Analysis and Design of Non-Rare-Earth Traction Motor and Drive

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Prof. Patrick Luk, Dr Weizhong Fei, Cranfield University

Prof. Pickert Volker, Dr. Chris Morton, Newcastle University

Prof. Keith Pullen, Dr. Niall McGlashan, City University London

Objectives

- *"The primary aim of this project is to showcase a high performance and low cost traction drive and has a **sustainable supply chain** that is critical for the uptake of the EV market"*. Specific objectives are:

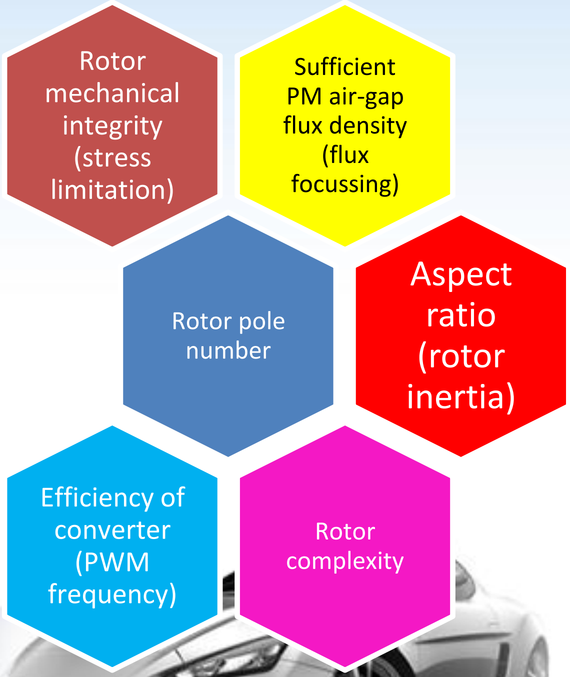
1. Develop a high performance ferrite motor with full functional integration with its converter.
2. Develop a power converter for the ferrite motor.
3. Mechanical and thermal integration of the motor and the controller with the following targets.

- $12/kW; 1.2 kW/kg; 3.5 kW/L,
- efficiency 93% (10%-100% speed at 20% rated torque)
- All data is based on 70°C inlet temperature at 8 l/min water/glycol 50/50 mix

Design Rationale

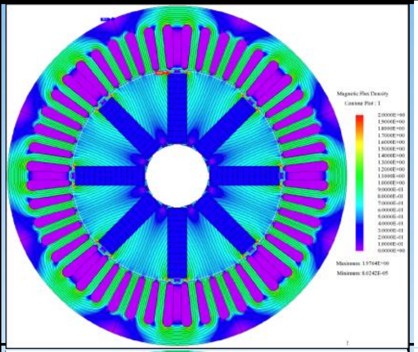
- Flux focusing to maximize PM torque --> high rotor pole number (>6)
- Saliency to boost reluctance torque--> multilayer interior magnets
- High power density --> high rotational speed
- Limited switching frequency --> low rotor pole number, low rotational speed
- Rotor integrity limitation -->low rotational speed, simple rotor structure

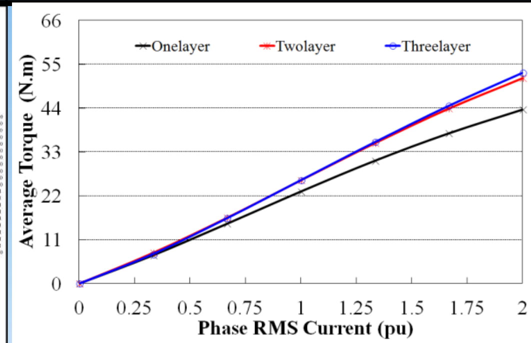
Estimated real power	20kW
Rotational speed	10,000rpm (rated); 20,000rpm (maximum)
Efficiency	>93%
Nominal Bar Bus Voltage	300V
Ambient temperature	60 degrees
Pole Pairs	4
Cooling	Water cooled



Magnet Layer Number(Initial)

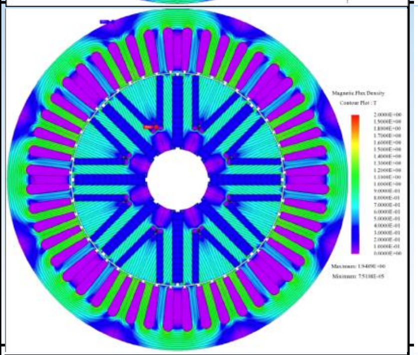
One layer

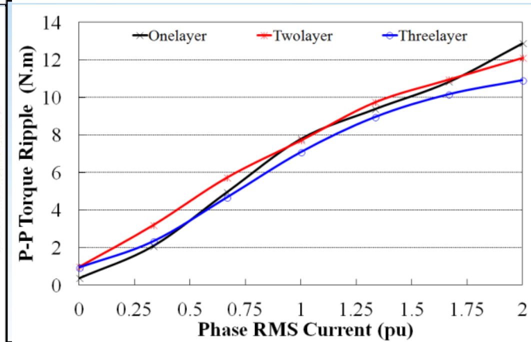




Two and three layers can deliver much higher torque than one layer, two and three layers deliver almost the same torque

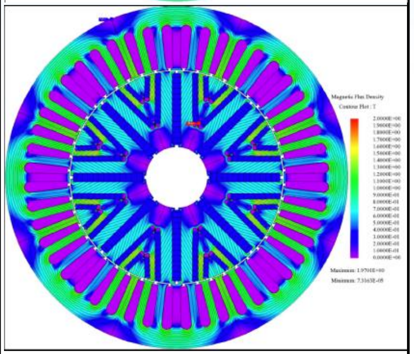
Two Layer

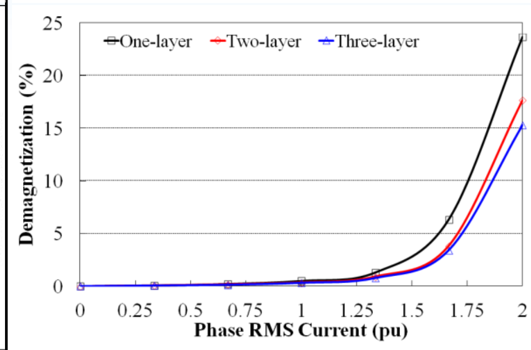




Three machines delver almost same torque ripple

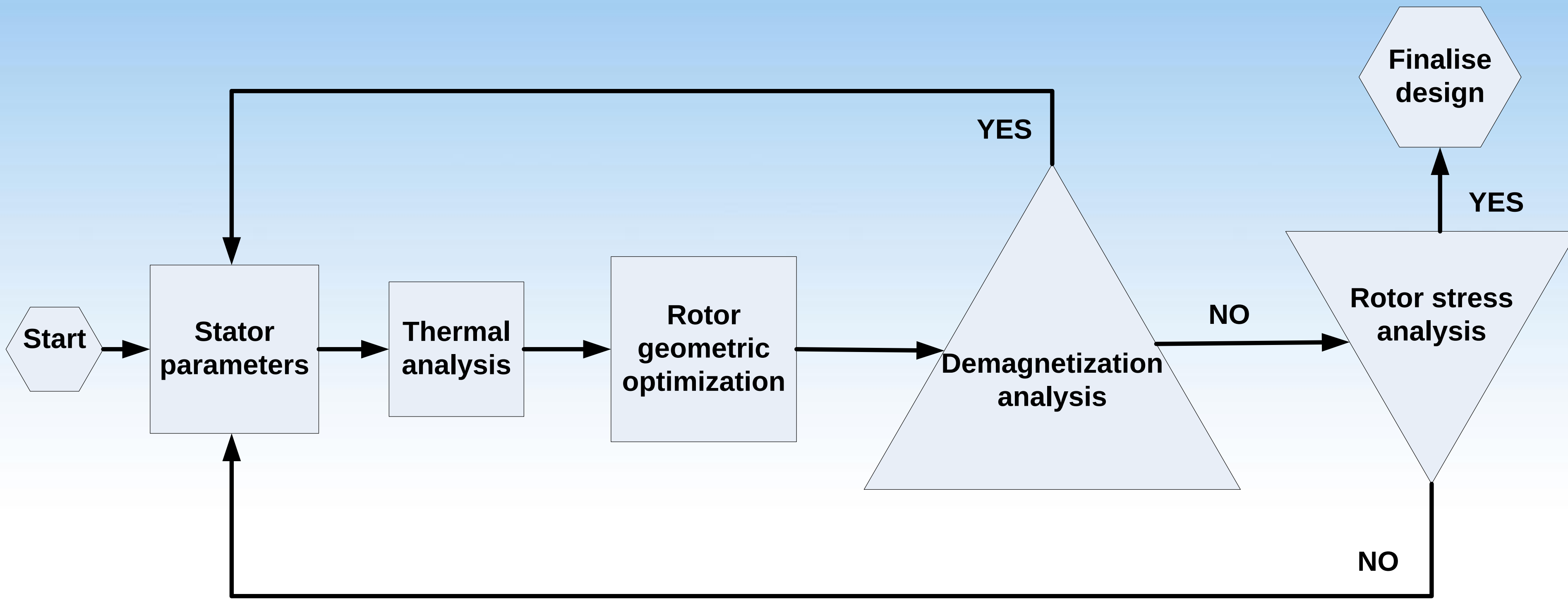
Three Layer



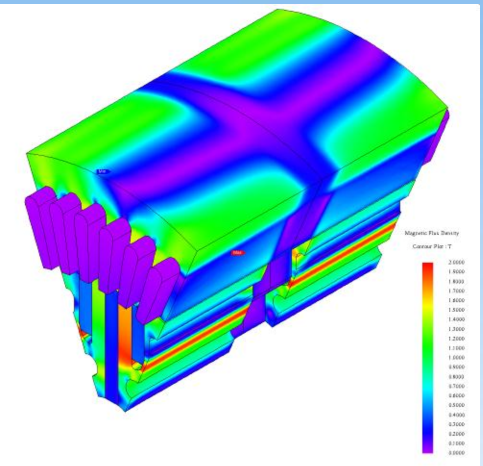


The demagnetization decreases as the magnet layer increases, two layer is chosen for compromise between rotor complexity and performance

