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Mechanically Actuated Variable Flux IPMSM for EV and HEV applications

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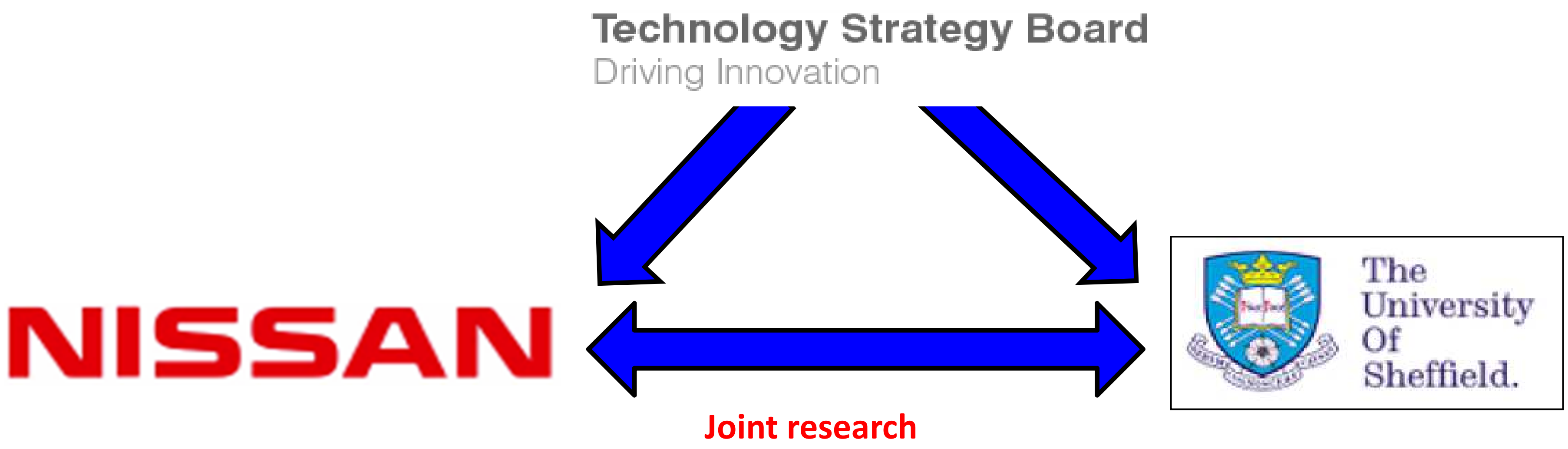
- Introduction
- Concept development
- Design optimisation
- Verifying the performance
- Prototype machine testing
- Conclusion

Mechanically Actuated Variable Flux IPMSM for EV and HEV applications

- Project was 2.5 year joint research project between Nissan R&D UK and the University of Sheffield Electric Machines and Drives (EMD) group
- Activity enabled by the UK Technology Strategy Board (TSB)



Mechanically Actuated Variable Flux IPMSM for EV and HEV applications

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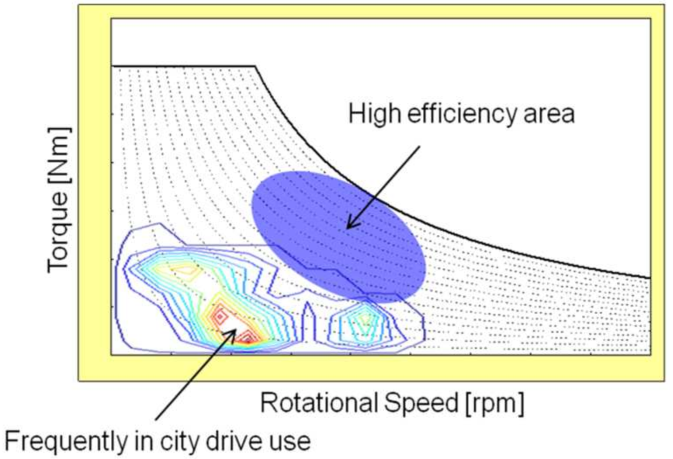
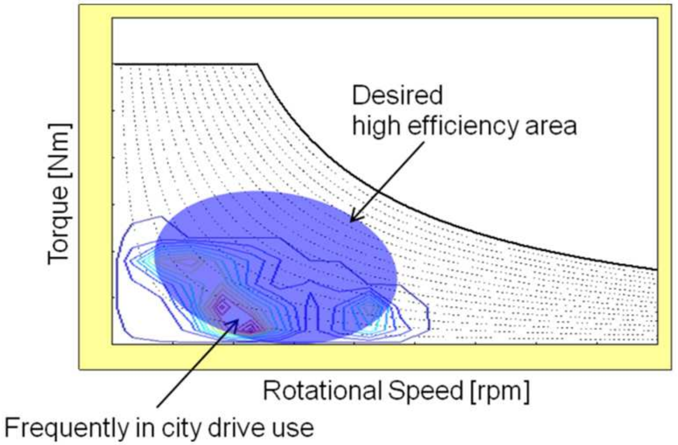
- PM motors are attractive to automotive traction applications due to their high torque density and very high efficiencies (>95%)
- Wide operating range required for automotive applications means that the highest efficiency band tends to be outside the low speed/torque region most frequented during city driving or highway driving.
- To solve this issue a method to move/expand the high efficiency band is required.
  - Target: increase EV range through increased efficiency.
  - Technology: Electrical or Mechanical flux control.





