Constant Voltage Permanent Magnet Wind Generator

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Material
Patent Pending

Overview

- Problem Description (3)
- Geometry Construction (8)
- Propose Solution (9)
- Review Solution
  - Power, Voltage, Efficiency (6)
  - BEMF waveform (2)
  - Cogging (6)
  - Rotor Losses (3)
  - Axial Force (1)

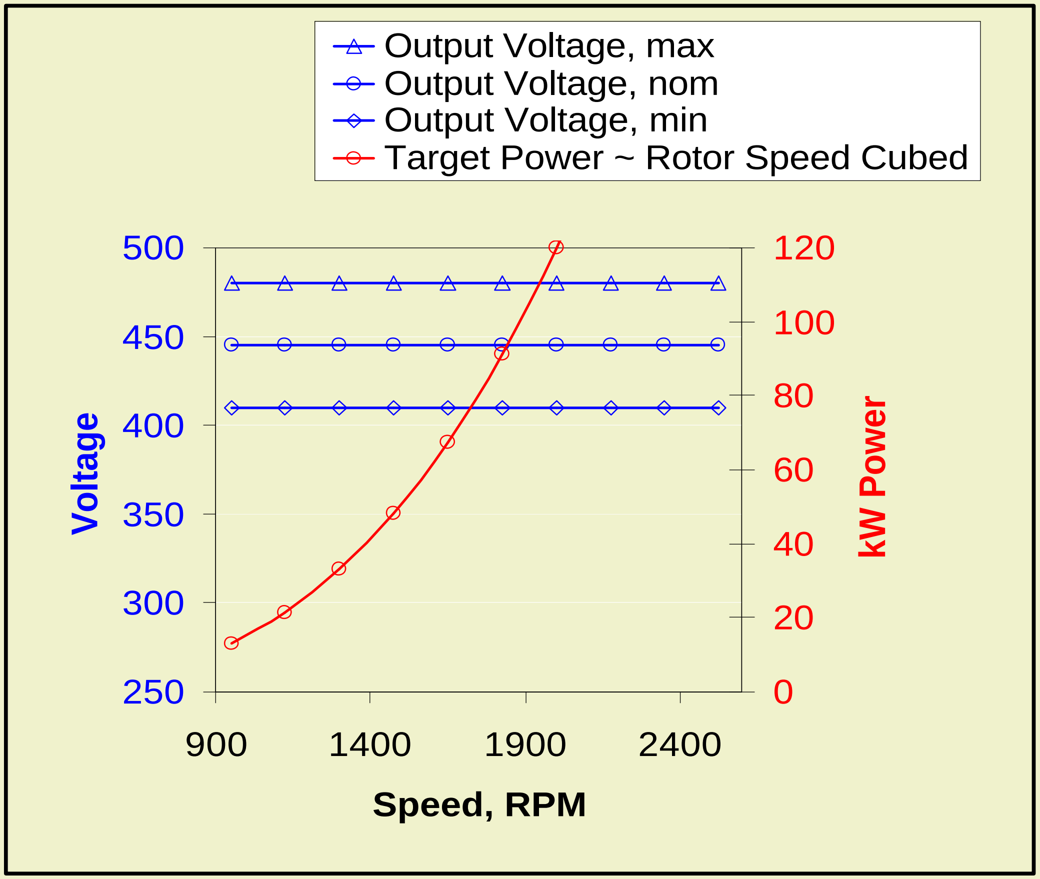
Project Definition

- Speed range: 1000 – 2000 rpm
- Voltage range: 410 – 480 Vrms (line)
- Machine Efficiency:
  - 90% min at lightest load
  - 95% min at maximum power
- Passive Rectification to DC
- Power Output Proportional to Rotor-Speed^3
- Power Output 100 kW at 2000 rpm

Wind Generator Goal
Power Output and Terminal Voltage

- Power ~ rotor-speed^3

- Voltage > 410 Vrms
- Voltage < 480 Vrms



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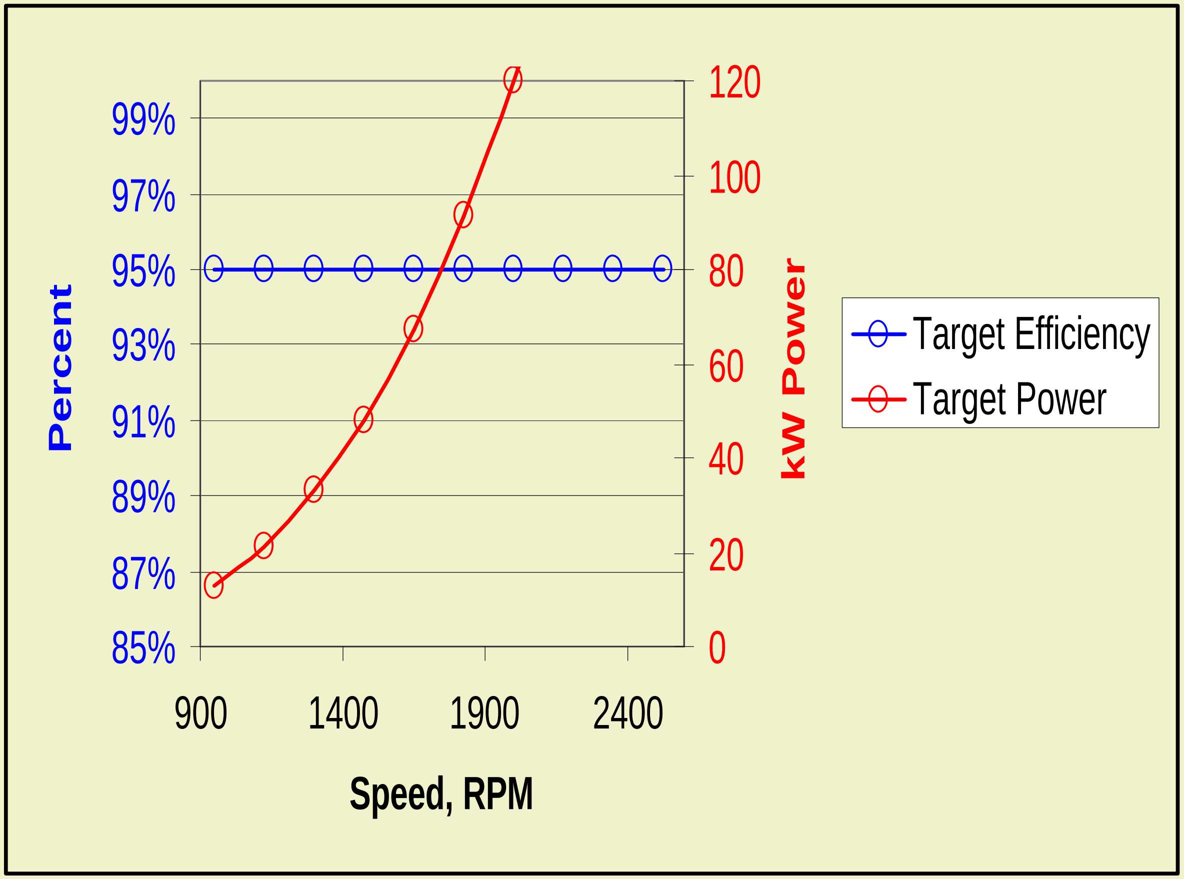
Wind Generator Goal
Power Output and Machine Efficiency



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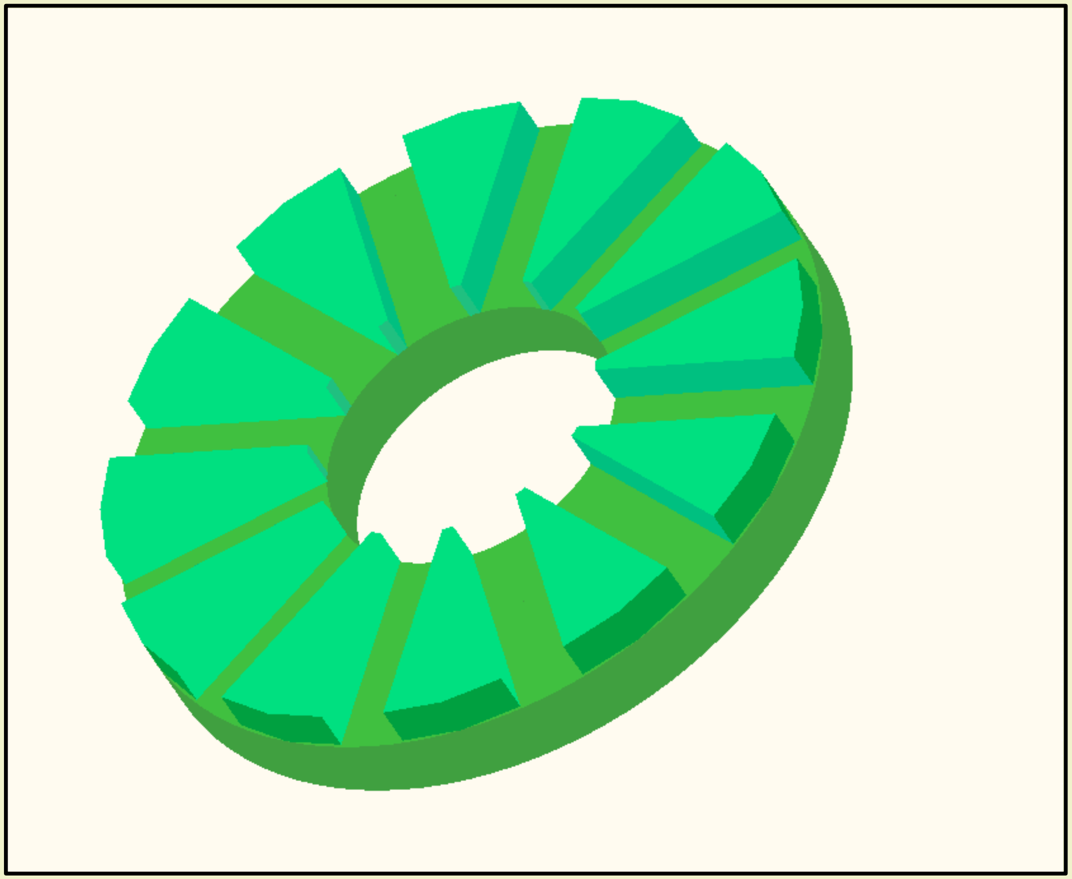
Axial Airgap Stator:
Example with 12 slots

- One stator shown

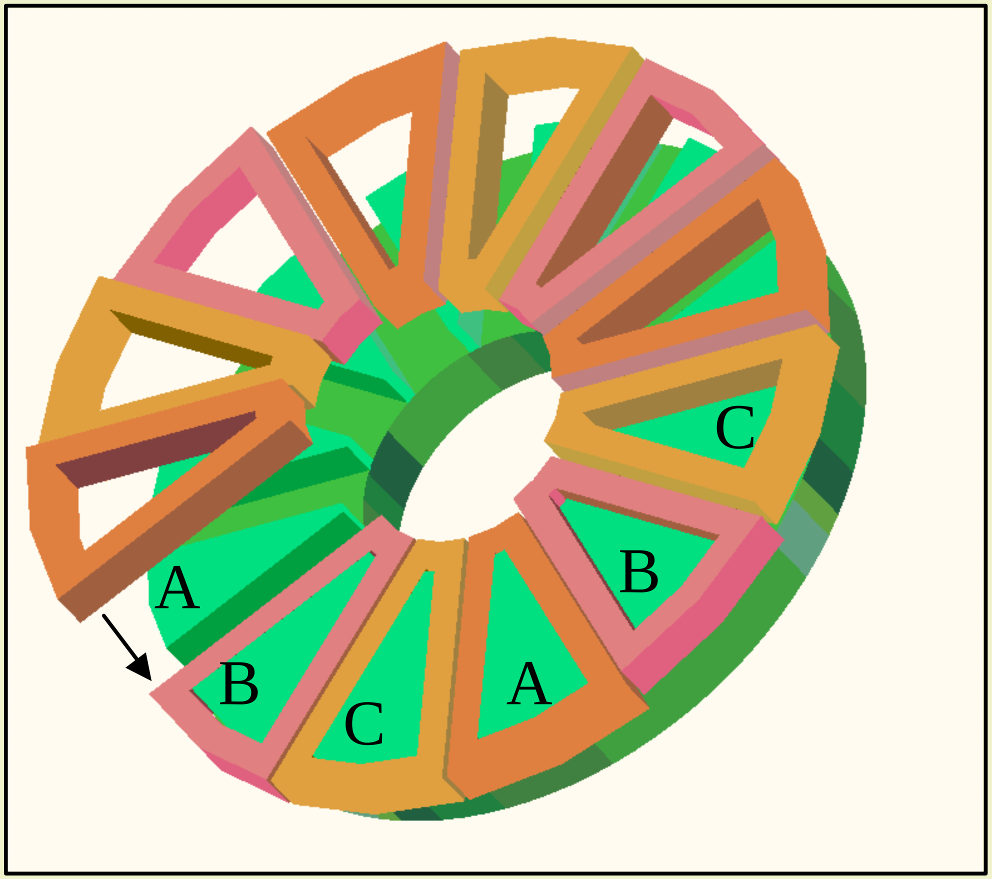
- Single wound amorphous metal ribbon, followed by slot cutting