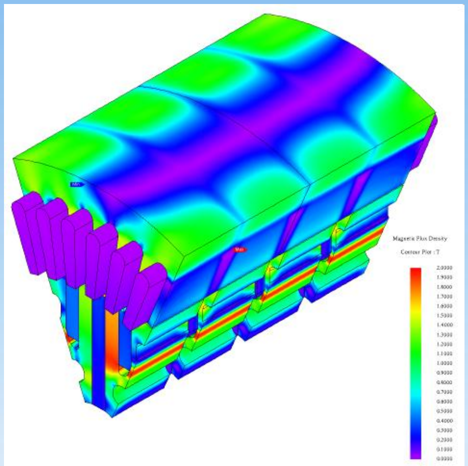
Integrated optimisation and design



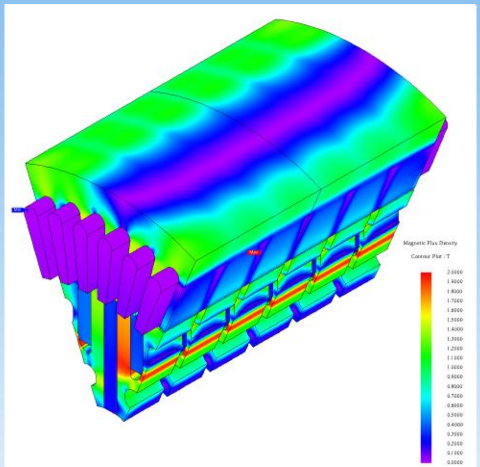
Rotor Axial Slot Optimization



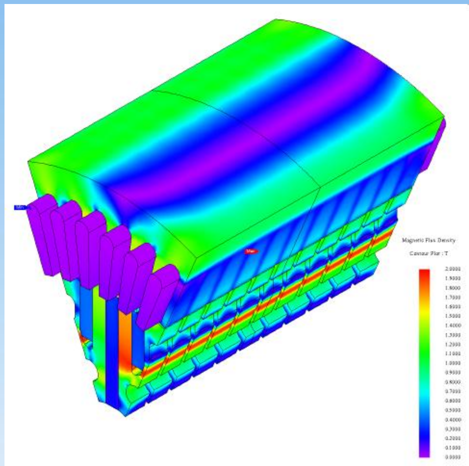
One slot



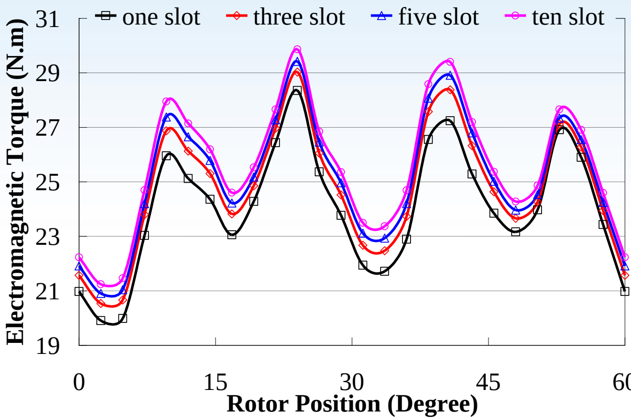
Three slots

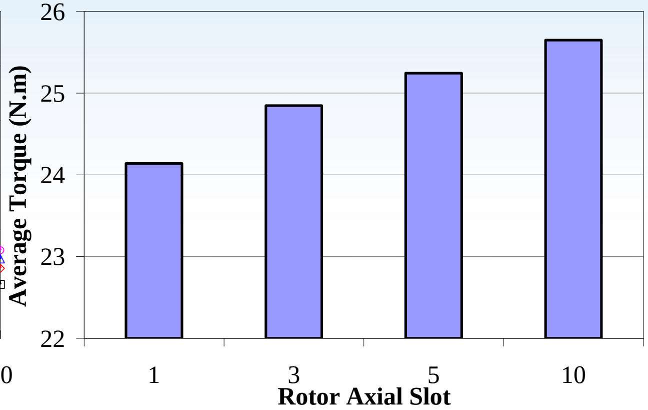


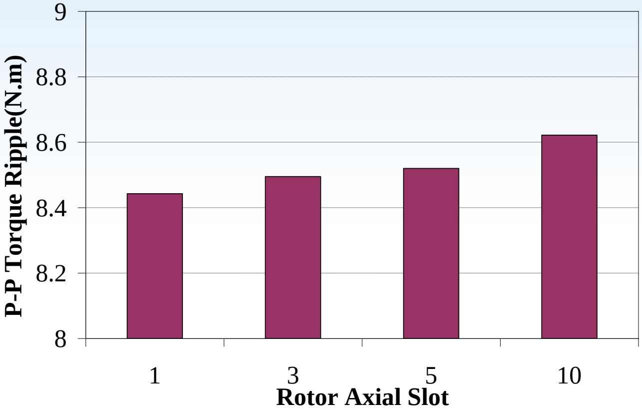
Five slots



Ten slots

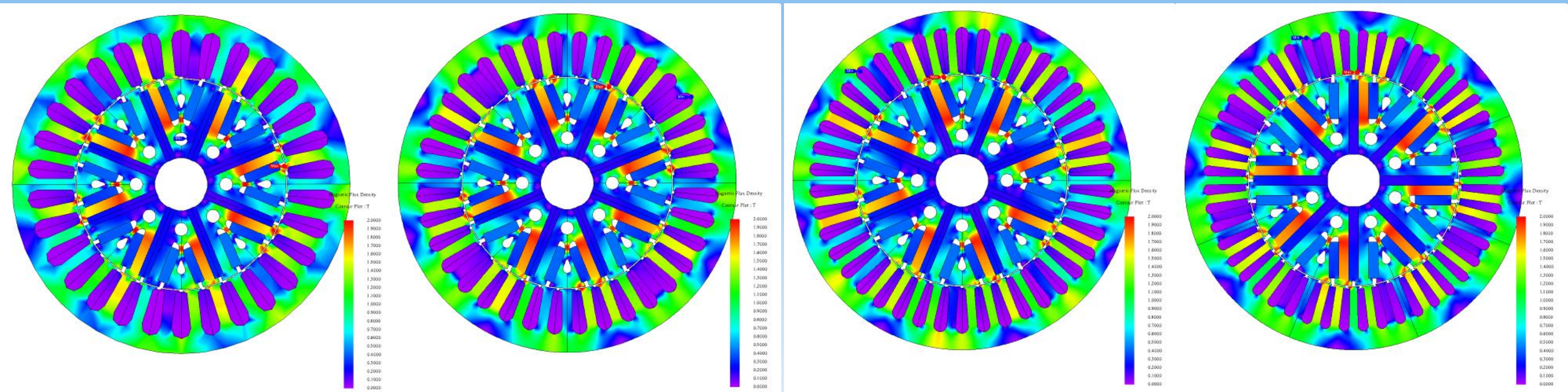




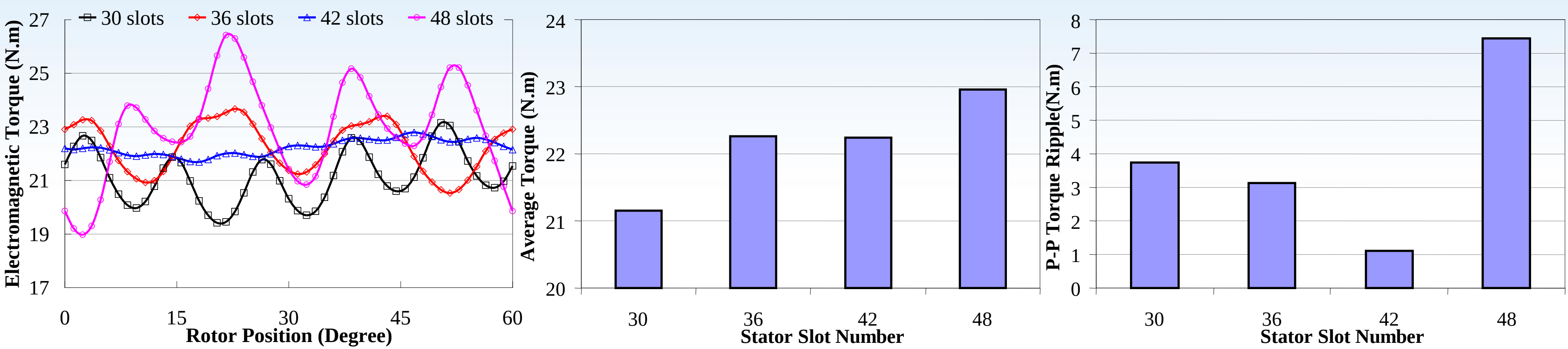


Ten-slot configuration is chosen for the final design

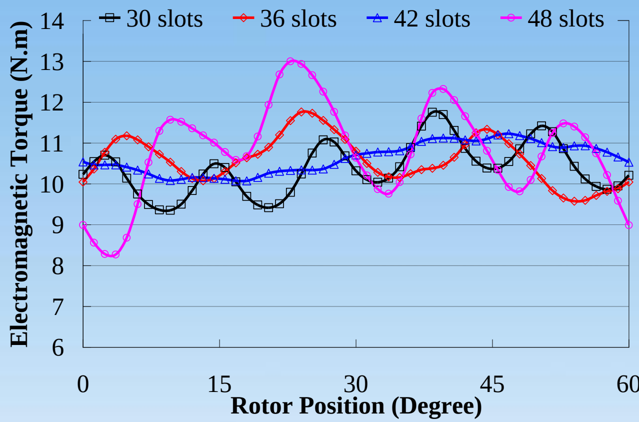
Stator Slot Comparison



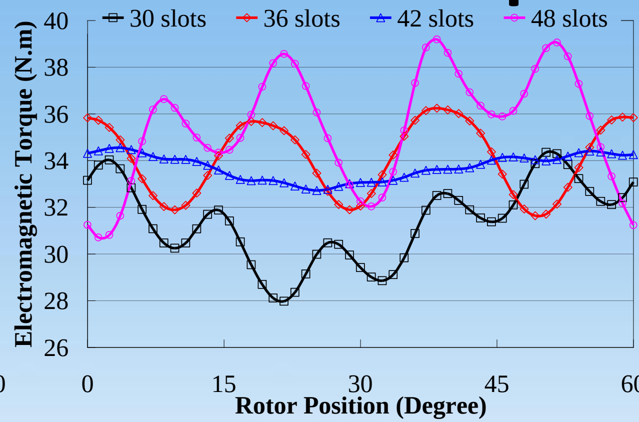
30 slots | 36 slots | 42 slots | 48 slots