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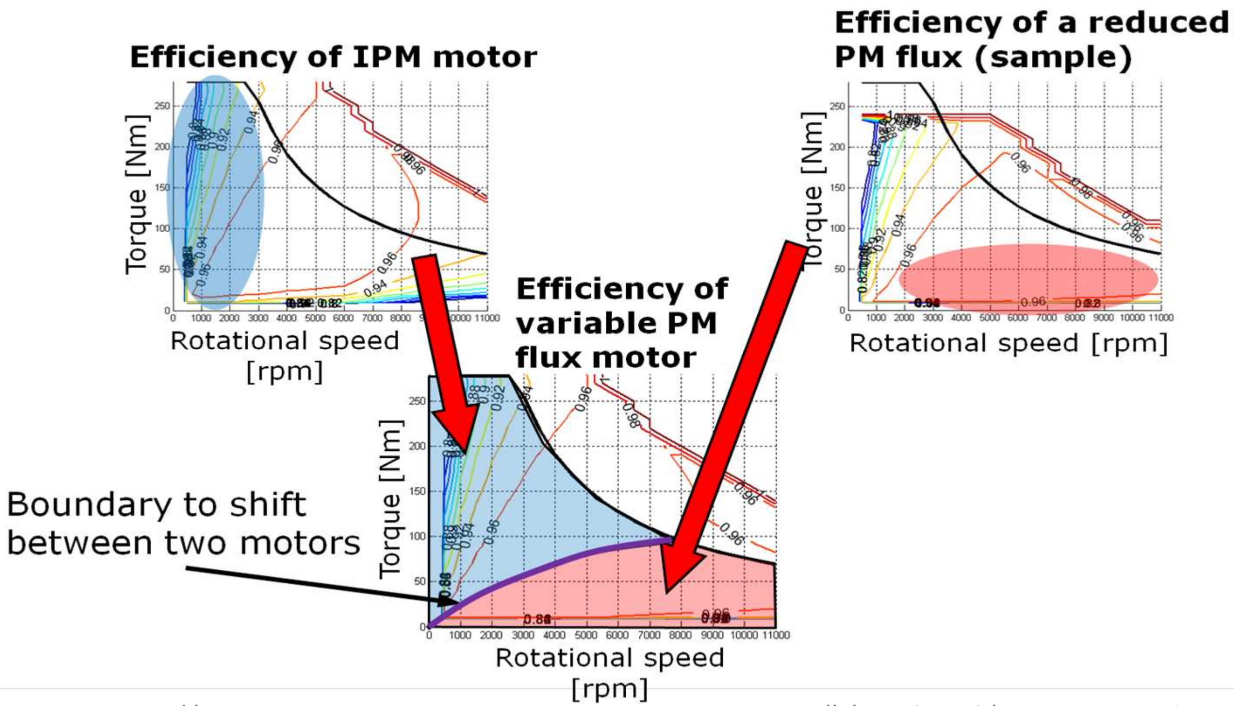
- Variable flux technology allows the flux linkage (Ψa) between rotor and stator to be varied
- This allows peak efficiency region to be shifted according to demand



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Mechanically Actuated Variable Flux IPMSM for EV and HEV applications

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- Introduction
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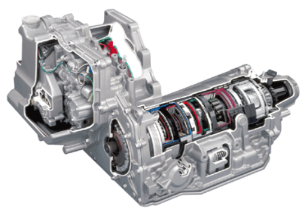
Potential solutions

- Gear box
  - A/T multi speed gear box allows motor to operat[e] peak efficiency band

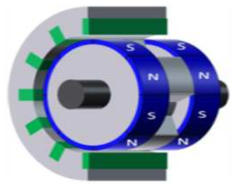


- ✓ Uses well established technology
- ✓ Potentially effective method of increasing overall drive train efficiency
- x Limited gain in efficiency for PM machine
- x Increased system cost, mass and complexity
- x Increased packaging requirements

- Dual Motor
  - Two motors, one large high torque motor, one small high speed motor
  - Large motor operates in low speed/high torque region, small motor operates in high speed/low torque region

- ✓ Potentially large gain in system efficiency
- x Complex system – dual machine, inverters etc
- x Increased packaging requirements
- x High cost