Maxwell 3D Magnetostatic

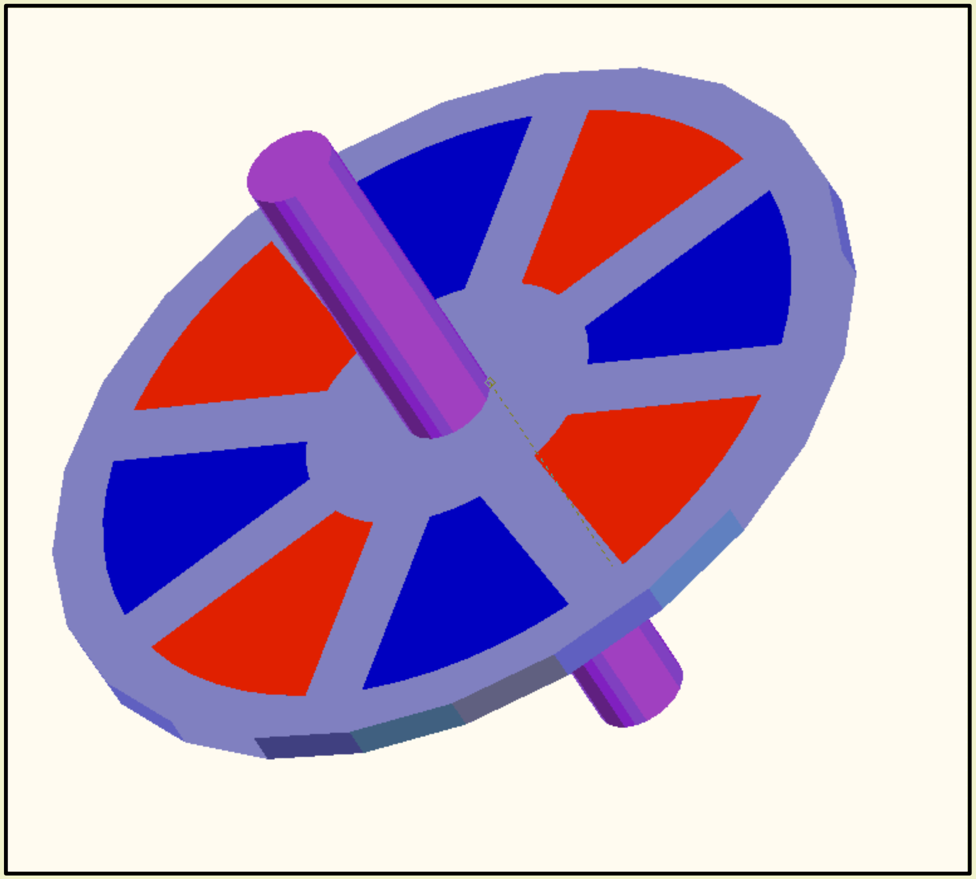
Stator shown with Phase Coils

- 0.5 slots/phase/pole
- Discrete coils
- Wired A-B-C-A-B-C



Axial-Gap Rotor and Shaft: 8 Poles

- Surface magnets (thru rotor)
- North red
- South blue
- Shaft and rotor shown for clarity



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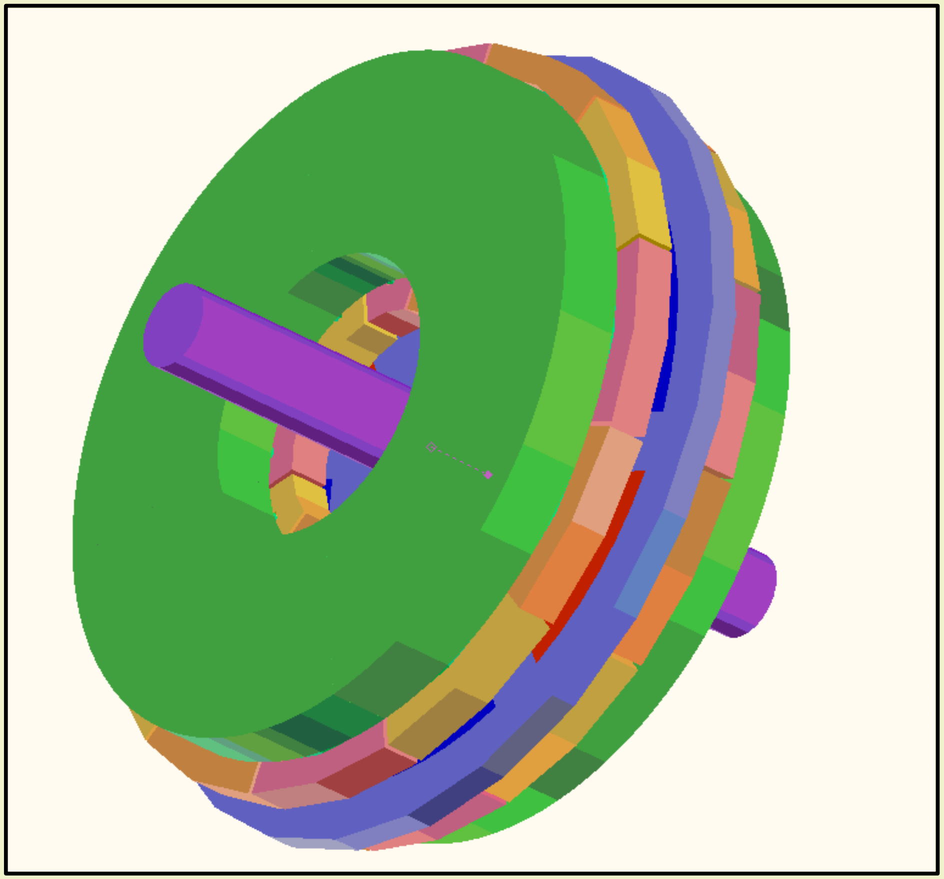
Complete Axial-Gap Machine: 12 Slots

- One rotor assembly
- Two stator assemblies
- Housing not shown



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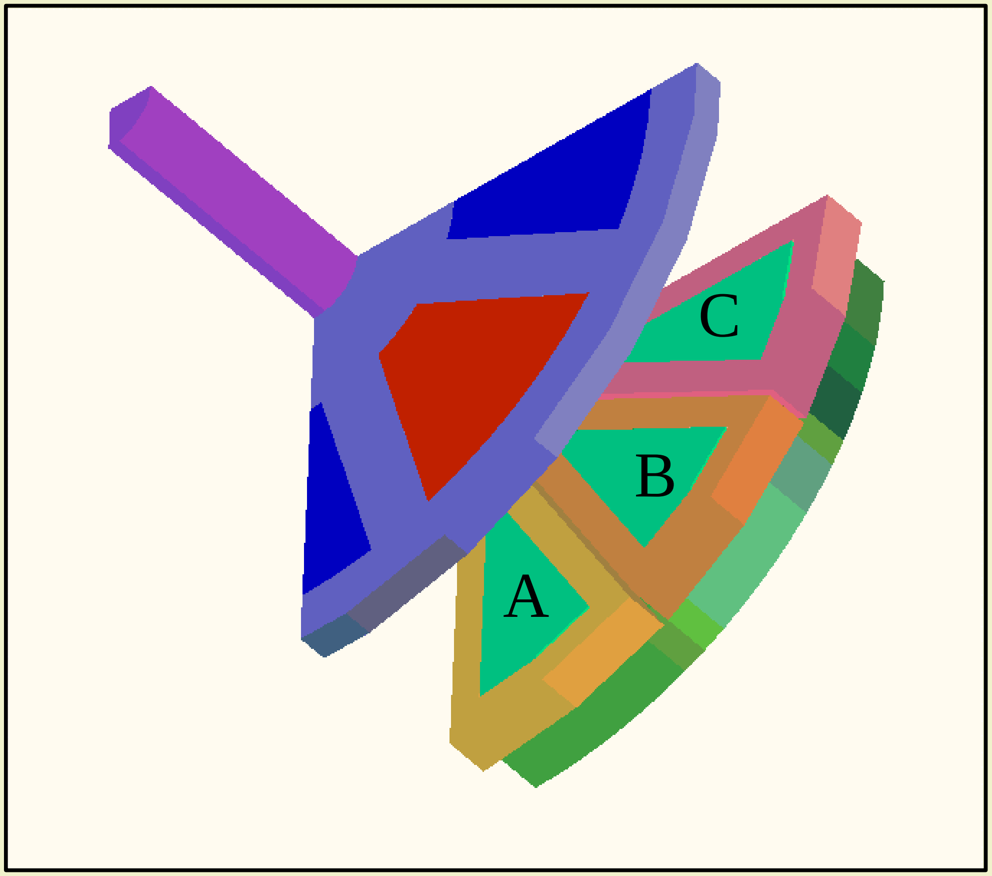
Minimum Machine for EM Analysis

- Shaft and disk not needed for analysis
- Actual airgap 2.5 mm



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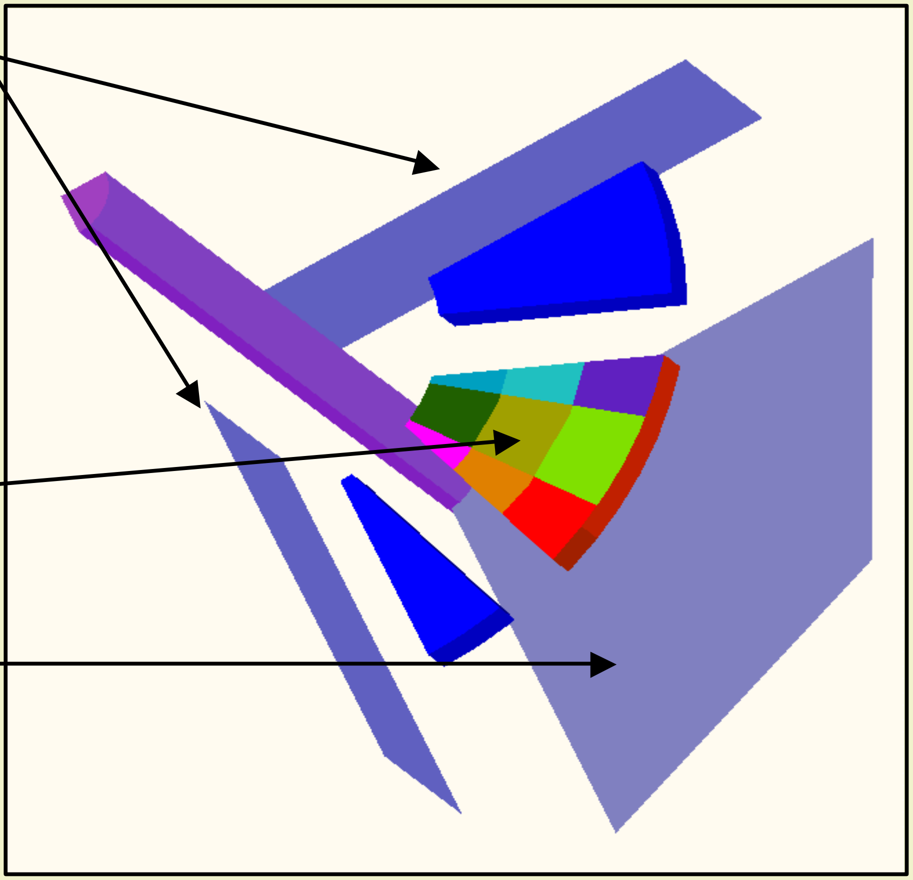
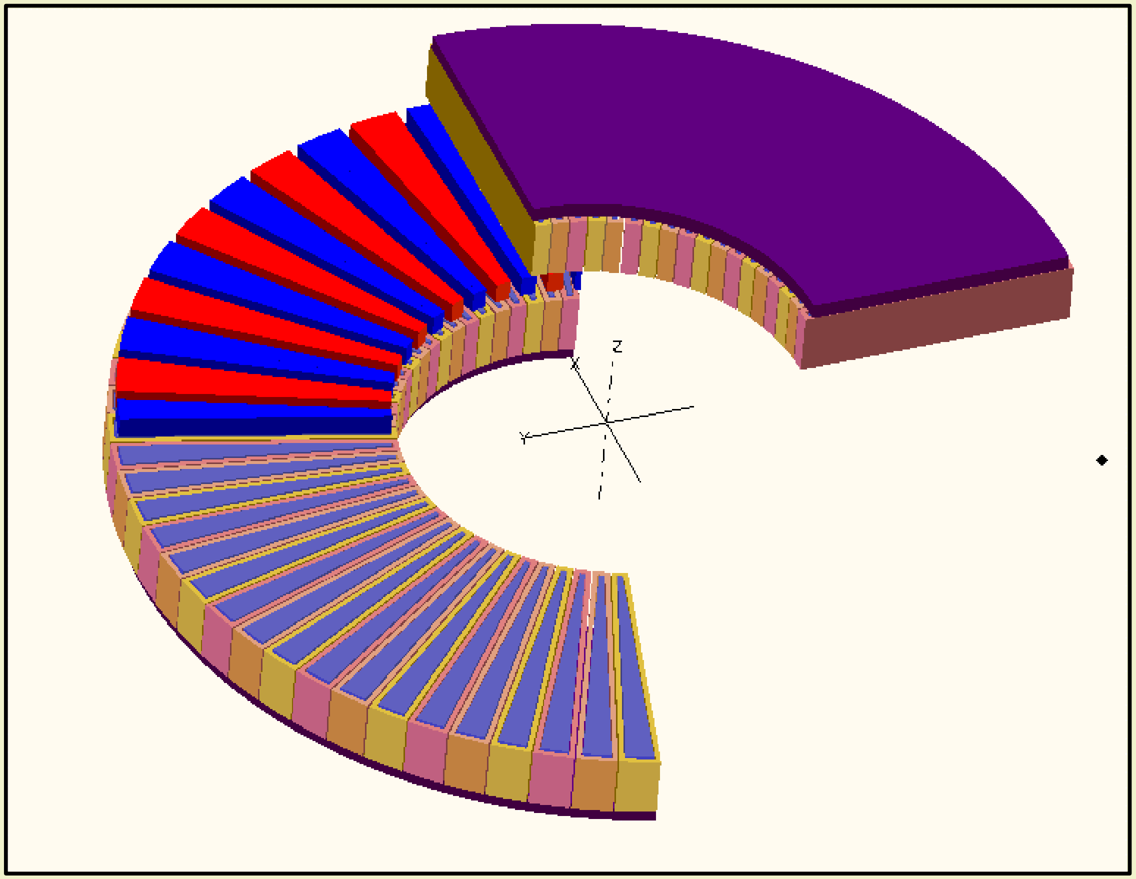
Boundary and Planar Entities: 12 Slots

- •Master-slave boundaries
- •Current sources (not shown)
- •Analysis surfaces; orthogonal grid
- •Tangent/normal boundaries