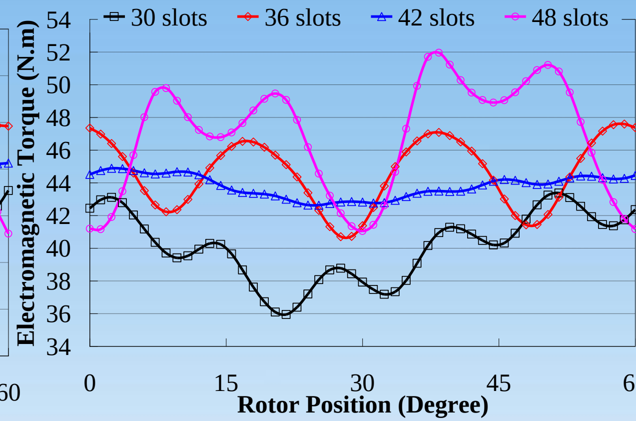
Stator Slot Comparison



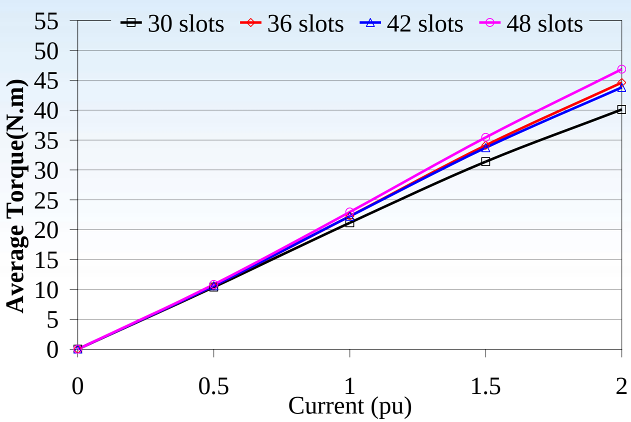
Half rated current

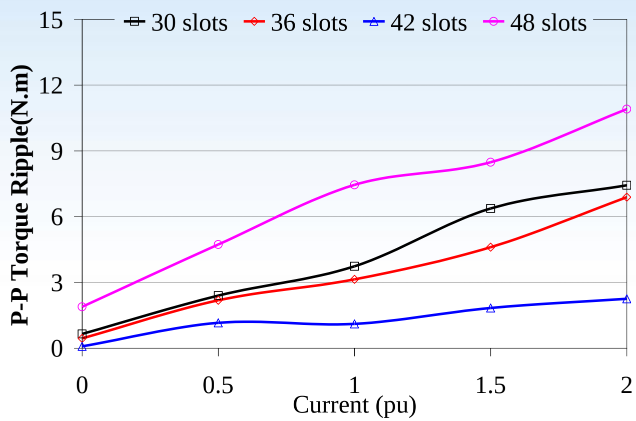


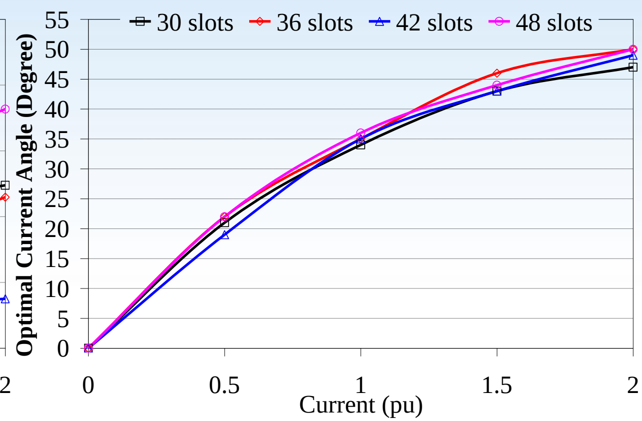
One and half rated current



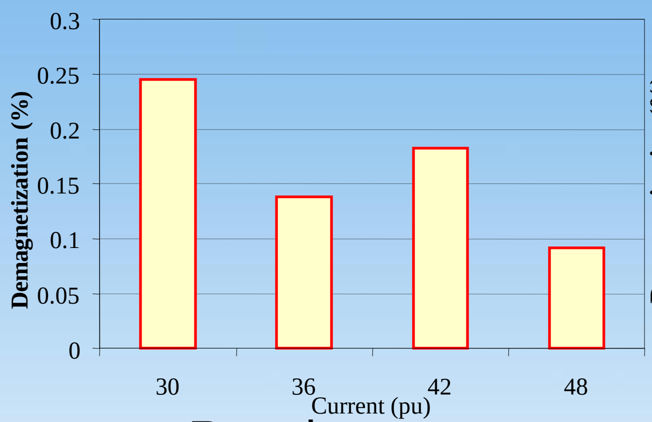
Twice rated current



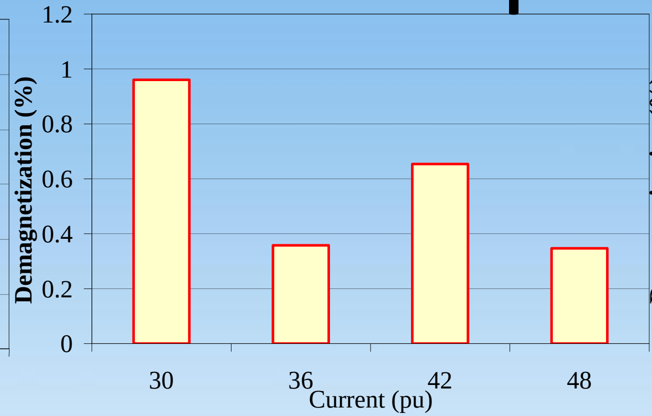




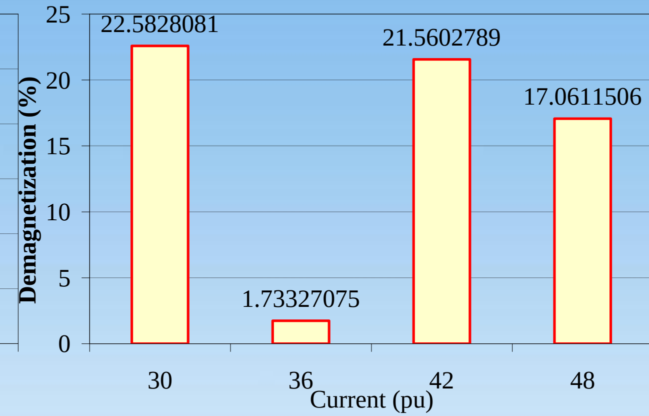
Stator Slot Comparison



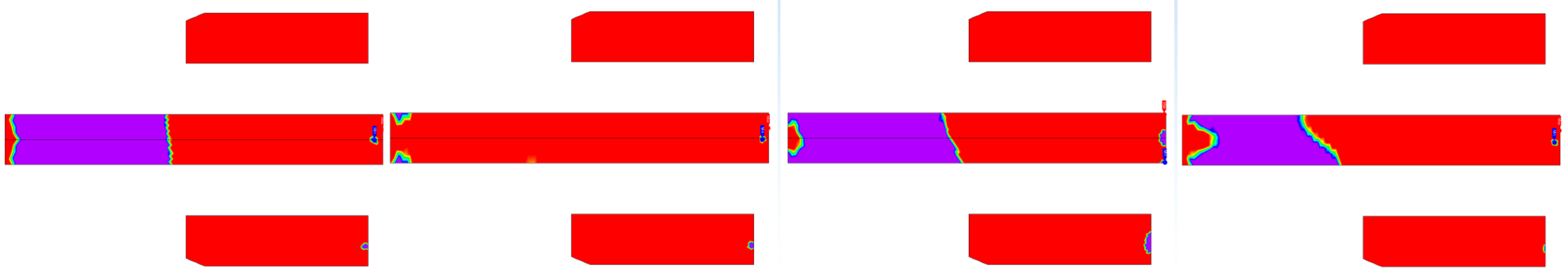
Rated current



One and half rated current



Twice rated current



30 slots   36 slots   42 slots   48 slots

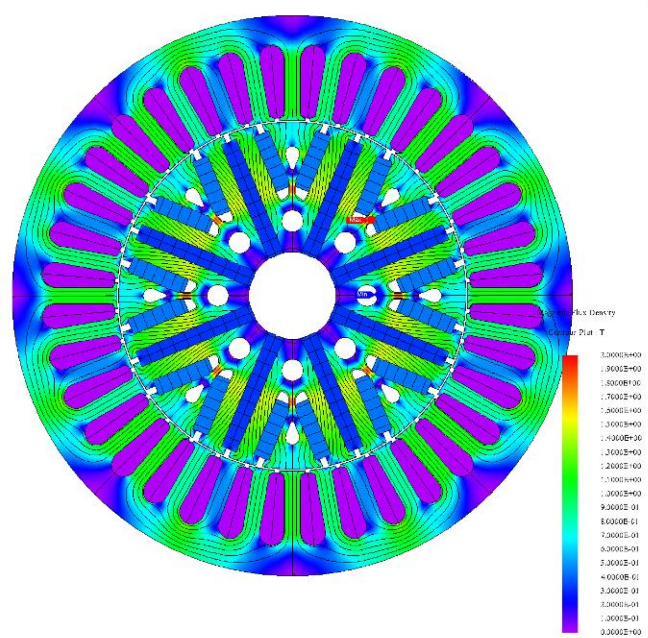
By considering the average torque output, torque ripple, and overload capability, 36 stator slots are chosen for the prototype machine.