- Variable flux machine
  - PM machine that can adjust flux according to demand, in effect a dual motor solution in a single package



- ✓ Reduced cost impact
- ✓ Potential for large gain in efficiency for PM machine
- ✓ Low packaging requirements
- x Mechanism potentially complex
- x Ease of implementation unknown

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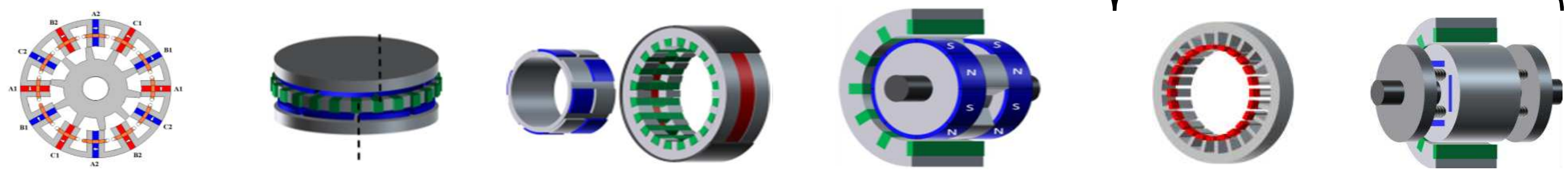
- Initial step involved detailed study of existing variable flux machine topologies and techniques

Novel Machine Topology

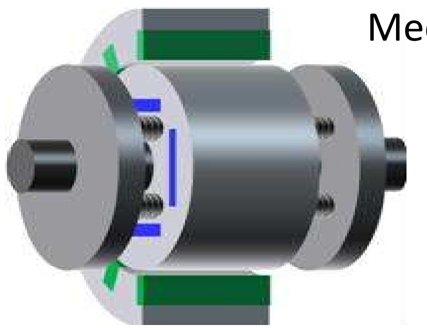
Addition to Conventional Motor



Evaluation Criteria

- High performance;
  - High torque density
  - High efficiency
- Realization Complexity;
  - Complexity (Reliability) of variable mechanism,
  - Overall complexity (reliability) and cost

Chosen Variable Flux Concept: Mechanically actuated end plates



- ✓ High torque density
- ✓ Mechanism contained within machine structure
- ✓ Adaptation of existing motor design reduces cost impact
- X Level of flux reduction unclear
- X Mechanical actuator complex

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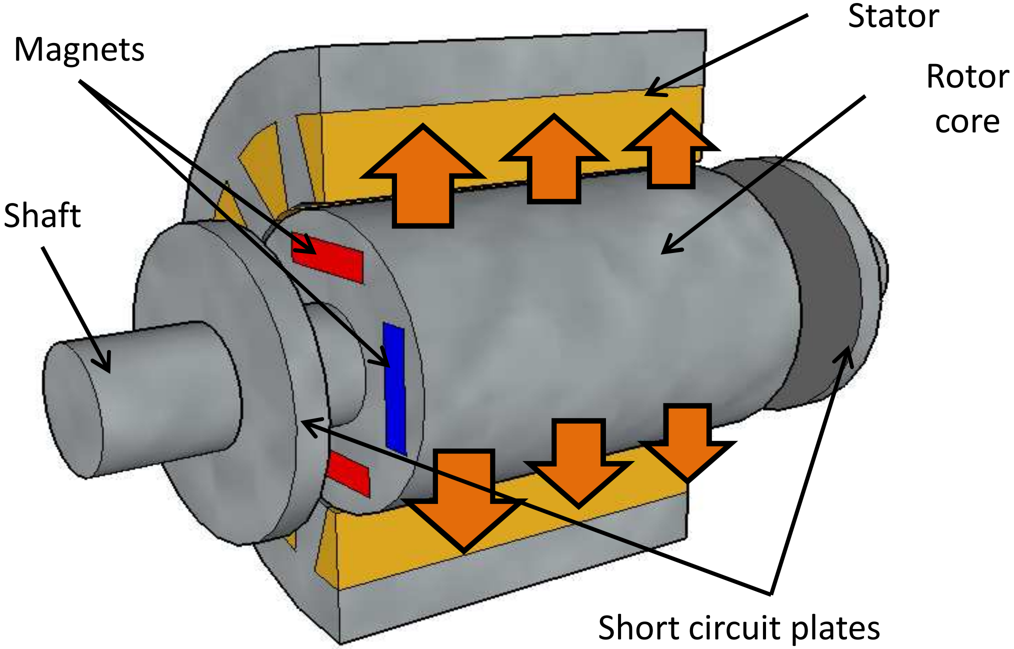
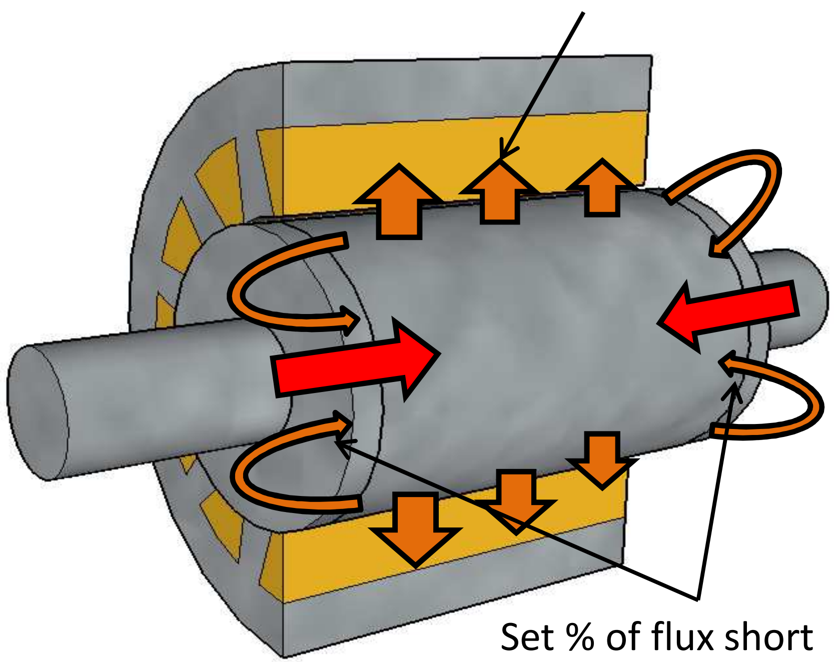
- Overview of actuation method