Actual Sized Machine to meet Project Specifications

- 466 cm diameter
- 13 cm axial length
- 72 Slots
- 24 Pole Pairs



Maxwell 3D Magnetostatic

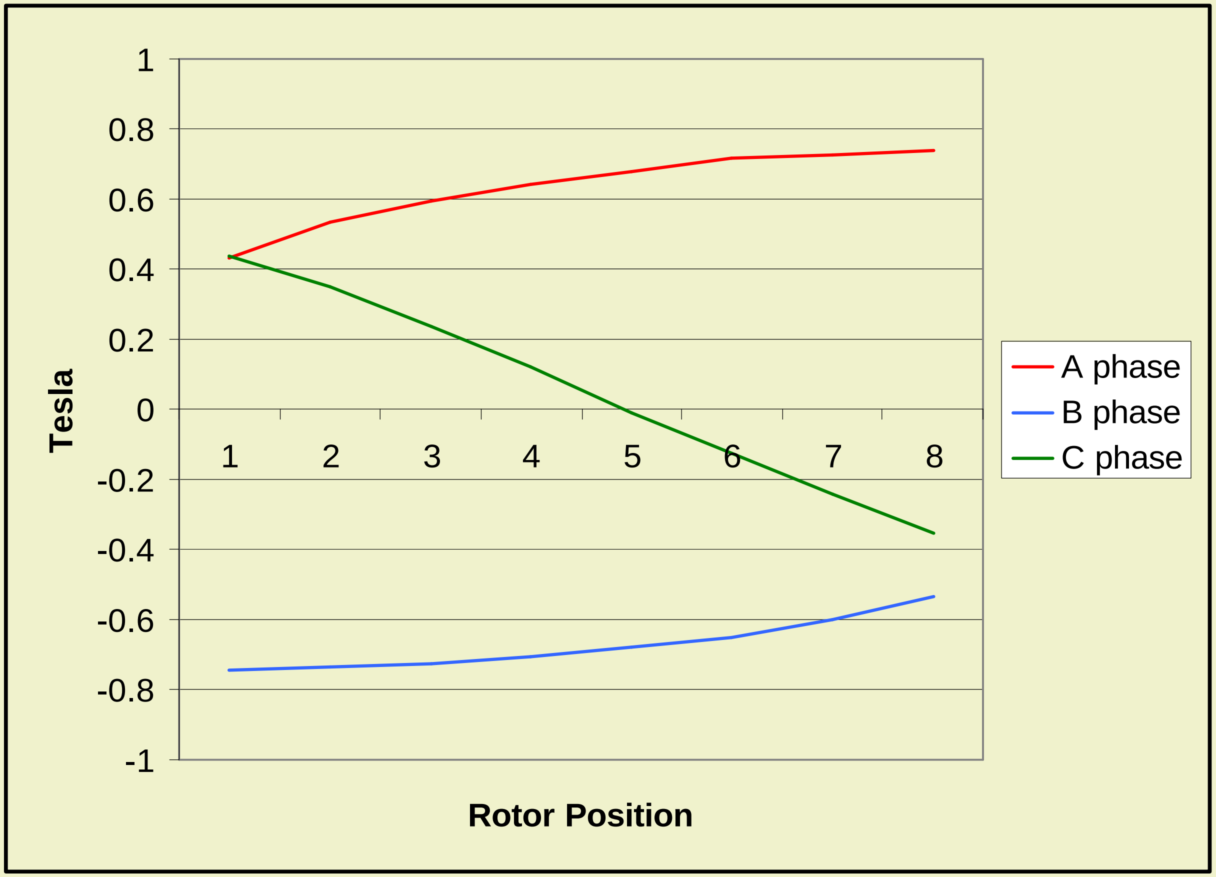
Maxwell 3D Macro

- 1200 lines main code; 400 lines post processor code
- Performs following:
  - Allows direct change to all parameters
  - Draws geometry
  - Assigns materials
  - Assigns boundaries
  - Defines solver options
  - Runs solver
  - Runs post processor macro
  - Writes inputs/outputs and writes to a .txt file
- Iterates all of the above, on any variable

Variation in Flux Density Inside Coils

Analysis for 1/6 of synchronous cycle, i.e. 1/6 of pole-pair angle.

Observation of symmetry concludes that this is all the analysis needed.



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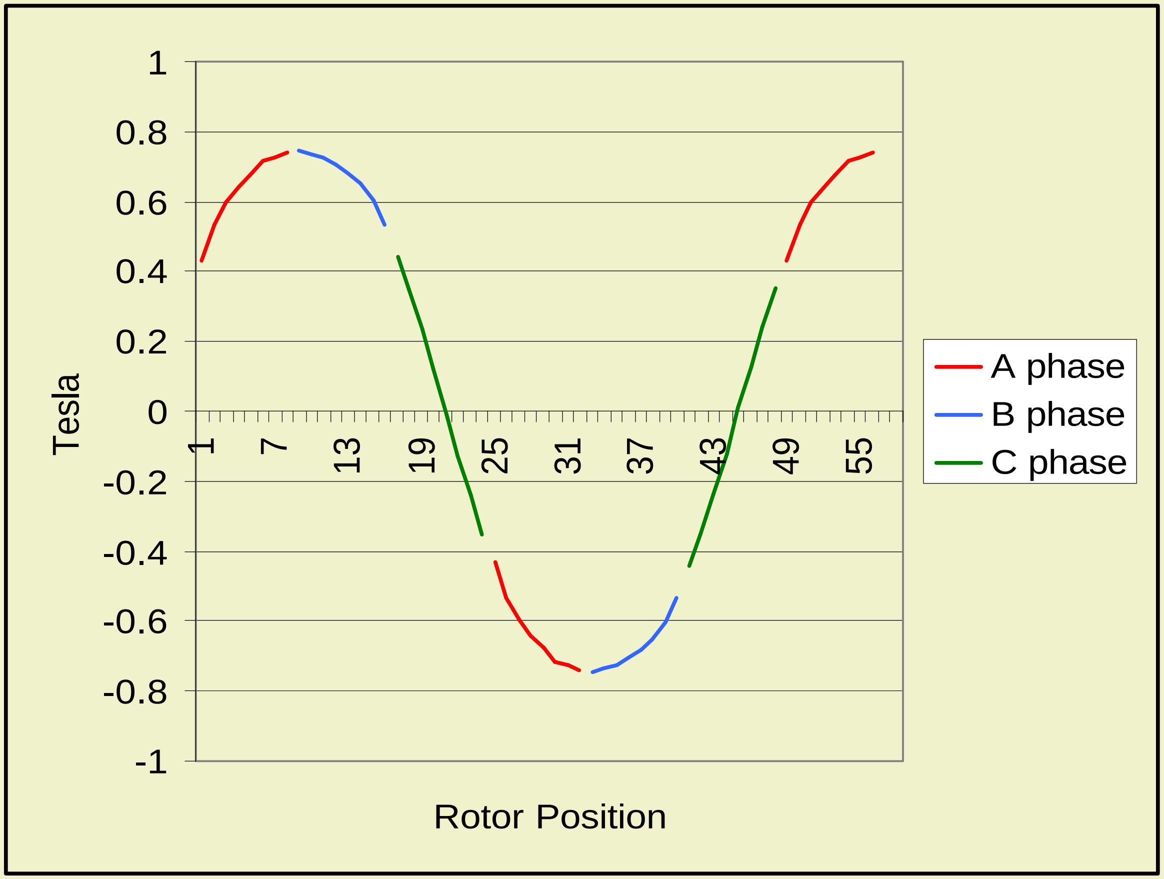
“Assembled” Variation in Flux Density

- Assembly of synchronous cycle from 1/6 analysis

- Makes macro code much faster and much easier to write



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Results from Macro

- Cogging
- Ripple
- Flux in core and backiron
- Flux variation in magnet – demagnetization potential
- Axial Forces

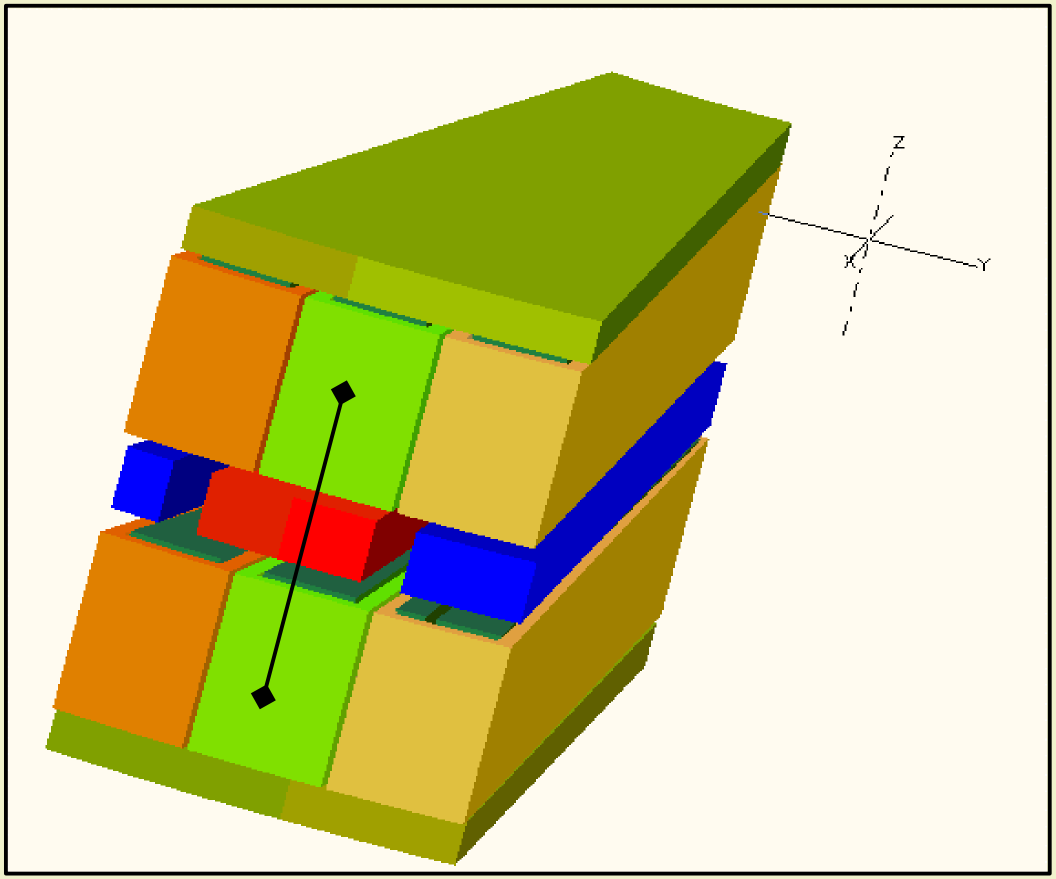
- Limited by your code

On to the Solution

- Need…
  - Constant Voltage plus
  - Increasing Speed plus
  - Increasing Power plus
  - Permanent magnet equals
- ….
- Not possible (?)

Stators In-line

Standard stator arrangement: Both stators are physically in-line, causing series connected voltage to add to 2X single-side voltage.



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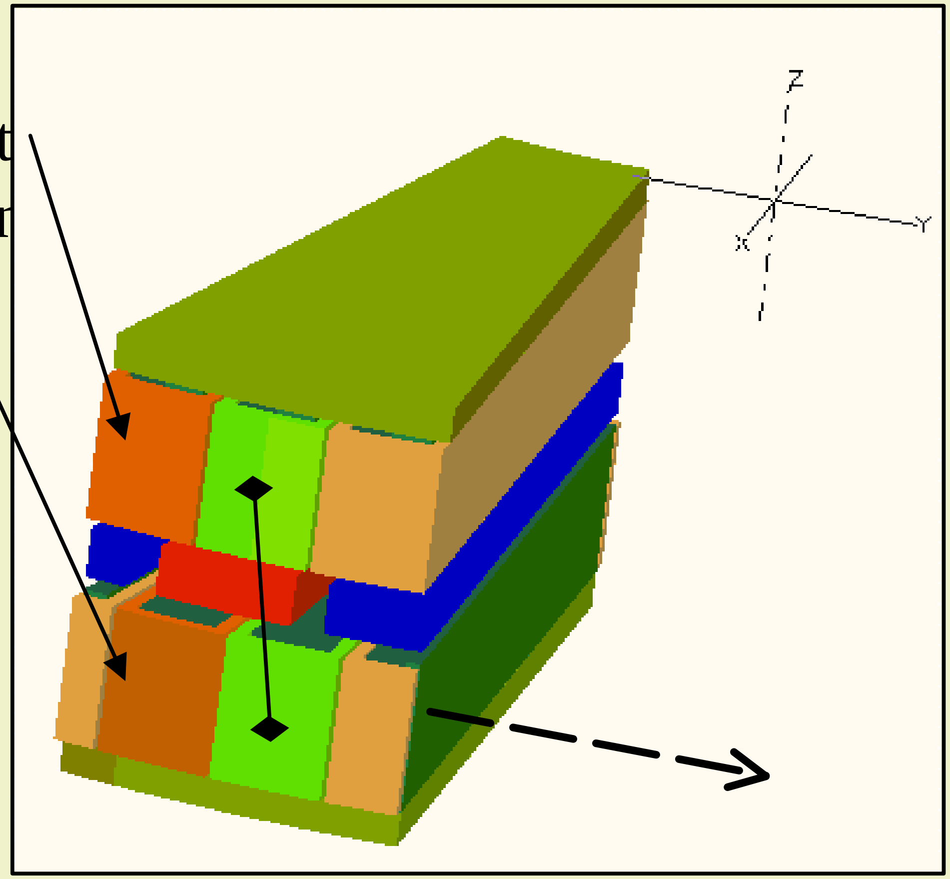
Stator Shifting: Method of EMF Control by Relative Rotation about Z-axis

Upper stator section is kept fixed relative to the rotation about z-axis of the lower section.

Previously in-phase coils are taken out of phase. Series connection causes additive resulting sine-wave voltage.