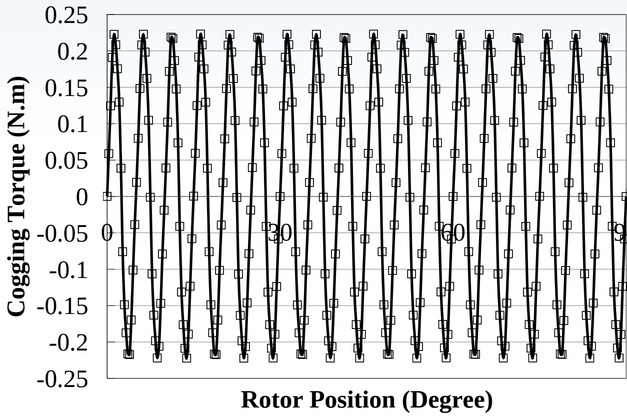
Final Design Parameters

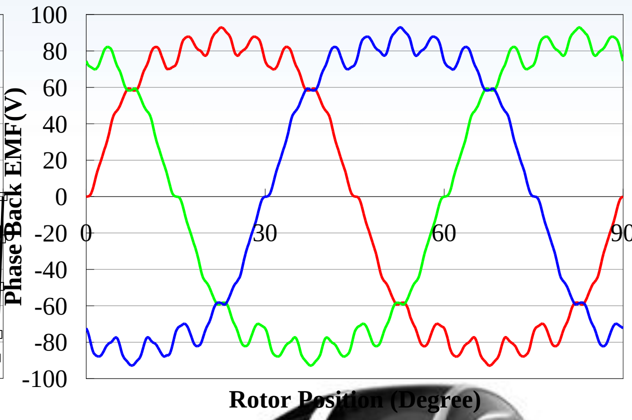
Stator Slot	Rotor pole	Turn per Coil	Coil per Phase	R (phase)	Ld	Lq
36	8	2	12 (In series)	8.7mΩ	0.21mH	0.55mH

Stator outer diameter	Stator inner diameter	Air gap	Stator stack length
144mm	96.4mm	0.5mm	86.5mm

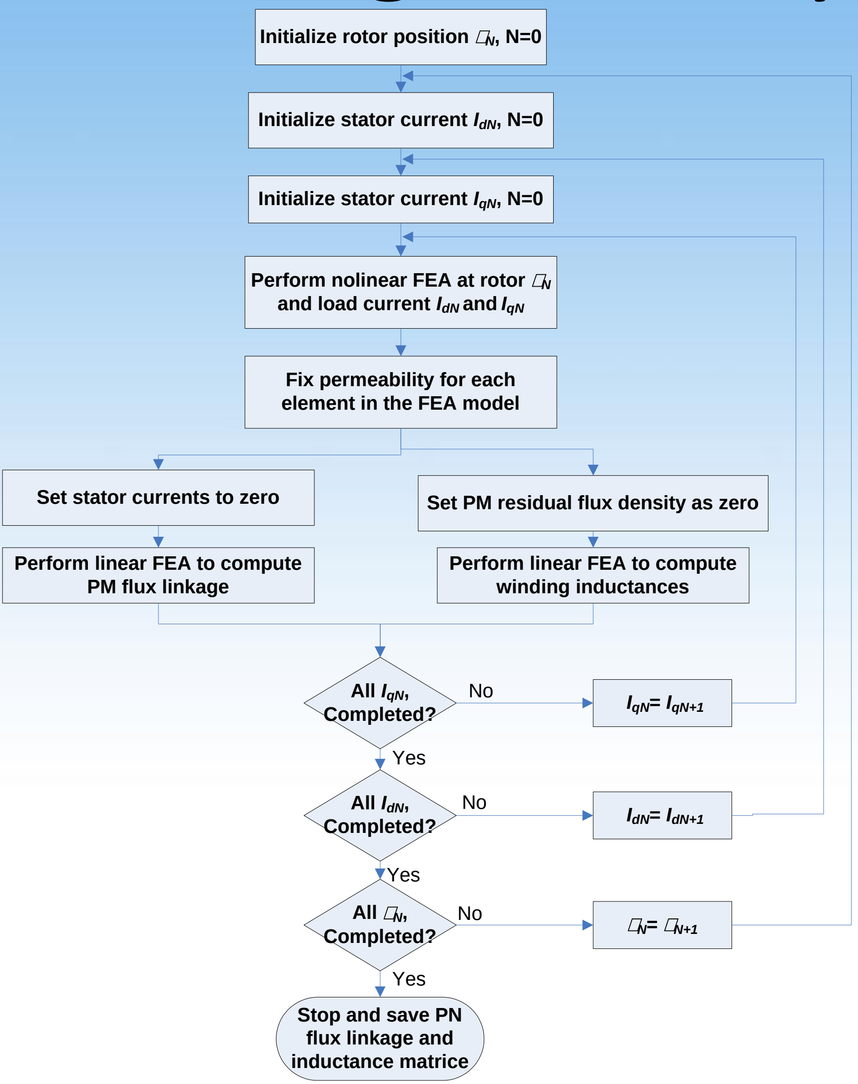
Rotor stacks	Rotor axial slots	Magnet volume
6.5mm*11	1.5mm*10	206.4cm^3







High Fidelity Machine Model



High Fidelity Machine Model based on the extracted PM flux linkage, inductance matrice, end winding leakage, and reluctance

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Circuit simulator with high fidelity power switch model and control toolbox

