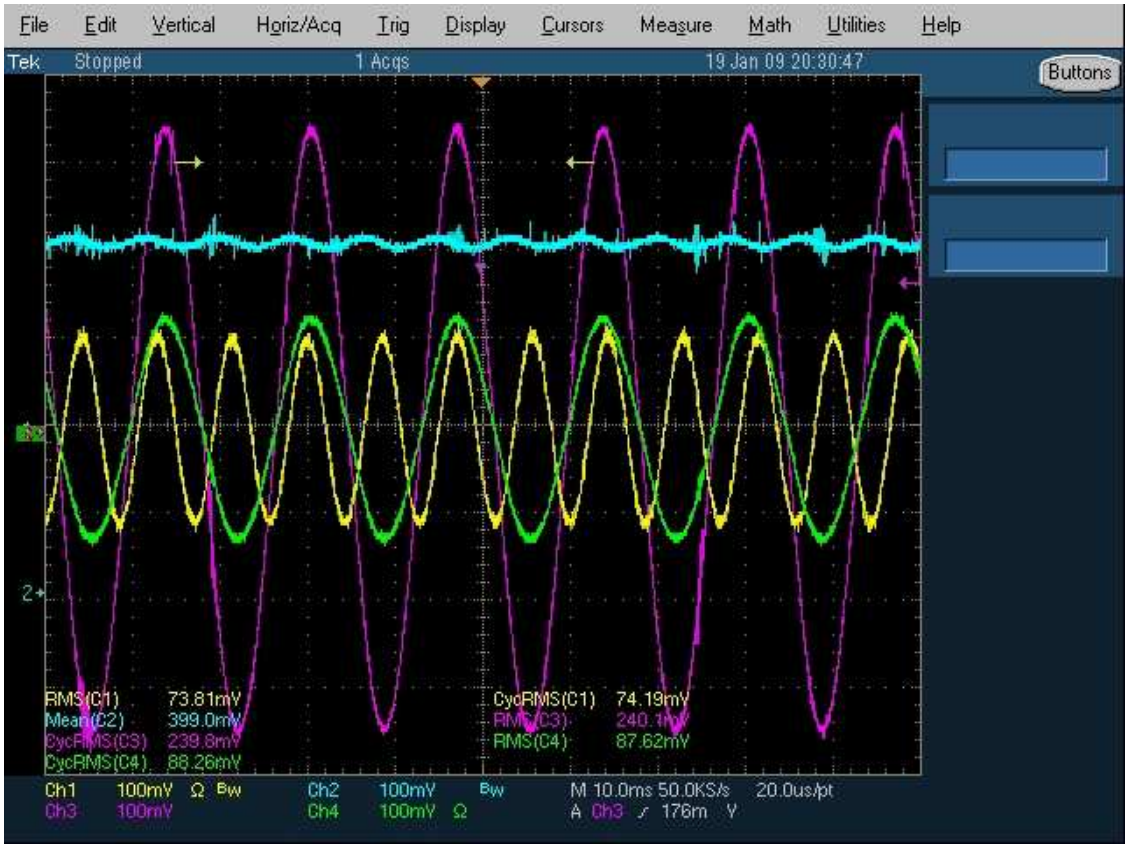
- Stator Tooth Flux Density / Saturation Point: 0.99082
- Stator Tooth Base Flux Density / Saturation Point: 0.95629
- Stator Backiron Flux Density / Saturation Point: 0.98946
- Permanent Magnet Demagnetization: 0.493
- Current Density / Allowable Current Density: 0.85207
- Maximum Slot Fill / Allowed Slot Fill: 0.55345
- Air Gap / Minimum Allowed Air Gap: 3.2199
- RMS L-N Voltage / Maximum Allowed Voltage: 0.83949
- Power Factor = 0.99276
- Torque: -6.6951
- Corrected Torque: -6.7866
- Conduction Losses: 120.8122
- Core Losses in Teeth: 14.1565
- Core Losses in Backiron: 20.0615
- Total Machine Loss: 155.0302
- Rectifier Loss: 73.0084
- Rectifier Efficiency: 0.96935
- Machine Efficiency: 0.9389
- Stator Resistance (Ohms) = 0.22046
- Q-Axis Inductance (mH) = 1.6345
- D-Axis Inductance (mH) = 1.6345
- Flux Linkage Due to PM (Vs) = 0.11811
- Q-Axis Voltage (V) = 80.624
- D-Axis Voltage (V) = 22.4575
- RMS l-n Voltage (V) = 59.1801
- Q-Axis Current (A) = -18.8952
- D-Axis Current (A) = -2.8806
- RMS Current (A) = 13.5153
- Electrical Power Out (W) = 2382.153

Power Electronics / Control



Packaged Hardware

System Waveforms



Purple: Output voltage (500 V/V)