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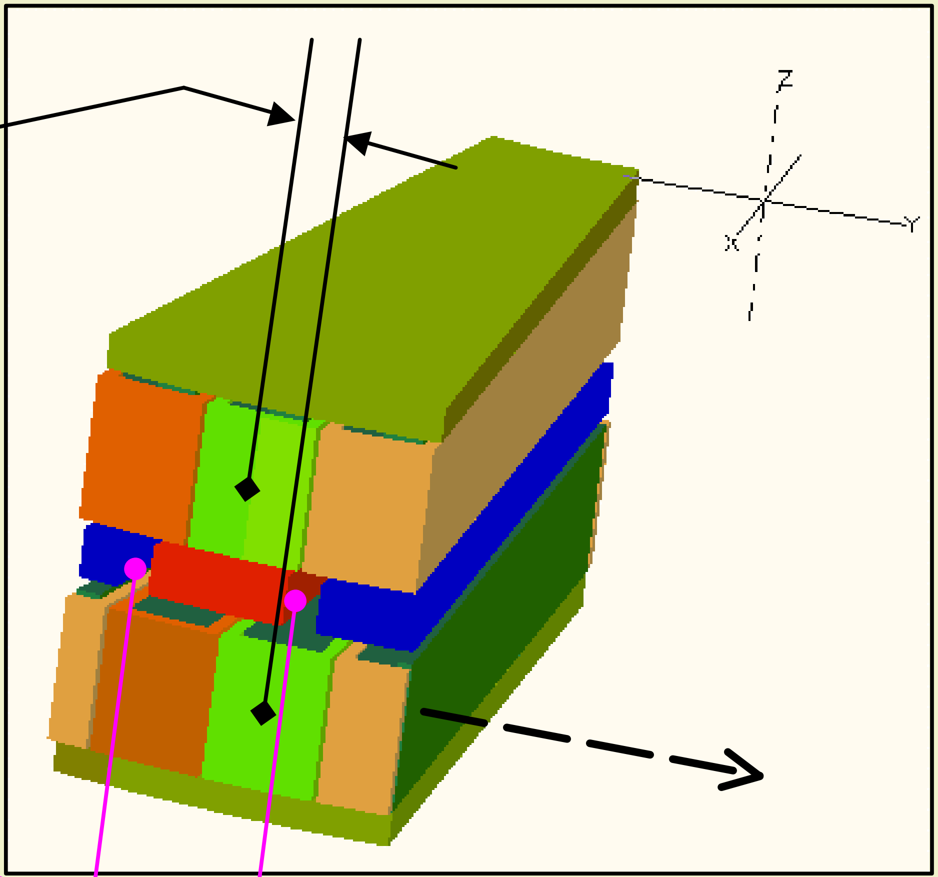
Stator Movement: Method of EMF Control by Relative Rotation

Amount of relative rotation …

never greater than …

1 pole pitch; in this example 1 pole pitch ~30 mm.



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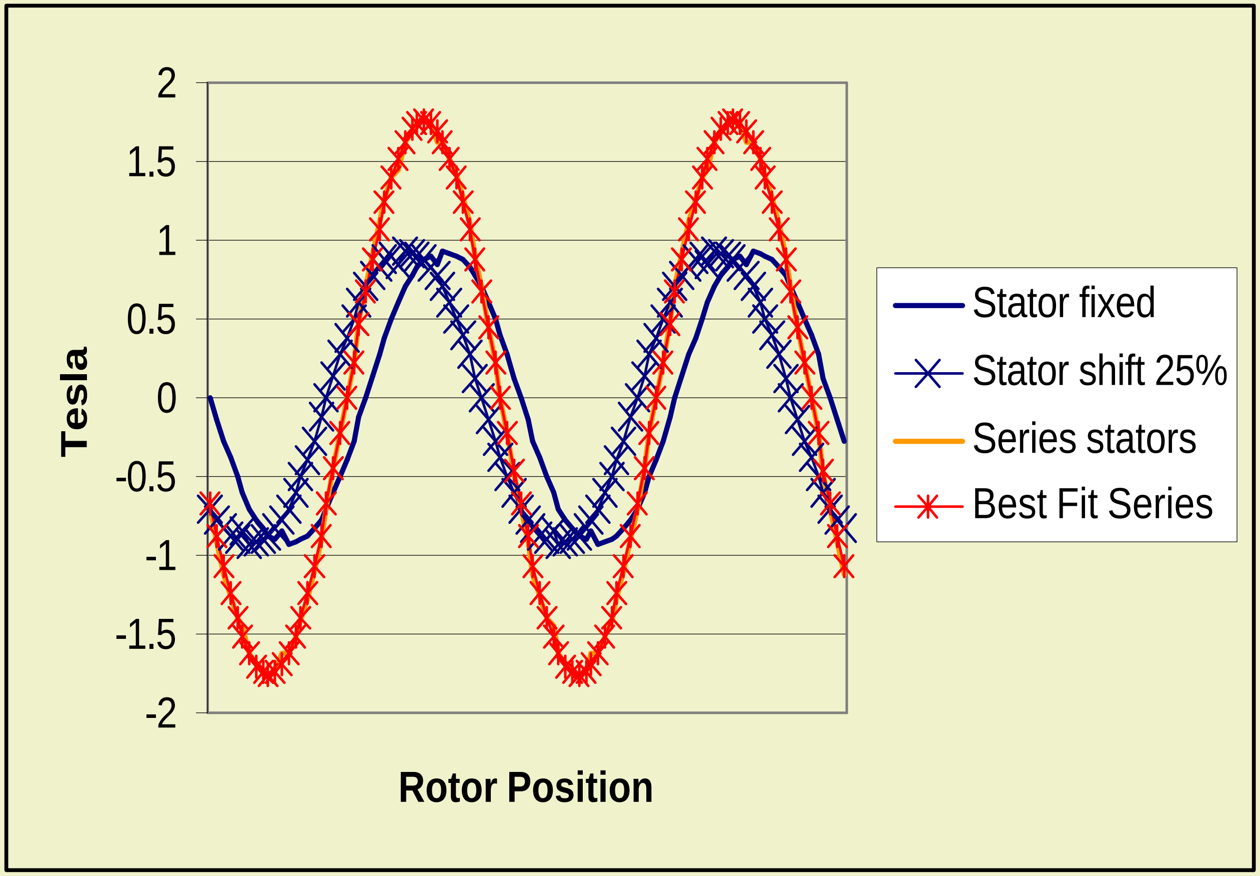
How much movement?

- 1 Pole Pitch = 7.5 degrees
- 1 Pole Pitch ~ 30mm circumferentially
- 1 Slot Pitch = 2/3 Pole Pitch

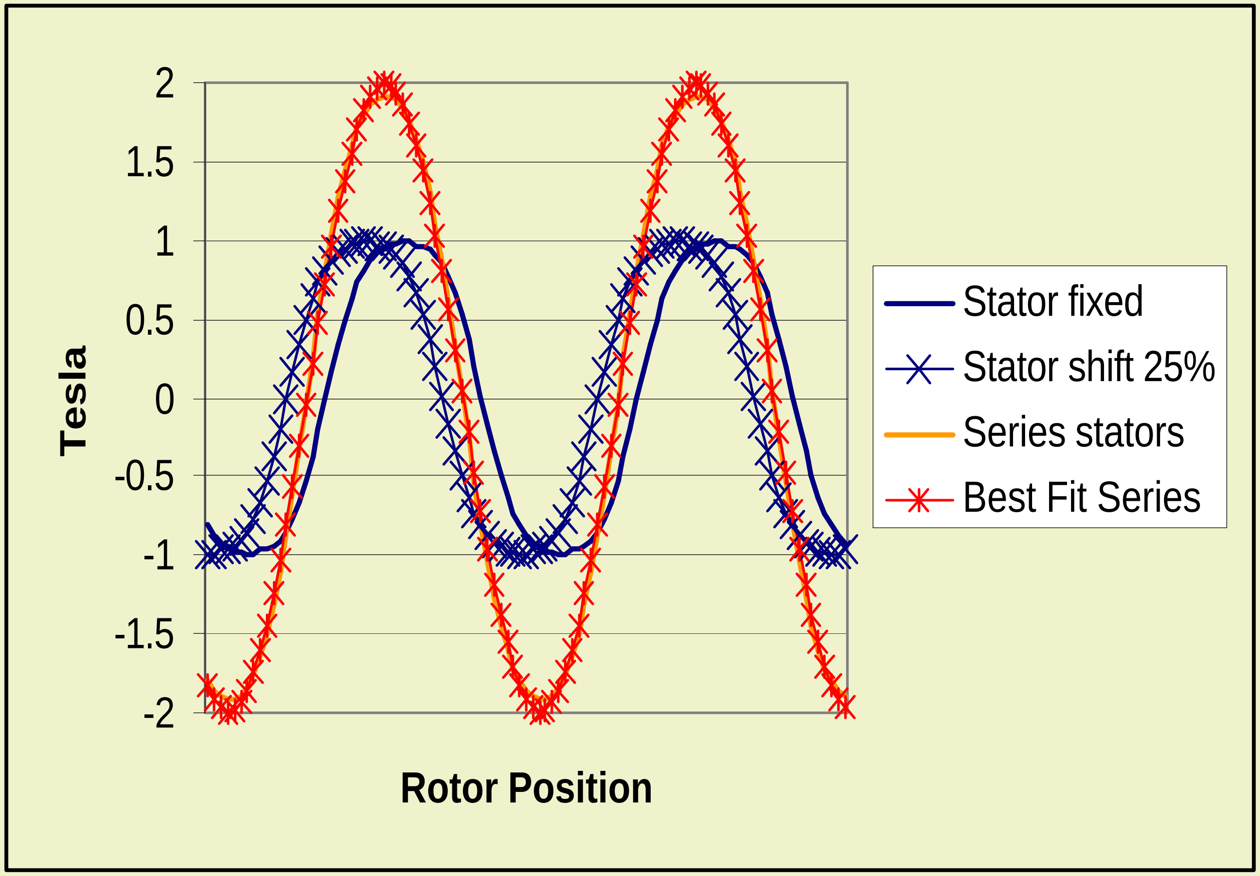
Stators Shifted by 25% Pole Pitch with Serial Addition of Waveforms

- No load
- THD=2%



Stators Shifted by 25% Pole Pitch with Serial Addition of Waveforms

- Rated load
- THD=4%



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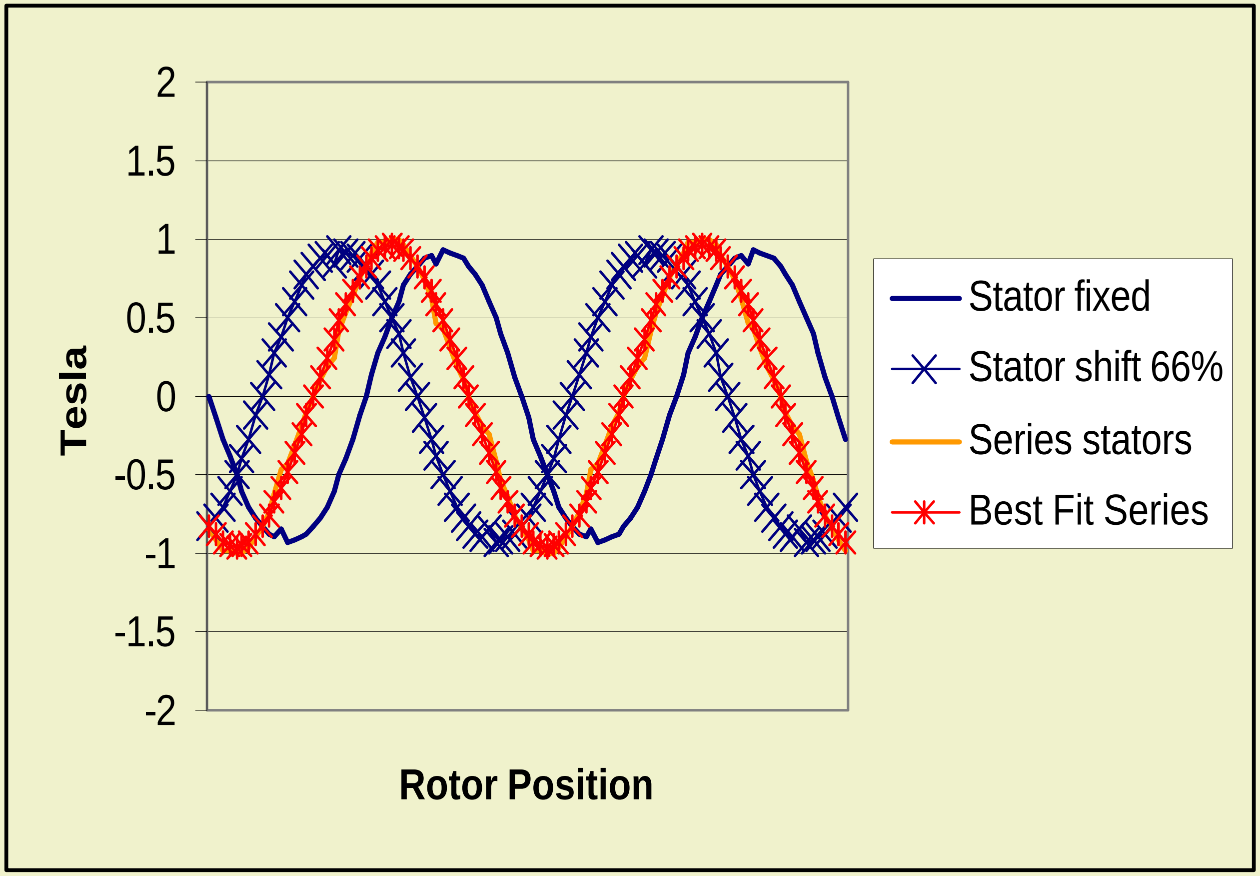
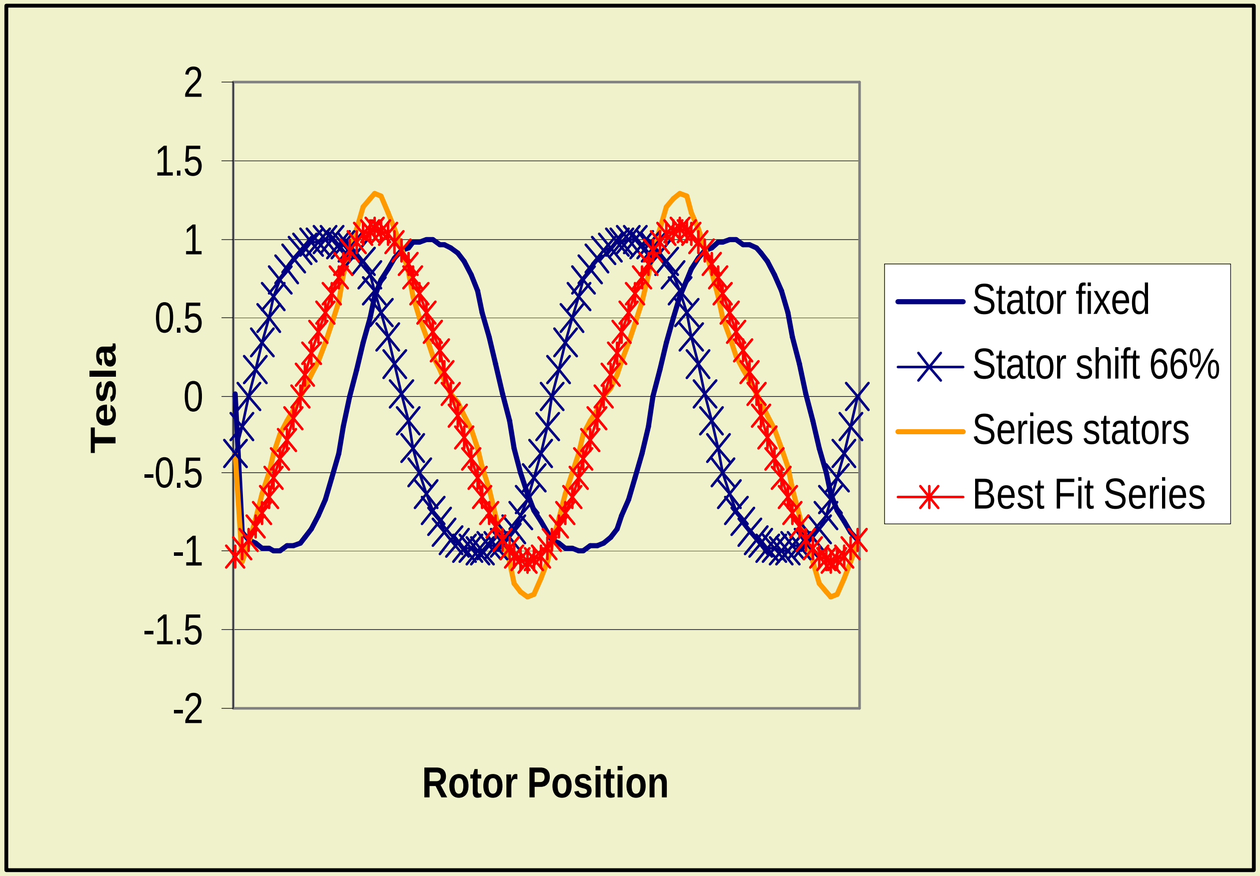
Stators Shifted by 66% Pole Pitch with Serial Addition of Waveforms