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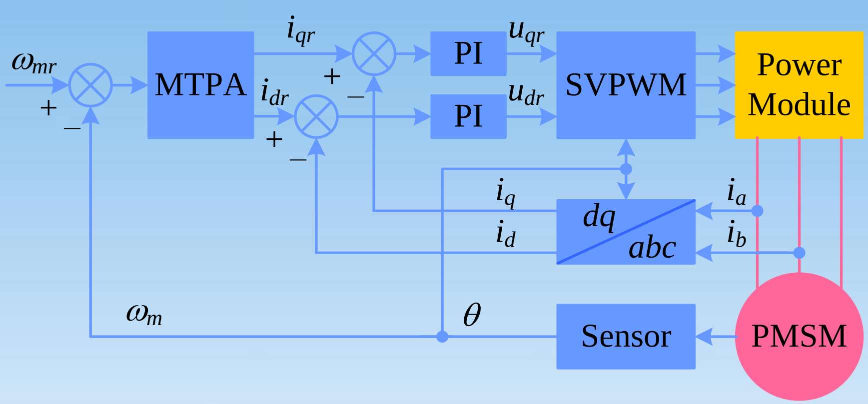
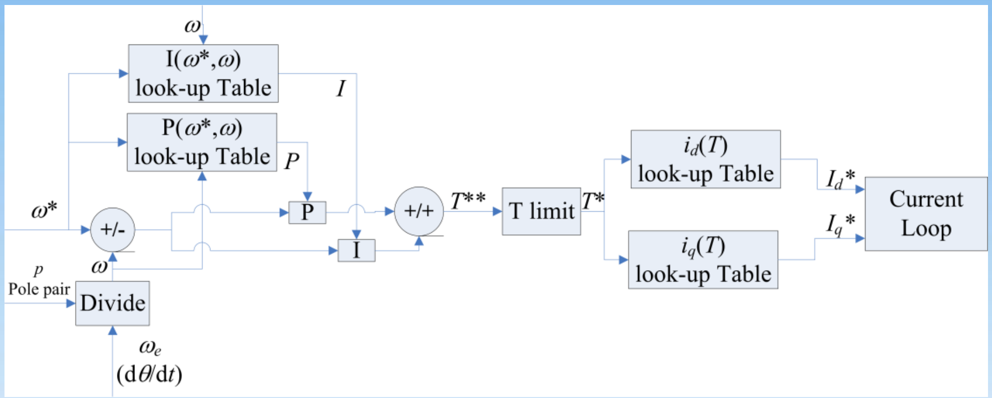
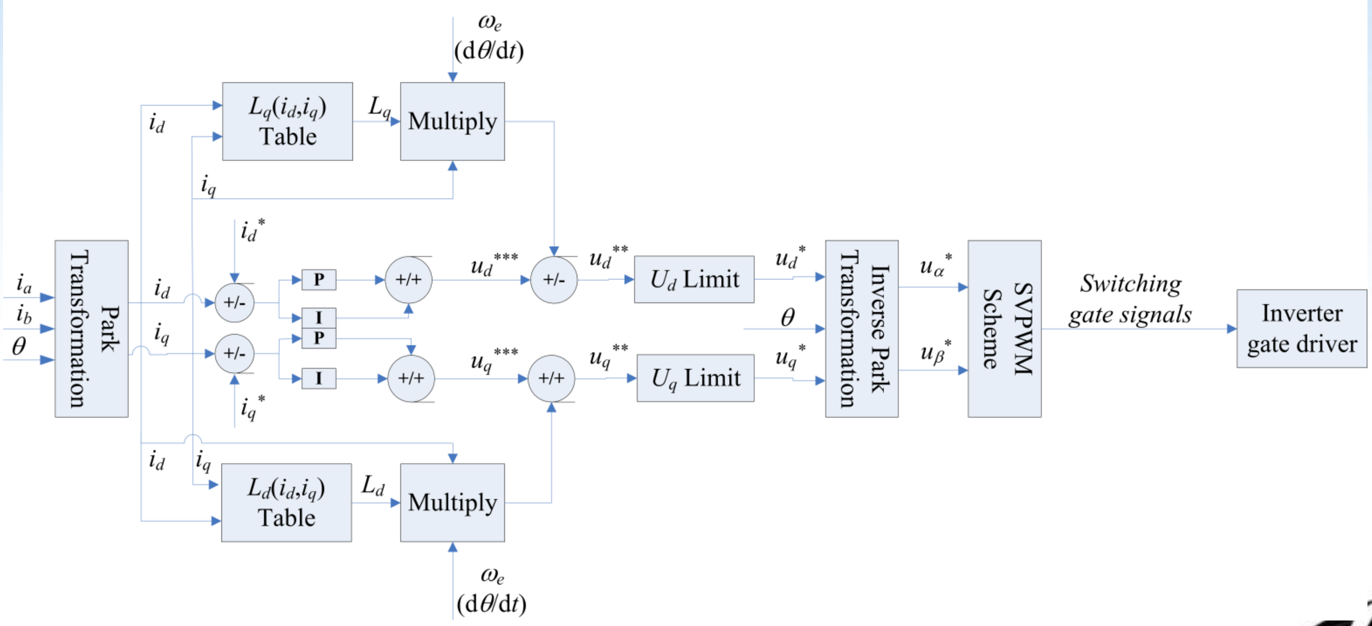
- Machine design validation
- System level simulation
- performance prediction
- Controller design
- Demagnetization assessment and prevention