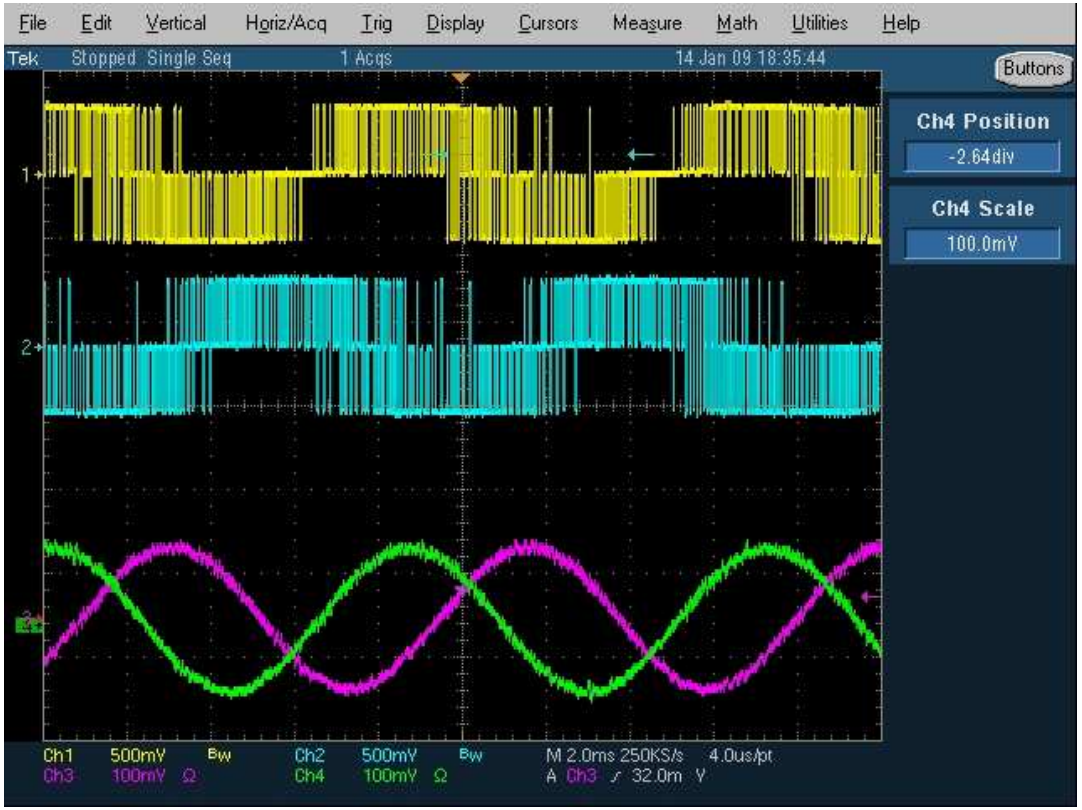
Blue:DC-link voltage (500 V/V)

Green: Output current (200 A/V)

Yellow: Alt. current (200 A/V)

2.1 kW Output

System Waveforms



Yellow: a-b voltage(500V/V)

Blue: b-c voltage (500 V/V)

Green: phase-a current (200 A/V)

Yellow: phase-b current (200 A/V)

2.1 kW Output

Performance Summary

- Alternator
  - Average Torque (estimated using phase currents/voltage) ~ 6.653 Nm
  - Input Average Power @3509 rpm = Te*speed ~ 2445 W
  - Output Power at Terminals = 2332 W
  - Efficiency ~ 95%
- Combined Active Rectifier/Inverter
  - Power Output = 2109 W
  - Power Input ~ 2332 W
  - Efficiency ~ 90%
- Overall Efficiency ~ 85%
- Mass
  - Alternator (Engine Mount) = 11.1 kg
  - Active Rectifier/Inverter (with enclosure) = 2.2 kg
  - Total = 13.3 kg

<u>Baseline System</u>
Efficiency ~ 72%
Mass = 17.8 kg

Savings Per Year:
$ 15 Million

Model Fidelity

Parameter	Design Code	Modified Code	Constructed Machine
Flux Linkage due to PM (Vs)	0.118	0.118	0.115
Stator Winding Resistance (Ohm)	0.205	0.22	0.24
q-axis Stator Inductance (mH)	1.37	1.63	1.65
d-axis Stator Inductance (mH)	1.37	1.63	1.65
Magnetic Mass of Machine (kG)	7.99	7.97	8.5
Machine Efficiency (%)	94.2	93.8	95.3

Code modifications:

End winding Offset (1.5 rather than 1 cm)

Packing Factor Assumptions (0.7 rather than 0.4)

Rectifier/Inverter Efficiency Predicted in System Simulation (Neglecting Switching Losses) = 92%

Measured Rectifier/Inverter Efficiency = 90 %

Opinions

- Evolutionary design will become standard methodology for electromagnetic / electromechanical design
- Analytical and magnetic equivalent circuit methods are still important in the design process
- Use of multiple regions / neighborhoods is clearly beneficial
- Discontinuous fitness function with direct encoding seemed to be most effective
- Machines classes should be compared in terms of Pareto-Optimal fronts
- GA/PSO/Simulated Annealing/Bacteria Foraging/ etc. debate will go on forever.

GOSET

- **GOSET** stands for **G**enetic **O**ptimization **S**ystem **E**ngineering **T**ool
- GOSET is a MATLAB based genetic algorithm toolbox for solving optimization problems
- GOSET Features
  - Wide range of choices for genetic operators
  - Single-objective optimization
  - Multi-objective optimization
  - Modular Structure
  - GUI Interface
  - GOSET DLL
- Available (at not cost) at:

http://cobweb.ecn.purdue.edu/~sudhoff/Software%20Distribution/index.html

Application Examples

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- J. Cale, S.D. Sudhoff, “EI Core Inductor Designs using Population-Based Design Algorithms,” 2007 Applied Power Electronics Conference, Anaheim, CA, February 25-March 1, 2007.
- R.R. Chan, S.D. Sudhoff, S.H. Żak, Y. Lee, E.L. Zivi, “Evolutionary Optimization of Power Electronics Based Power Systems,” 2007 Applied Power Electronics Conference, Anaheim, CA, February 25-March 1, 2007.
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