- No load
- THD=7%



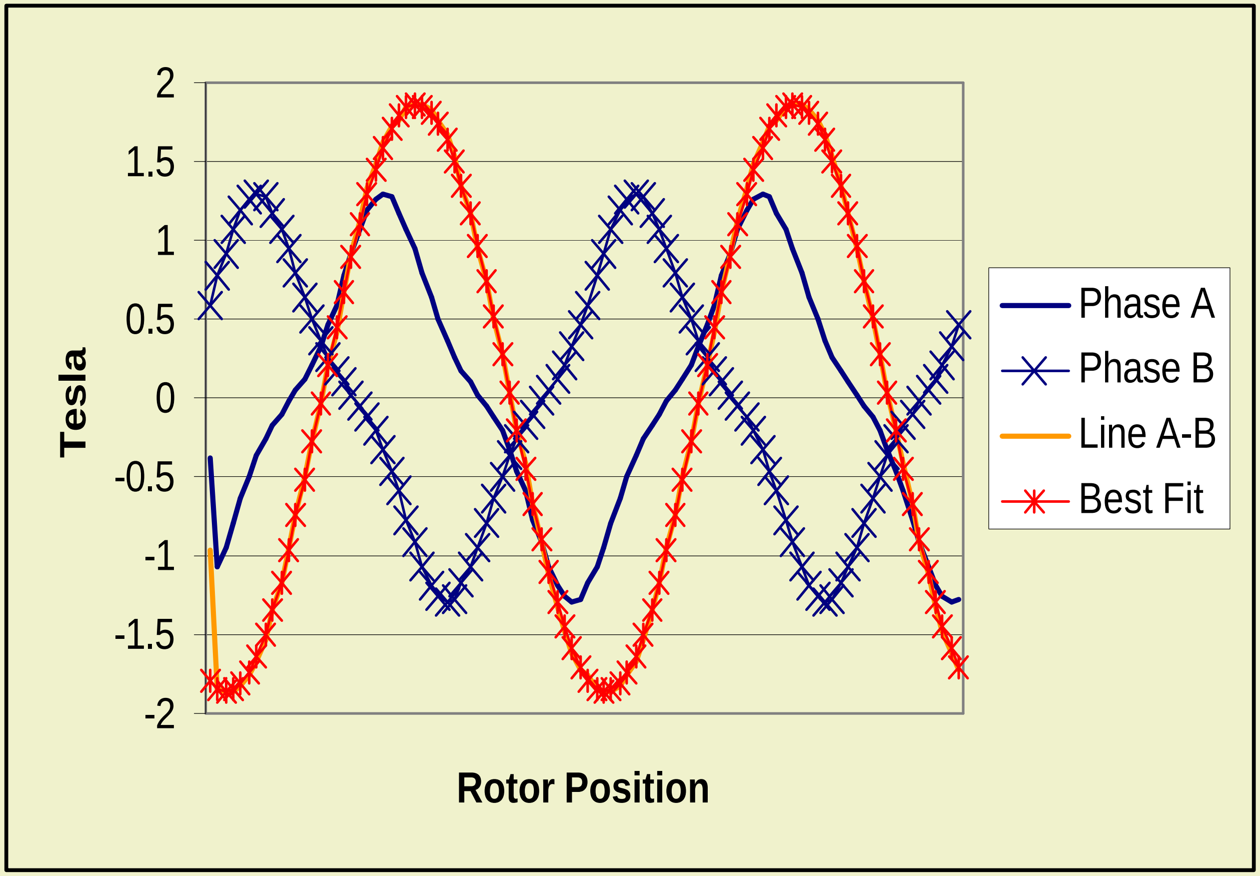
Stators Shifted by 66% Pole Pitch with Serial Addition of Waveforms

- Rated load
- THD=20%



Stators Shifted by 66% Pole Pitch with Serial Line-Line Waveform

- Rated load
- THD=6%

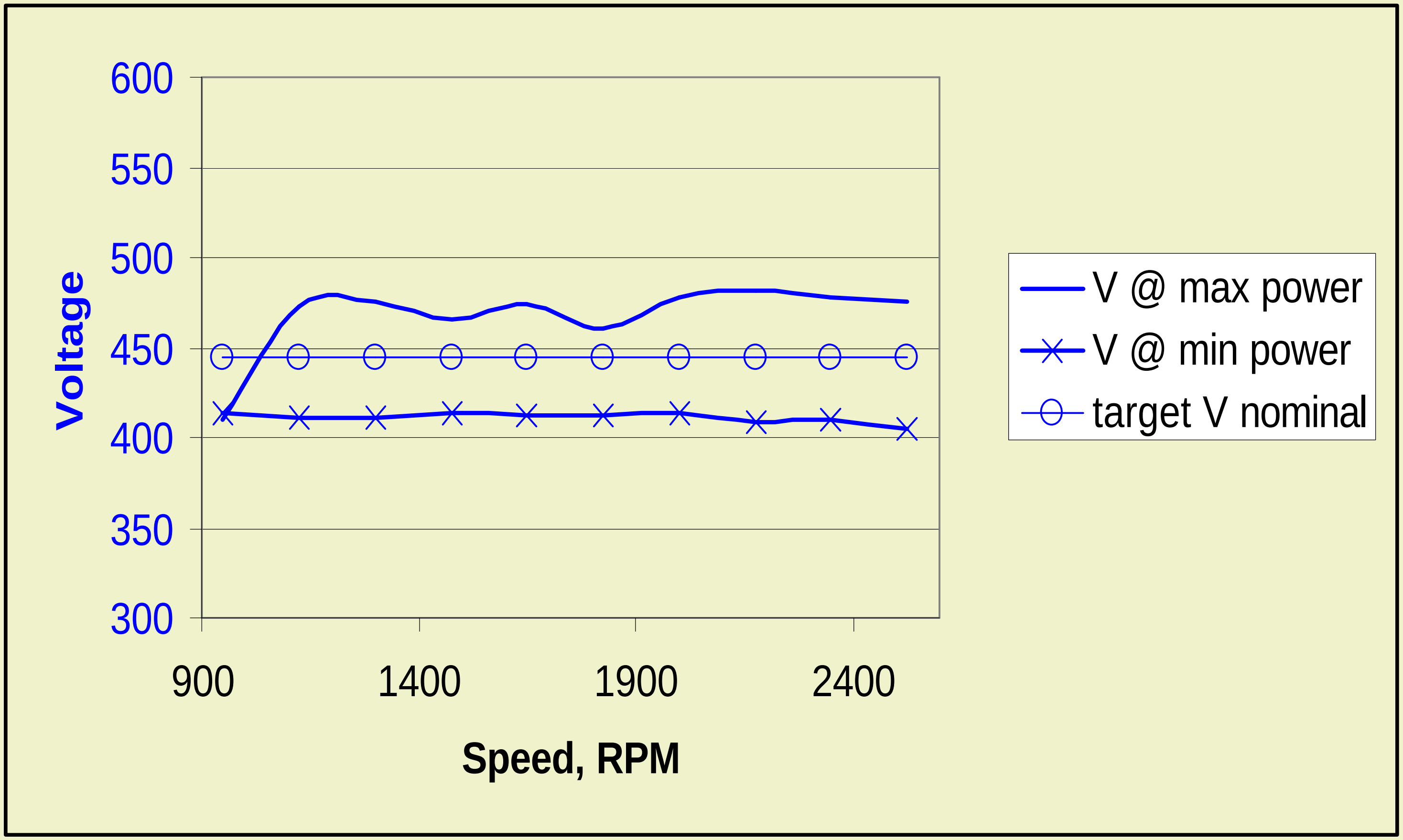


How is this all useful?

- Find a machine solution, passive rectification using basic phasor diagrams and algebra
- Solve at lowest speed, 0% shift
- Solve at increasing speed, while increasing the stator shift to keep terminal voltage near constant

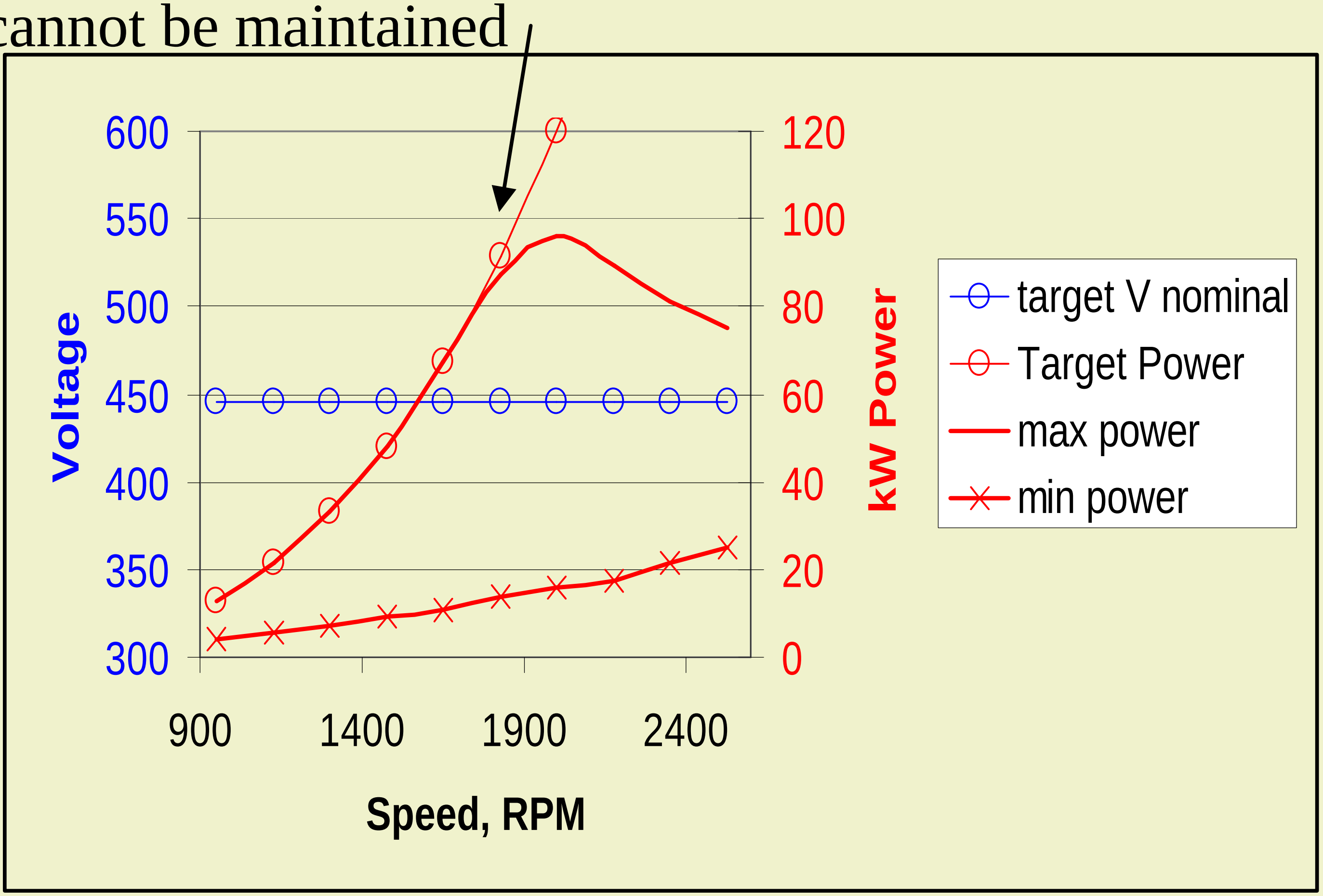
- Solution: 73% pole pitch shift needed = 22 mm movement circumferentially