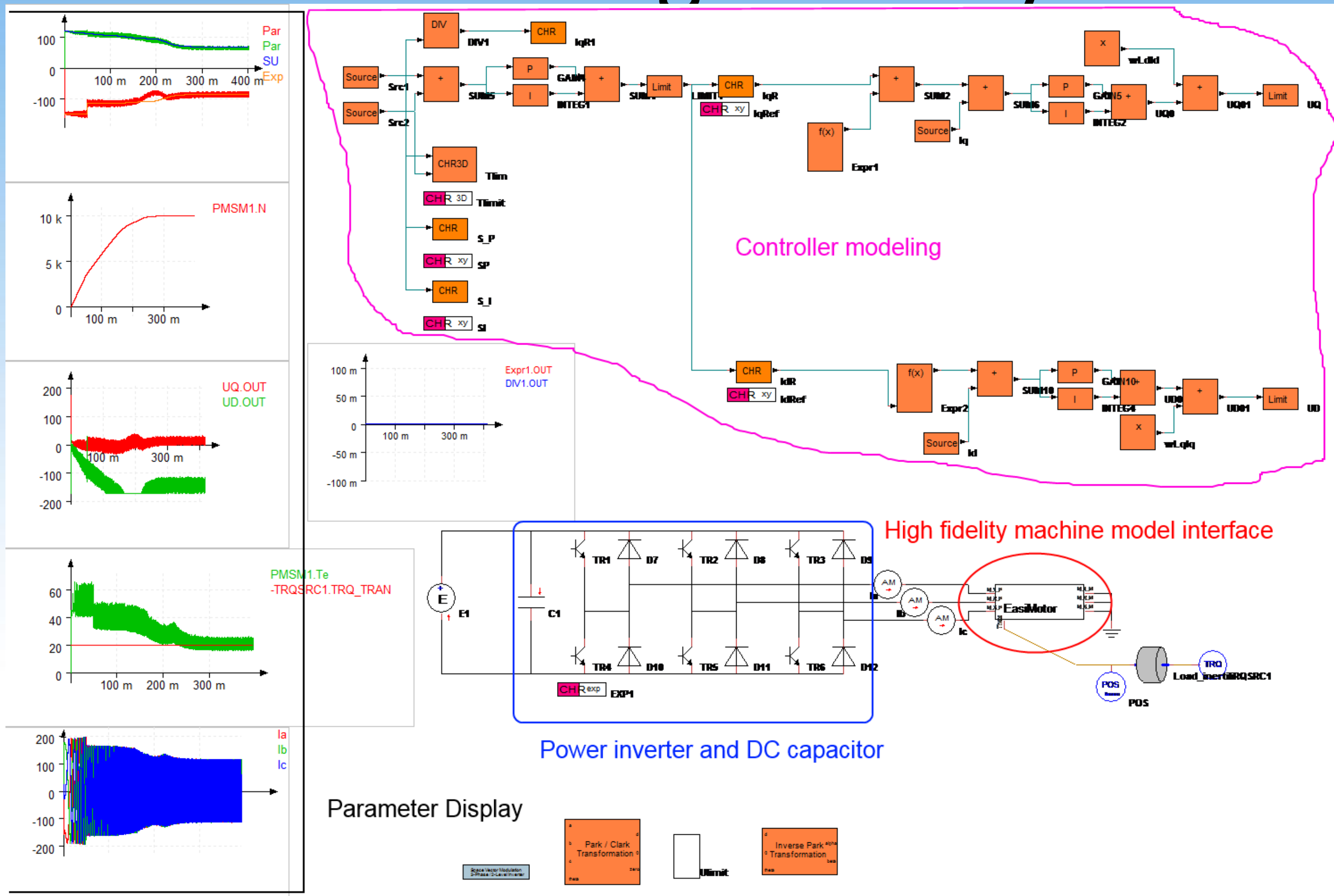
Control Structure





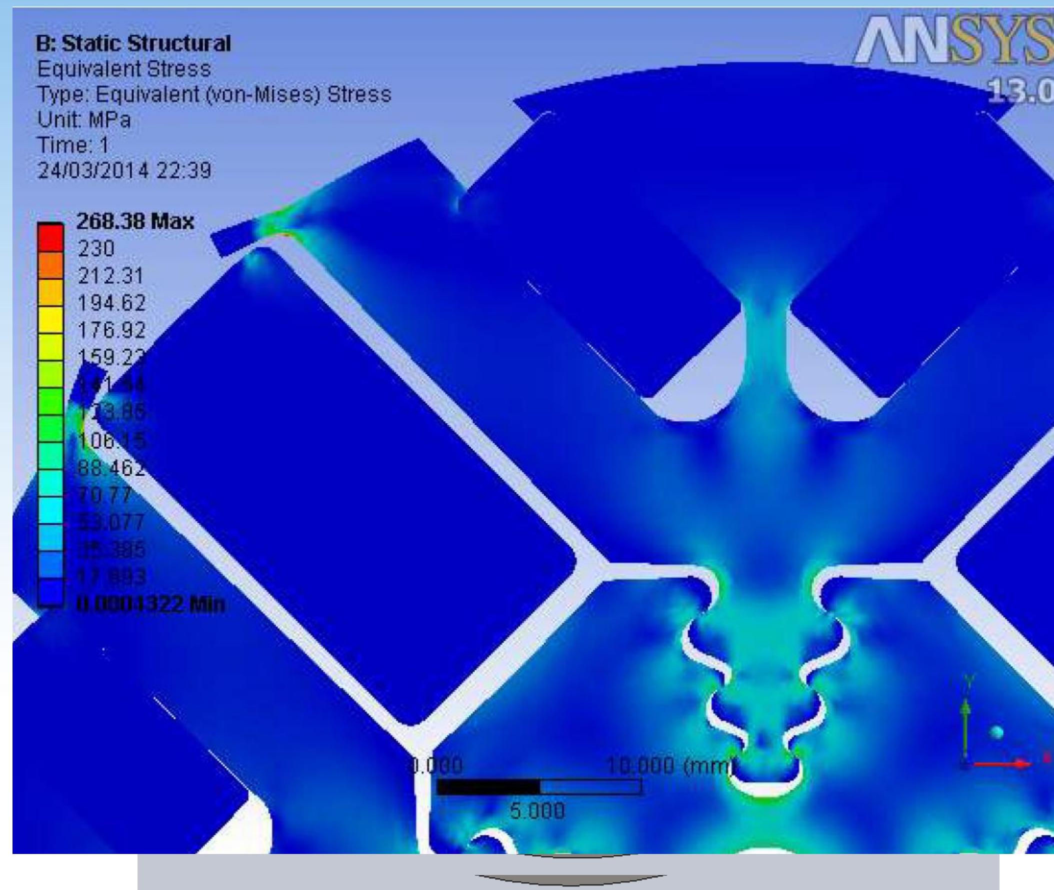


Portunus with High fidelity model



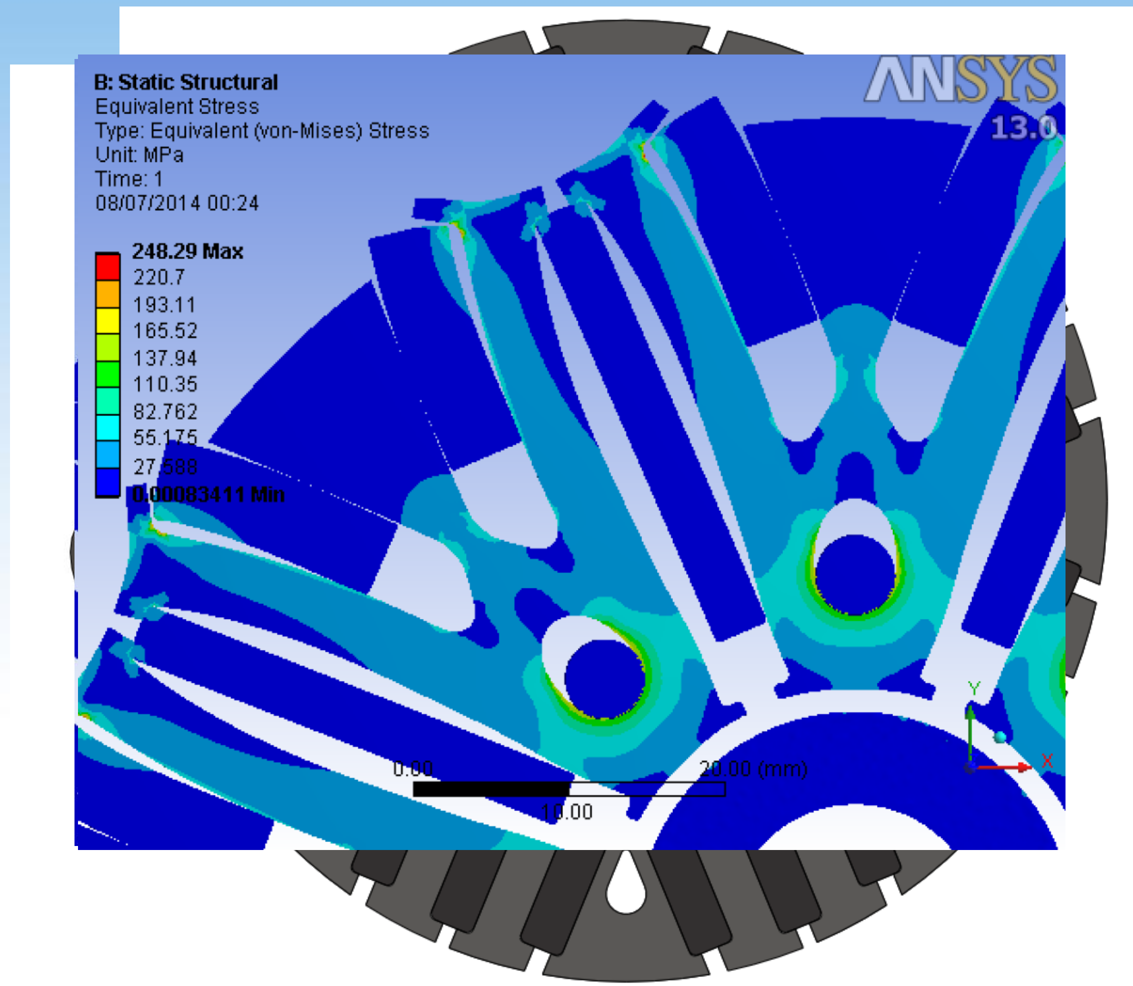
Rotor Slice Design

- The principle design problem faced is to contain the magnets and stator lamination wedges against centrifugal action.
- Recap: Tried various geometries using a supporting peg which proved adequate when rotor diameters were low.