Results Voltage vs. Target Voltage



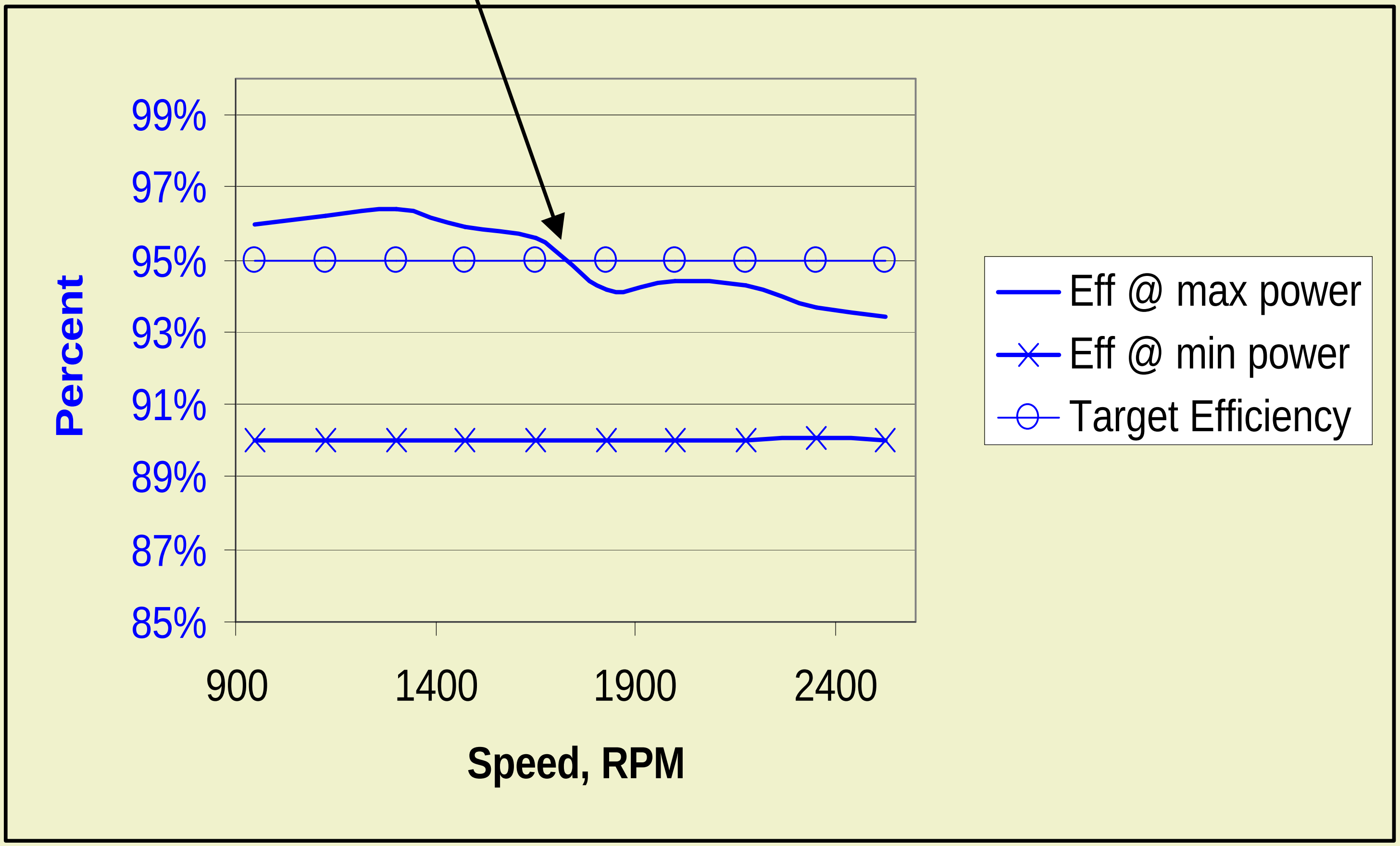
Results Power vs. Target Power

Voltage would be exceeded
So power cannot be maintained



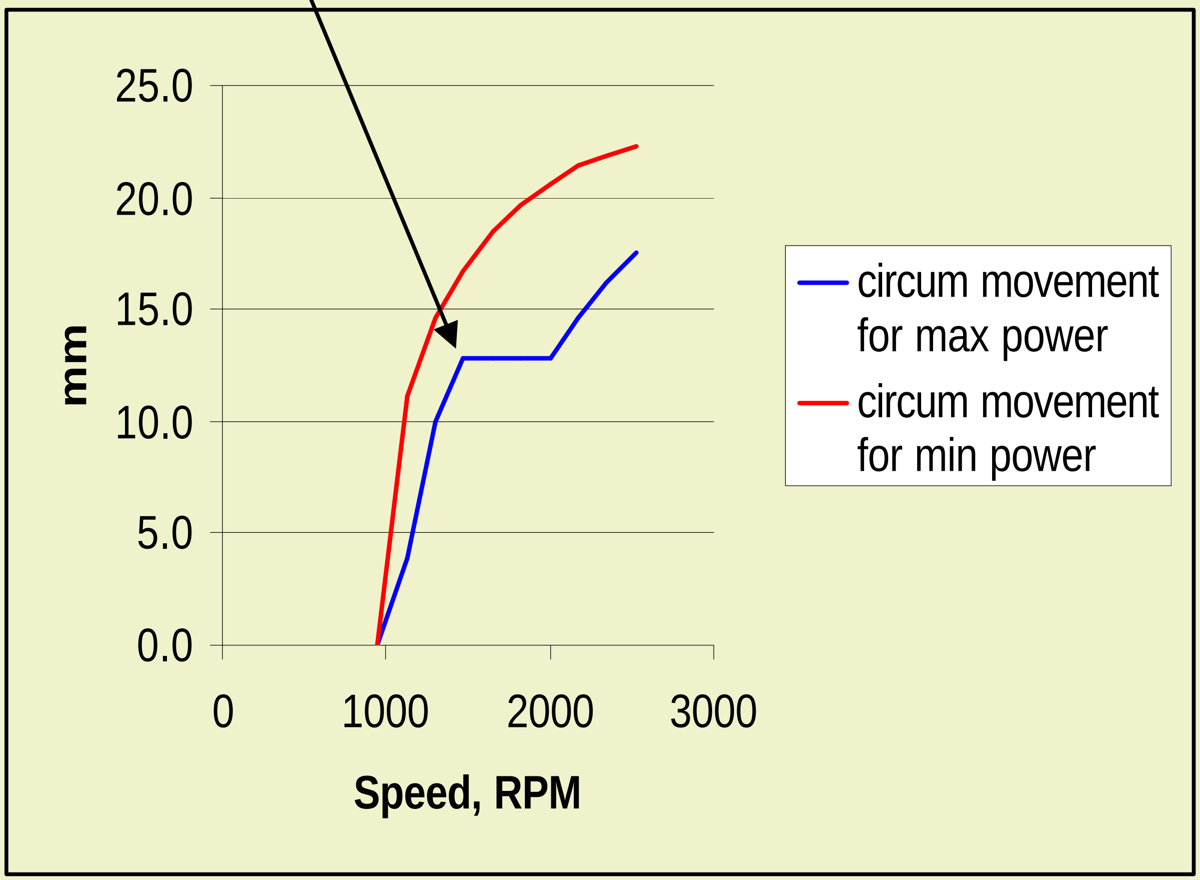
Results Efficiency vs. Target Efficiency

Voltage would be exceeded
So current must increase



Resulting needed Stator Movement

Voltage would be exceeded



Ref:
30 mm=pole pitch
20 mm=slot pitch

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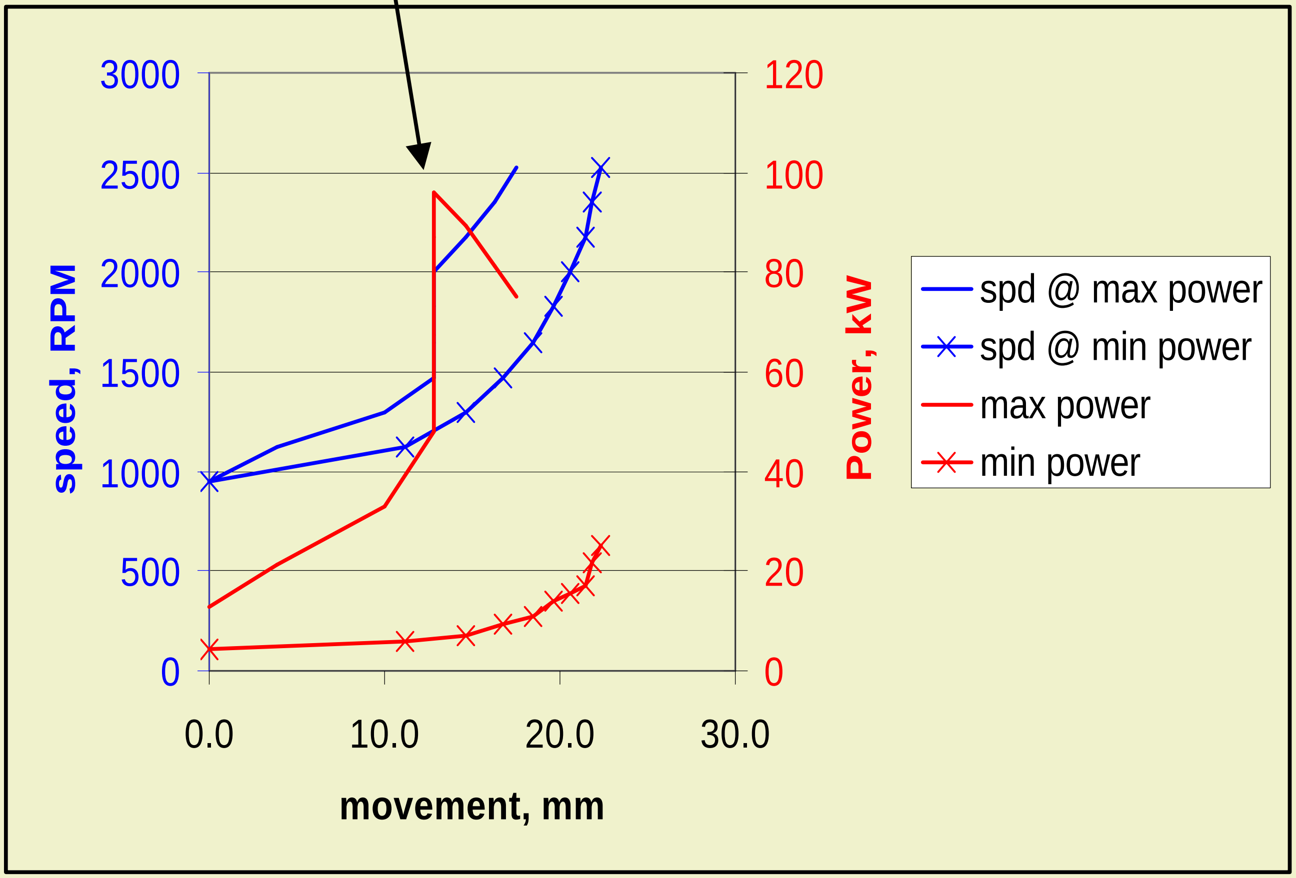
Speed and Power vs. Stator Position

Voltage would be exceeded



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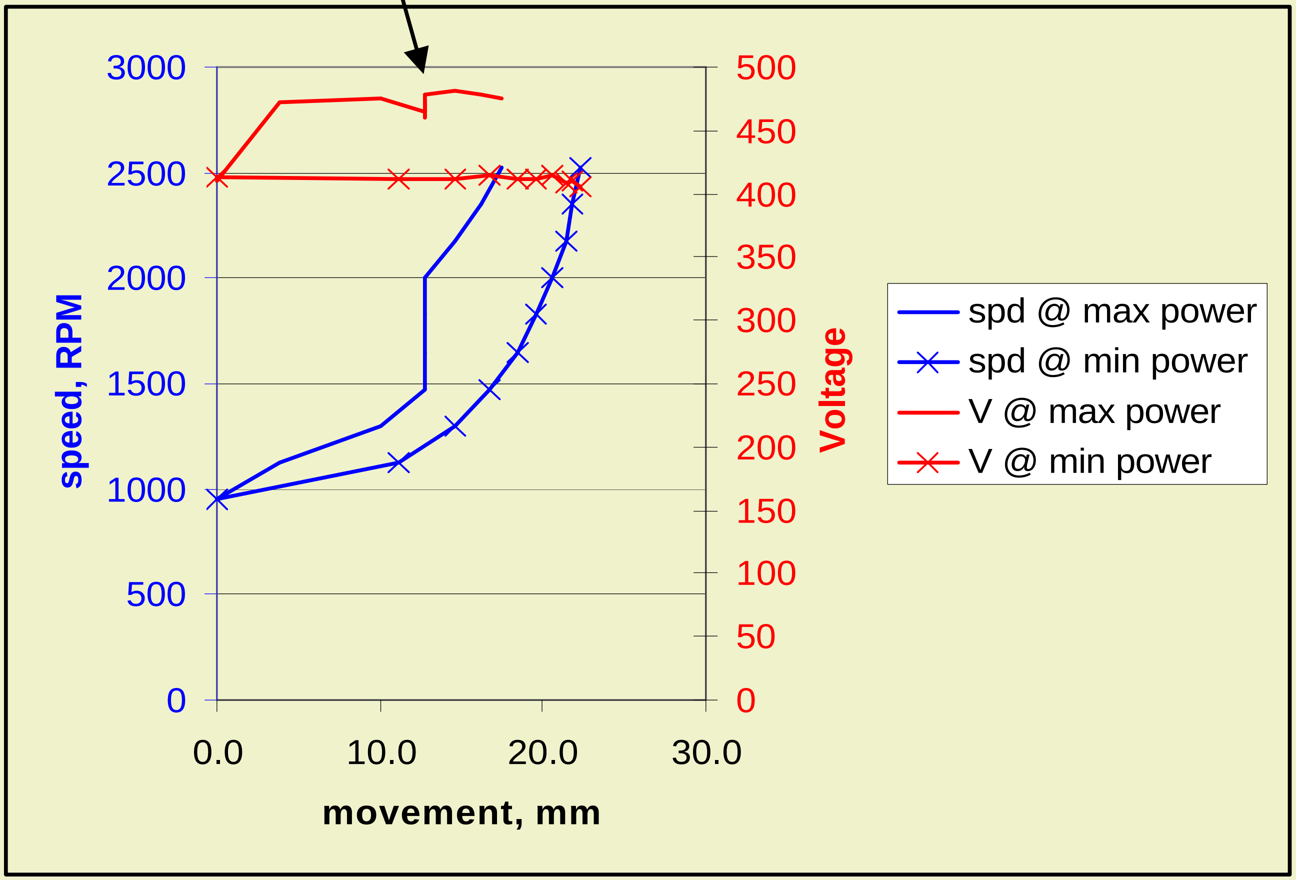
Speed and Voltage vs. Stator Position

Voltage would be exceeded



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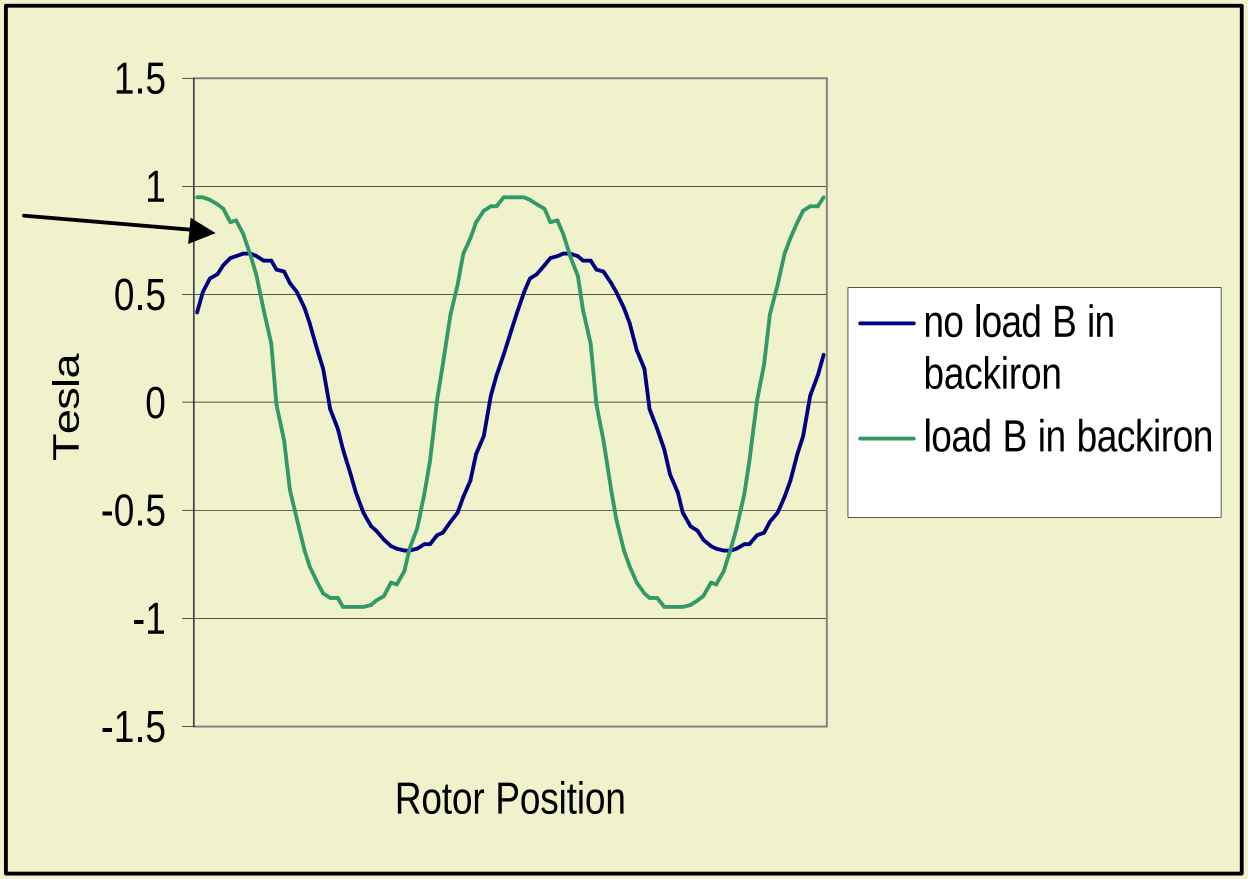
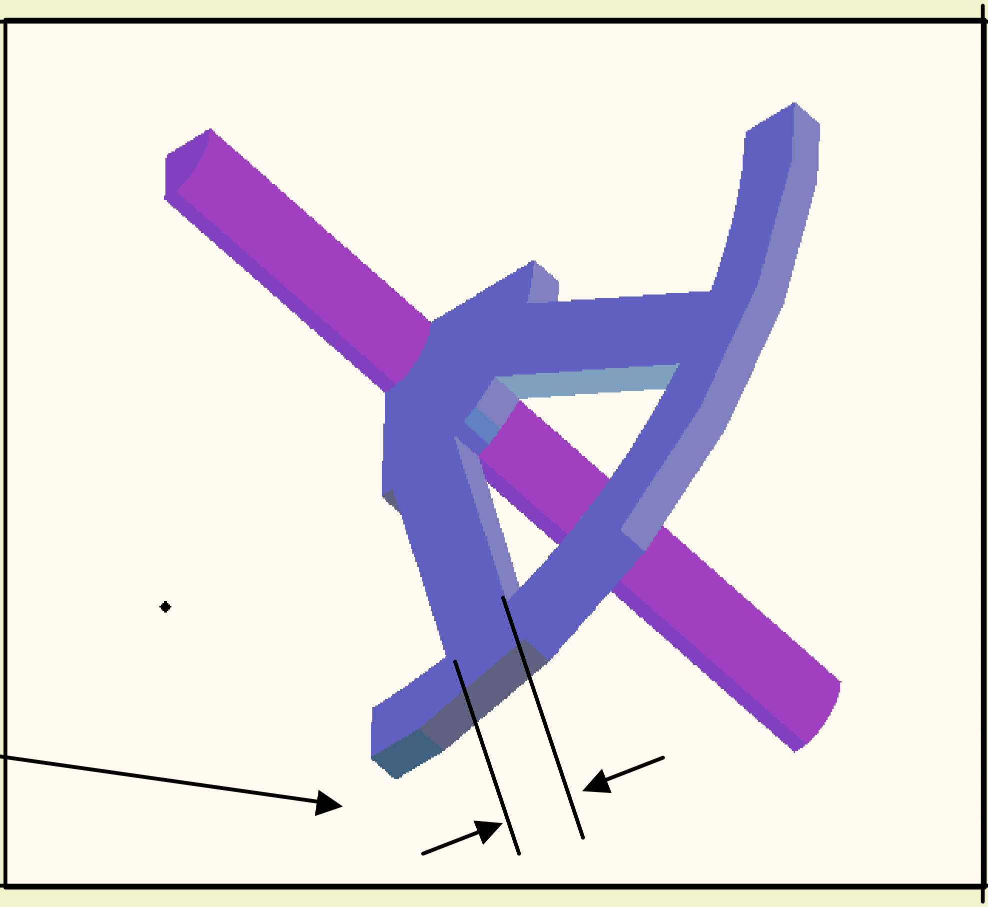
Other items of interest: Flux Density in Backiron

Discontinuity is not real, it's a function of solver accuracy



Cogging Controlled via 3D Optimized Magnet Spacing

Typical approach to design minimal cogging into machine is via 3D analysis and variation of magnet spacing.



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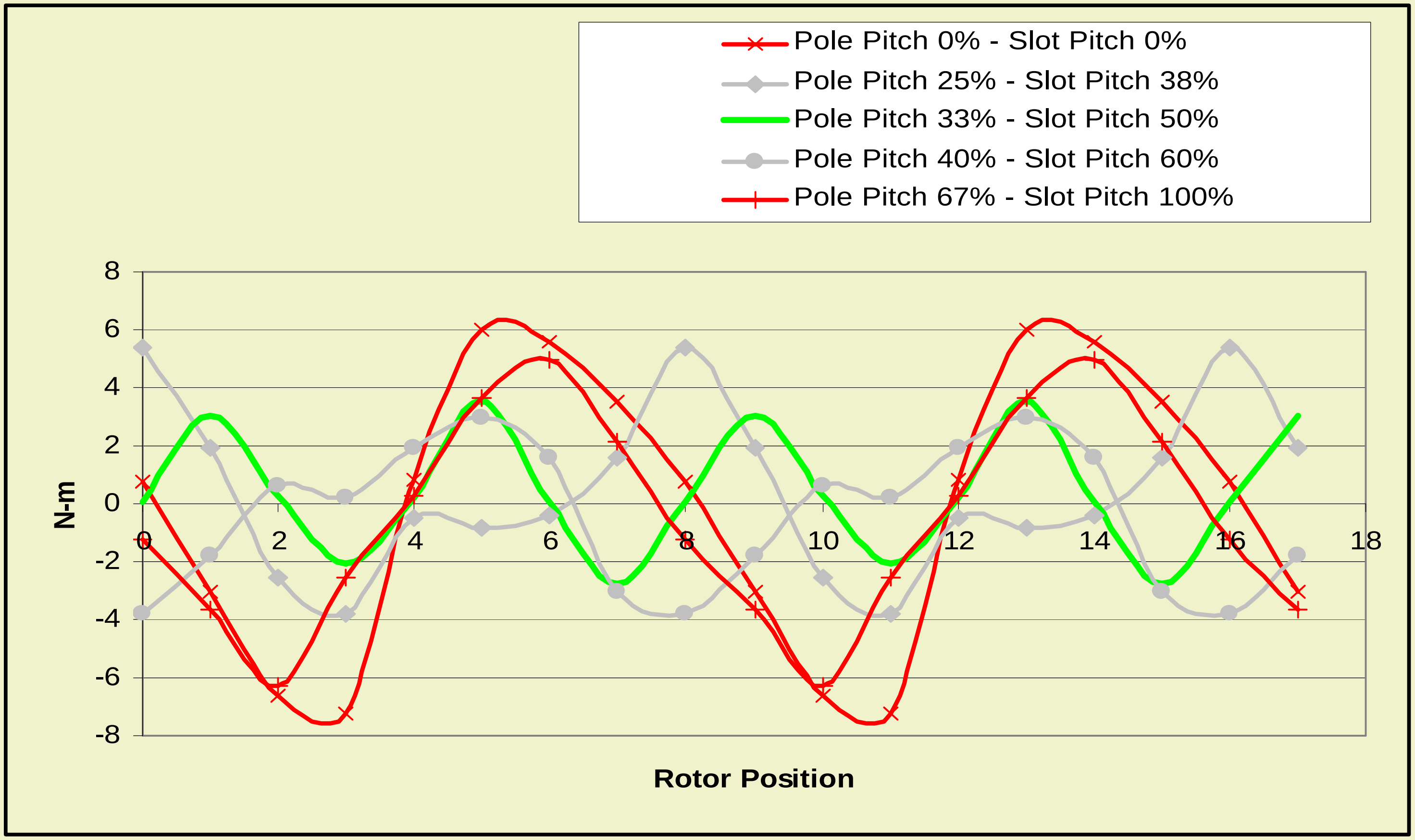
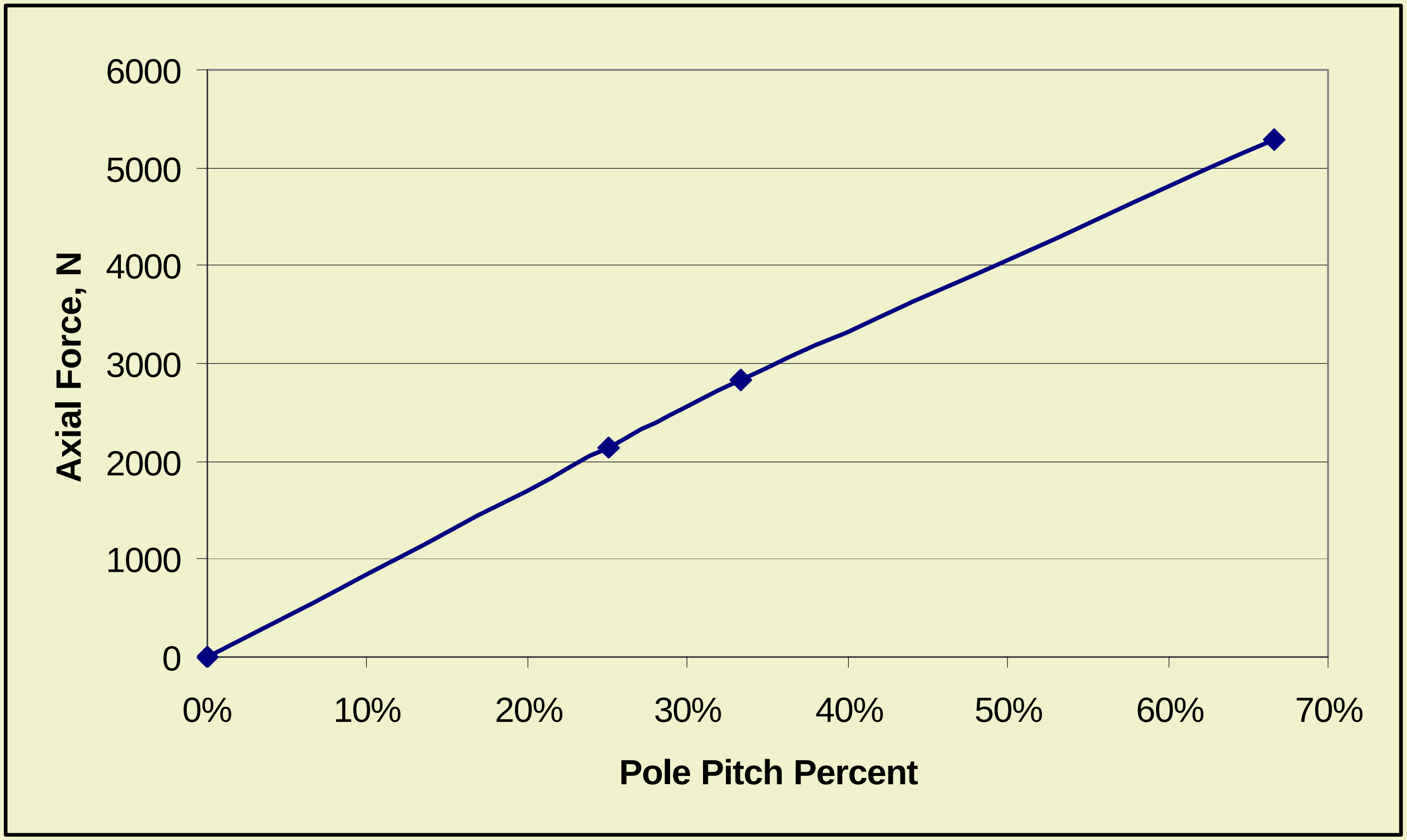
Stator Shifting and Effect on Cogging