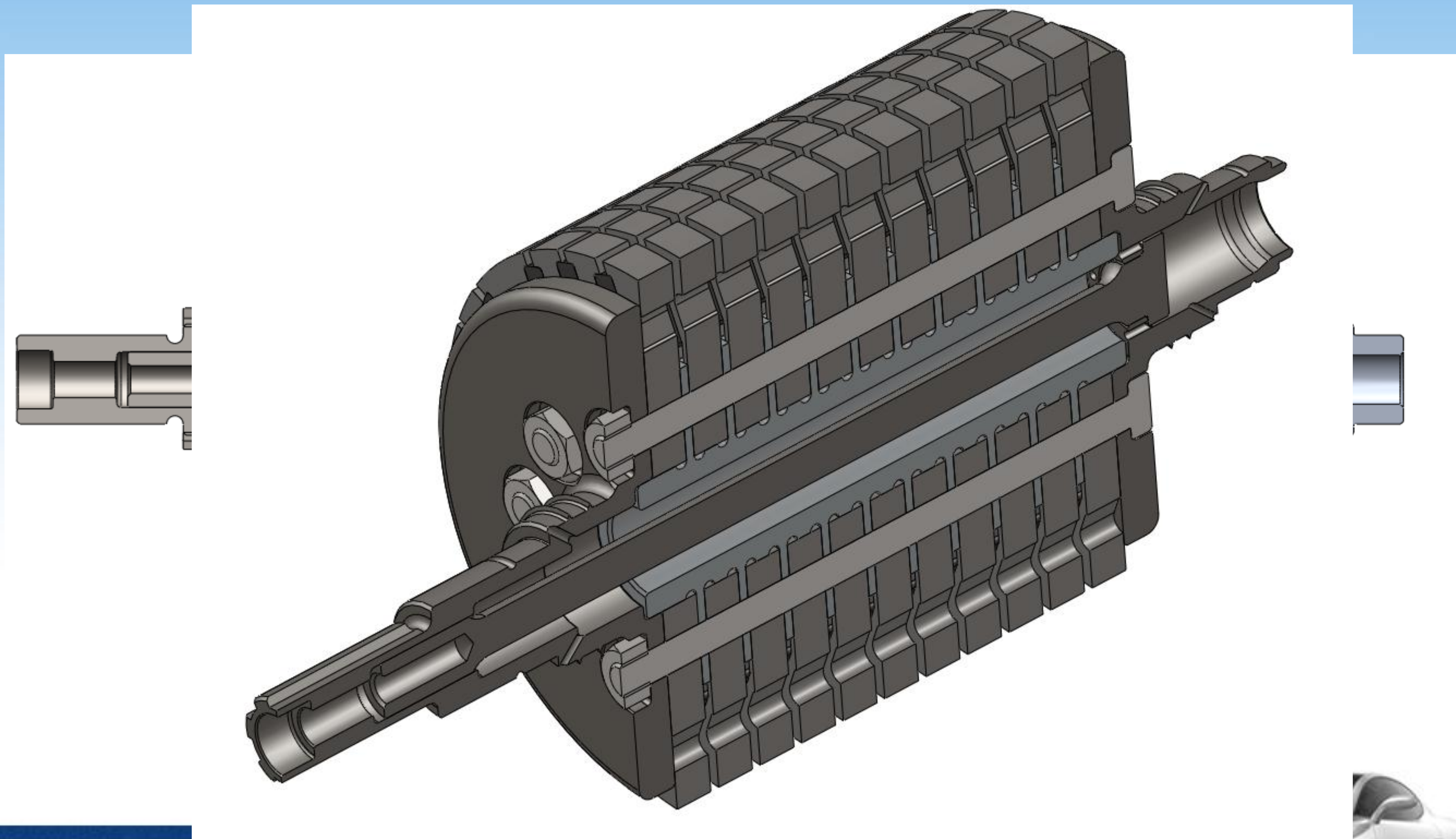


Rotor Slice Design -Cont

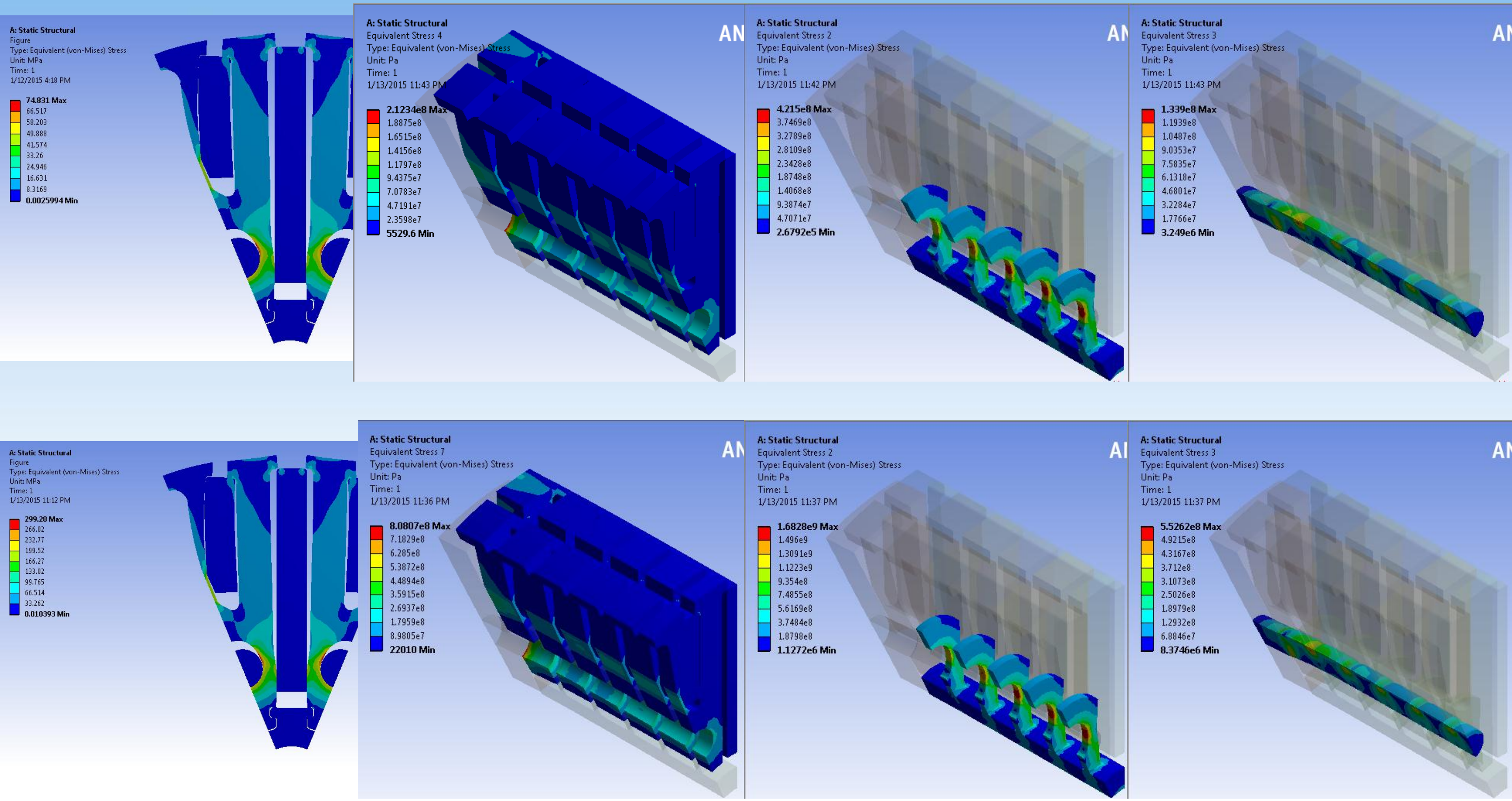
- Magnetic analysis showed that rotor diameter and number of poles needed to increase
- The result was unacceptable stress levels in the peg type arrangement even after optimisation.
- A pin supported design was suggested to reduce the stress in the lamination steel to an acceptable level



Rotor/Shaft Mechanical Features



Final Rotor Stress Analysis



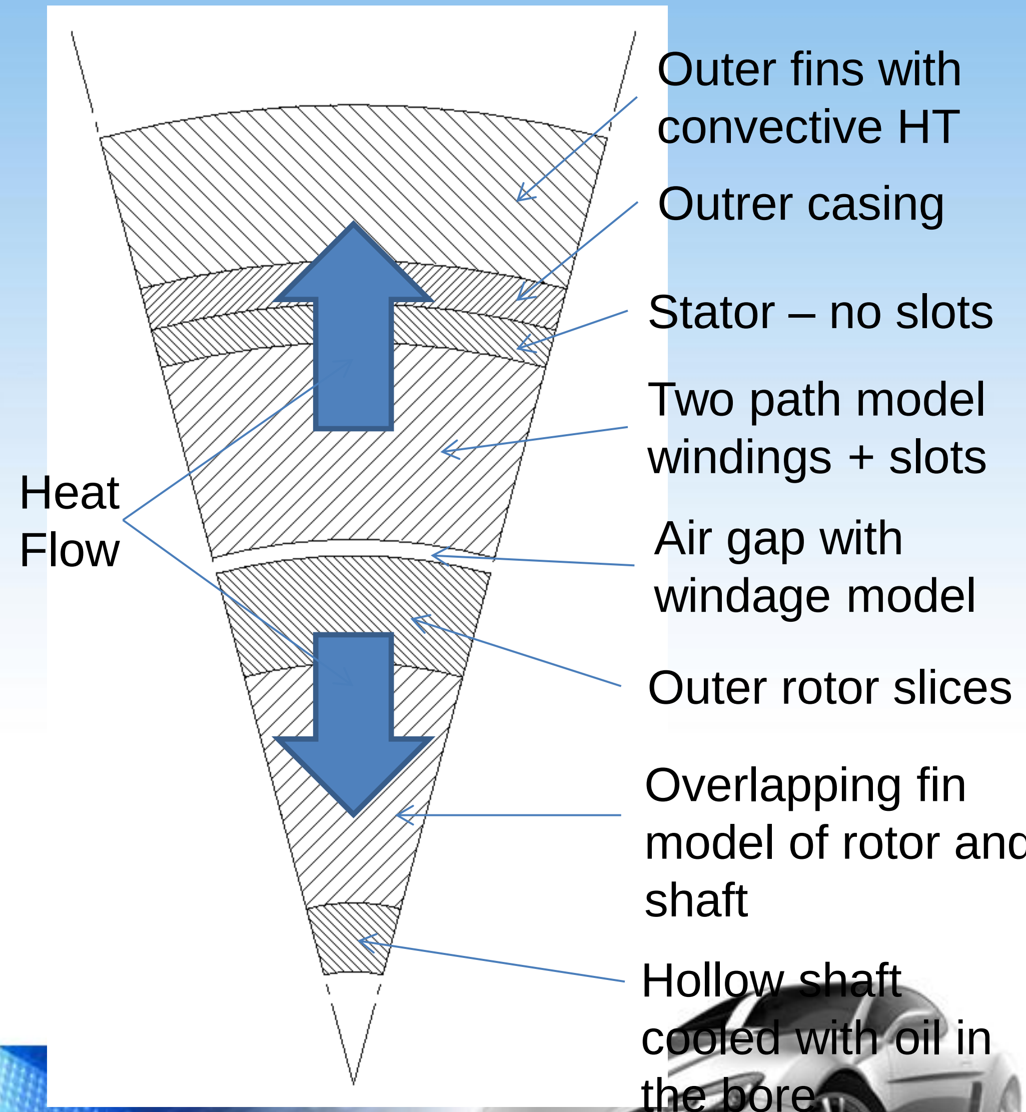
Motor Cooling Design - Model

- A 1.5D, transient heat transfer model was developed to estimate radial temperature distribution in the motor.
- The model allows for heat generation in stator, rotor and the windage gap.
- The composite rotor design is modelled as two overlapping fins and the stator by considering winding and slot conduction in parallel.