Unfortunately, Axial Forces Increase with amount of Stator Shift



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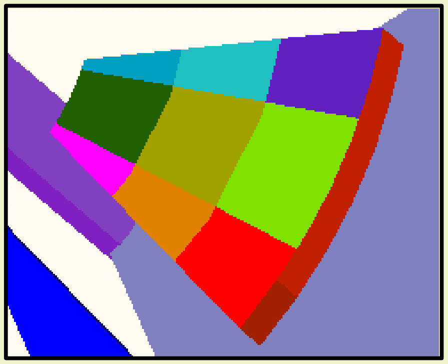
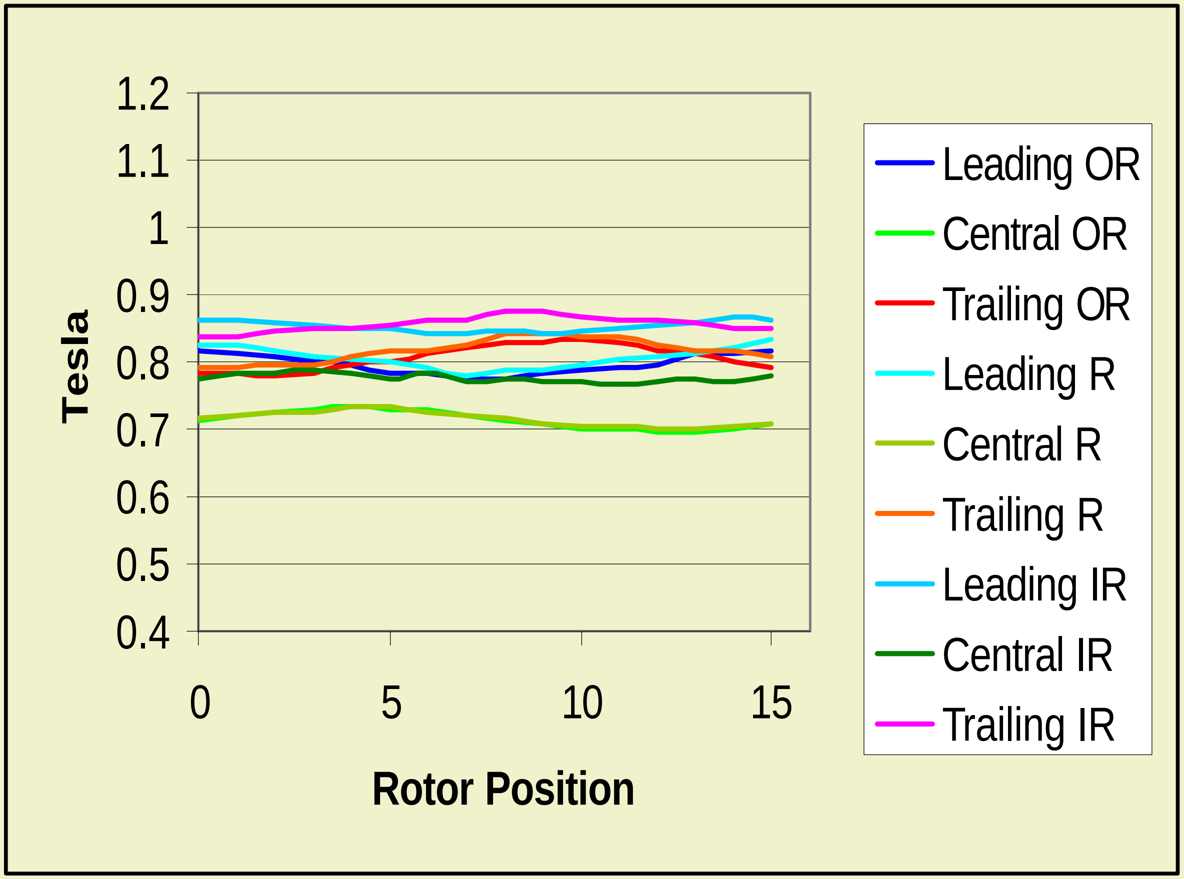
No Load;
Review Flux Density in Magnet Grid





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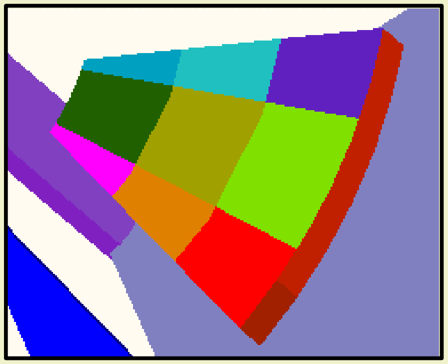
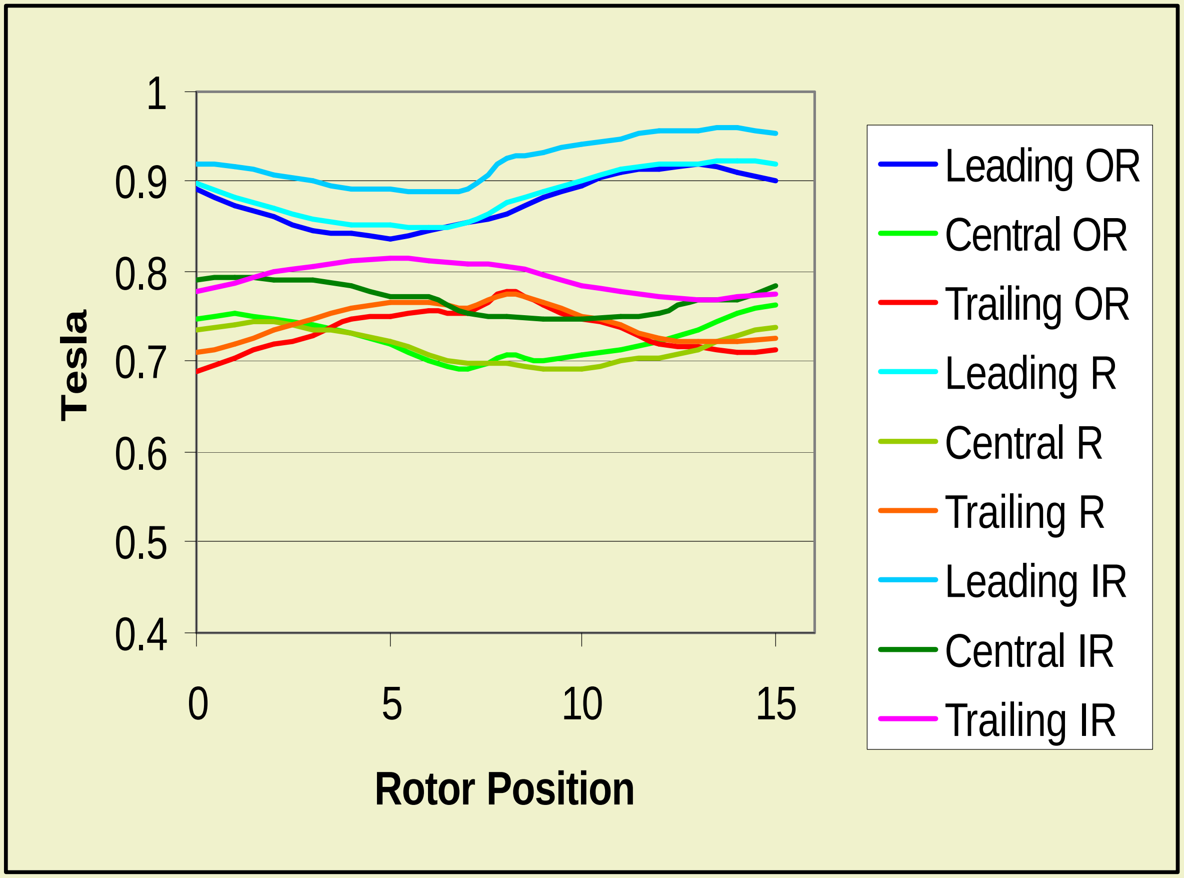
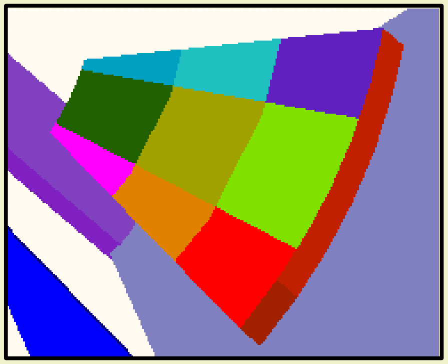
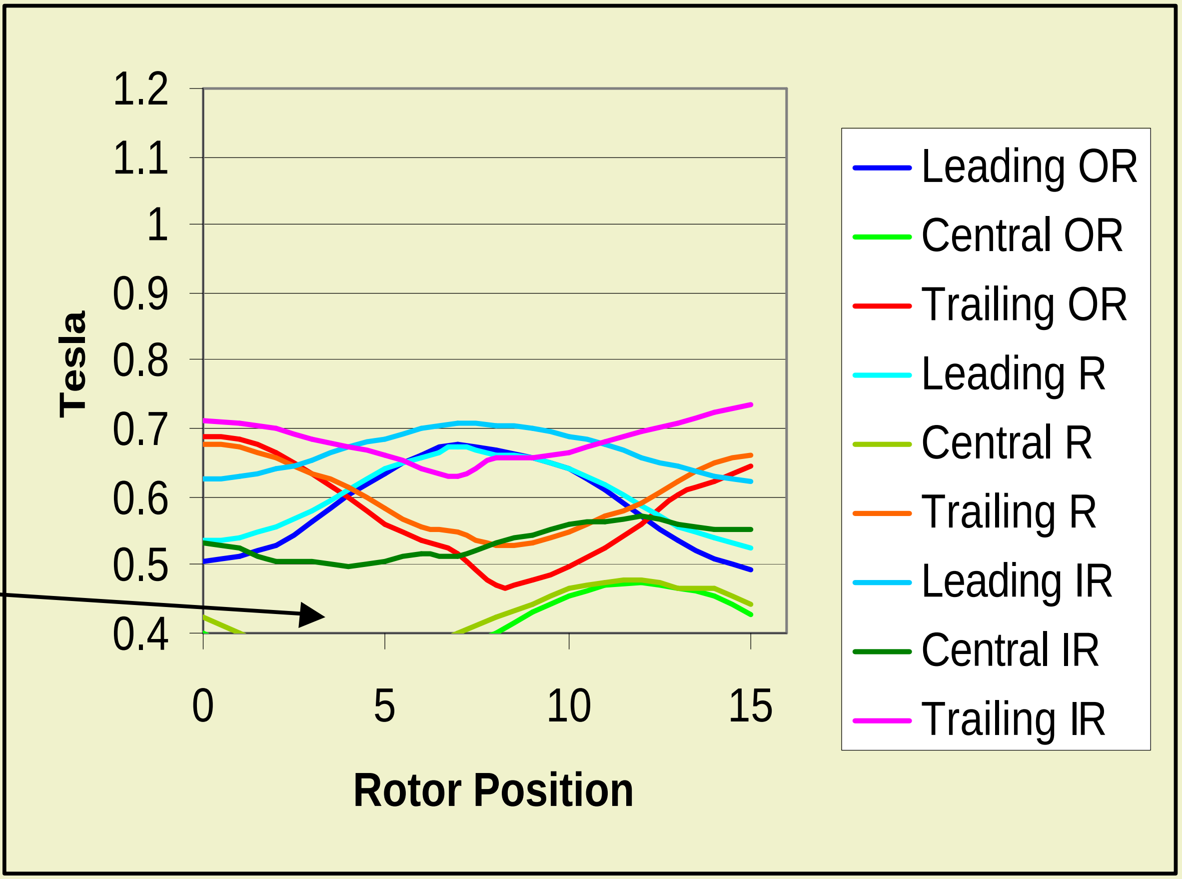
Rated Load;
Review Flux Density in Magnet Grid





3X Rated Load; All current in D-axis Review Flux Density in Magnet Grid

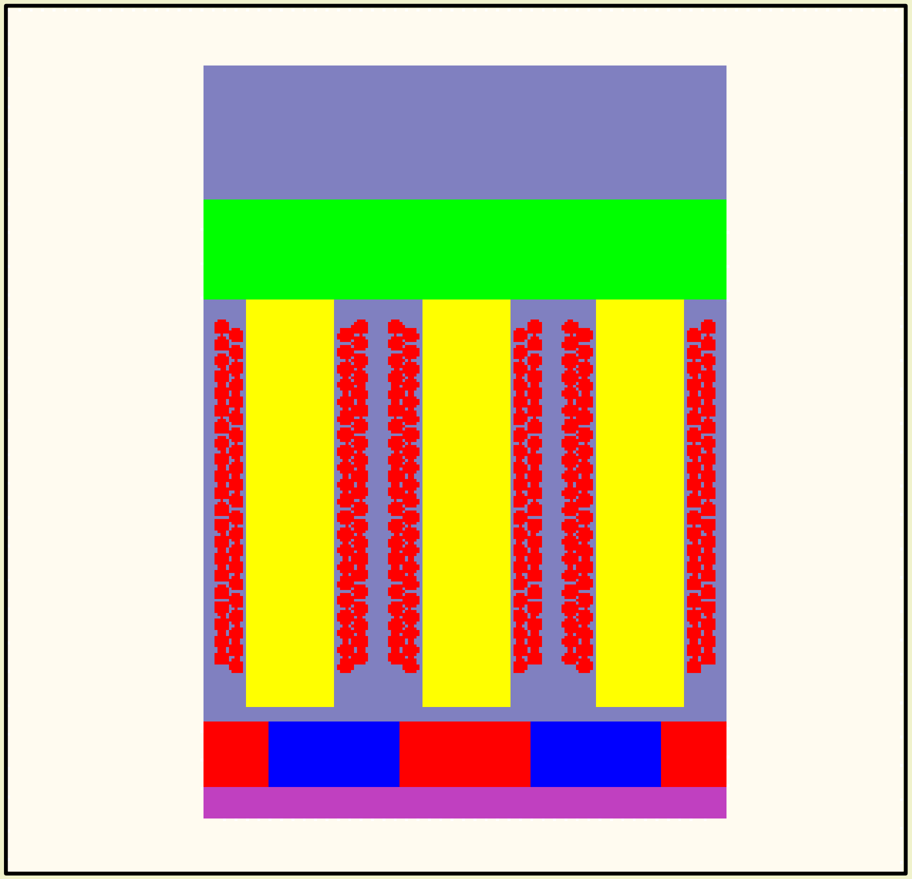




De-magnetization is a real concern!

A Plug for Maxwell 2D: AC Ohmic Loss

- 2D transient analysis
- Determines AC losses
- Due to proximity effects
- +/-20% error vs. test



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Maxwell 2D Transient Solver

Solution Results

- ↑ Power = 98kW at 2000 rpm
- ↑ Power follows rotor-speed^3 for 2X speed range
- ↑ Voltage stays within 410 – 480 Vrms range
- ↑ Efficiency > 94%

- ↓ Harmonic content increases (changes) with Stator Shift
- ↓ Axial force increases with Stator Shift