$$\rho Cp \frac{\delta T}{\delta t} = k_r \left(\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right) + \dot{q}$$

$$q_{wall} = -k_r \frac{\partial T}{\partial r} \dots \dots \dots T_{const}$$

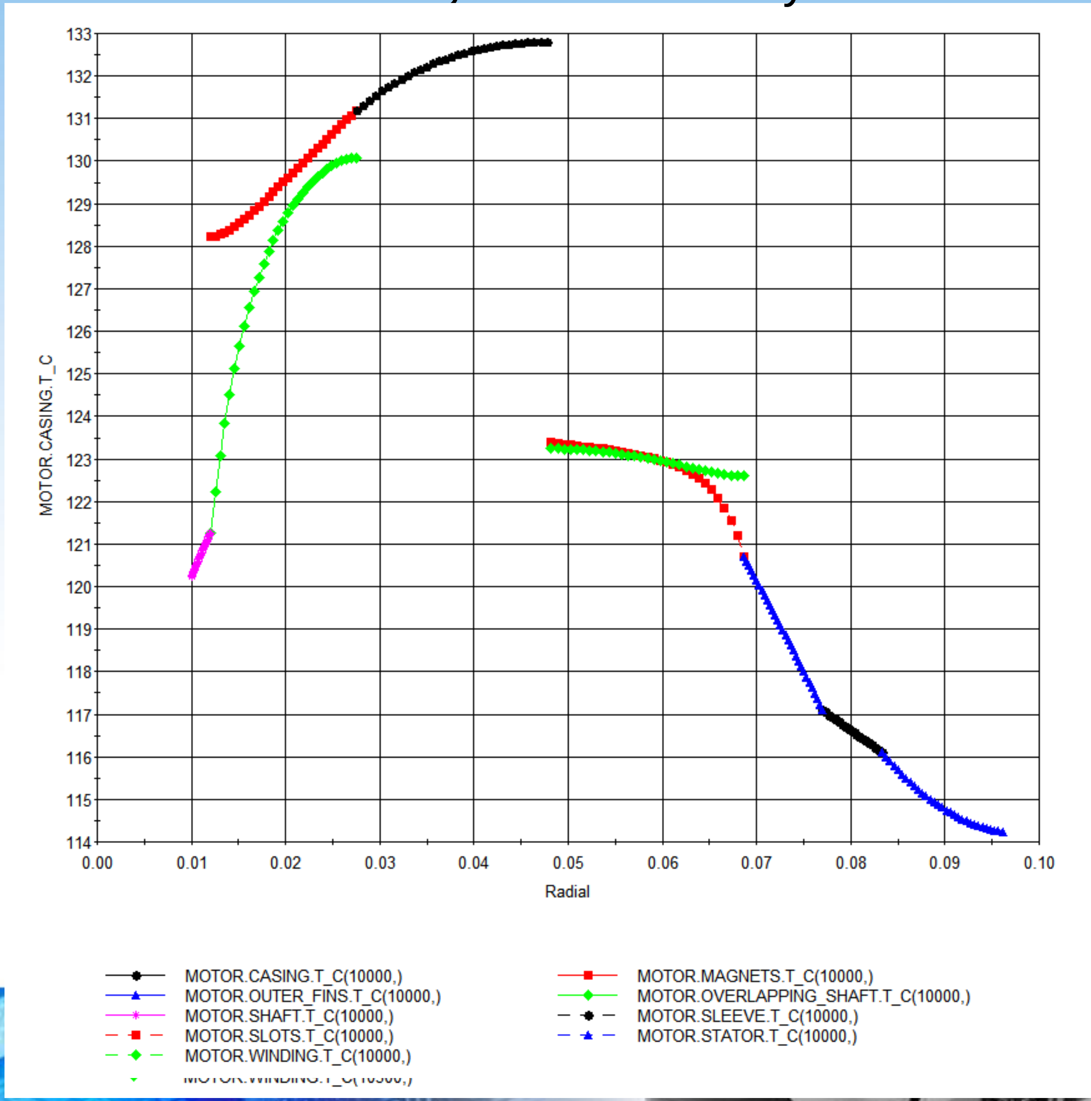
$$-k_r \frac{\partial T}{\partial r} = h(T_\infty - T_{wall}) \dots \dots h_{const}$$



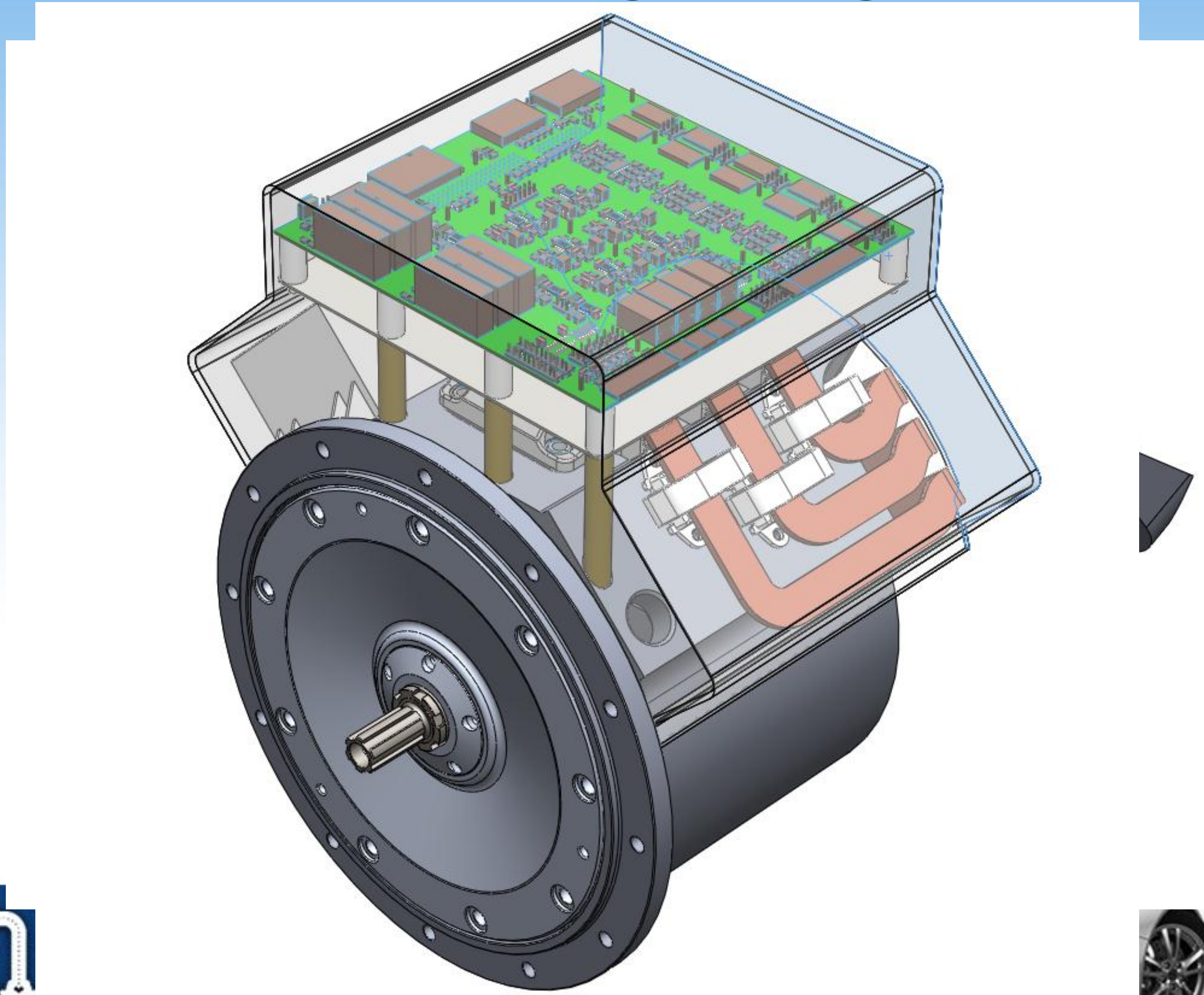
Motor Cooling Design - Results

- Assumptions:

1. Average coolant T = 72.5^{o}C.
2. Motor Nominal Power 20 kW.
3. Combined loss in motor of 5%: 4% shared amongst stator components; 1% in rotor.
4. Windage loss and heat transfer from: ESDU 07704 and Howey *et al 2012.*
5. *$h_{cooling}$* fin based on flat plate convection model.
6. *h_{oil}* based on thin film conduction model.



Overall Package Design



Key Features of Final Design

- Nominal rating: 20 kW at 10,000 rpm.
- Max speed 20,000 rpm.
- Fully subcritical machine design.

- Water cooled aluminium body with integrated cooling of semiconductors.
  a) Fins on motor barrel arranged in a multi-start helical format
  b) Semiconductor cooled by fined heat exchanger aligned with main fins.

- Oil cooled rotor and bearings.
  a) Oil lubricated/cooled bearings fed with oil through hollow shaft arrangement.
  b) Two spring preloaded, deep groove bearings used to support main shaft.
  c) No cooling fan required.

Future works

- Prototype manufacture and assembly (by End of March)
- Rotor integrity test at high speed in City University London
- Improve high fidelity machine model based on 3-D FEA results, and temperature effects
- Full performance profile evaluation of the machine
- Demagnetization analysis to derive current vector limit for each rotor position, embedded in the final controller design to prevent demagnetization
- Develop more sophisticated control algorithm based on high fidelity model to improve overall performance
- DSP programming and machine on load testing