Maximum flux condition
Short circuit plates moved away from core

Minimum flux condition
Short circuit plates attached to the core

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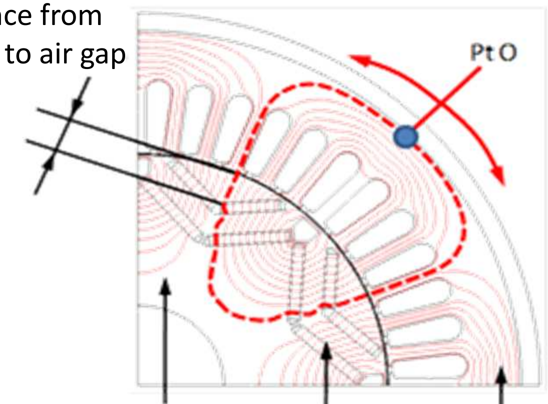
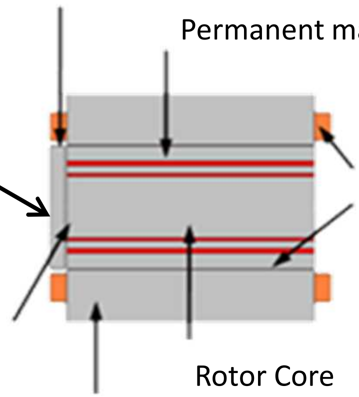
- 2D FEA models created to allow design parameters to be identified and investigated



¼ Radial section of motor

Single short circuit plate only to ease modelling



Simplified model for parametric study

$$\alpha = \frac{\lambda_{norm} - \lambda_{SC}}{\lambda_{norm}}$$

Ratio α used to indicate level of flux reduction during study

- Initial parameters identified :
  - Distance of magnets to the radial air gap
  - Layout of buried PM (single layer, dual layer etc)
  - Influence of stack factor on axial flux path

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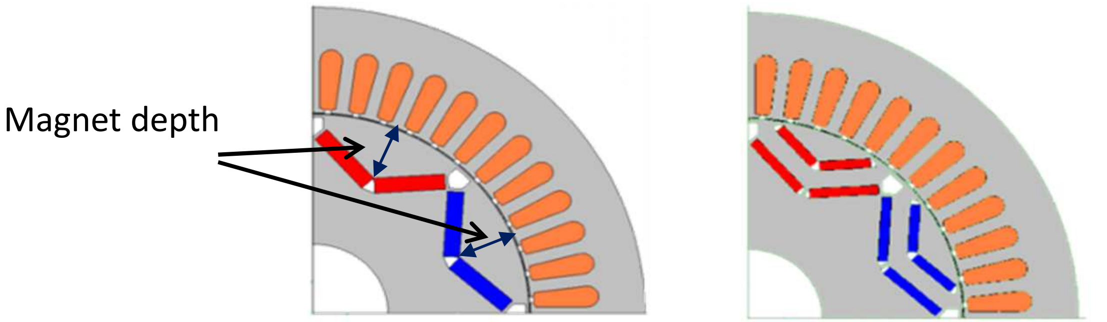
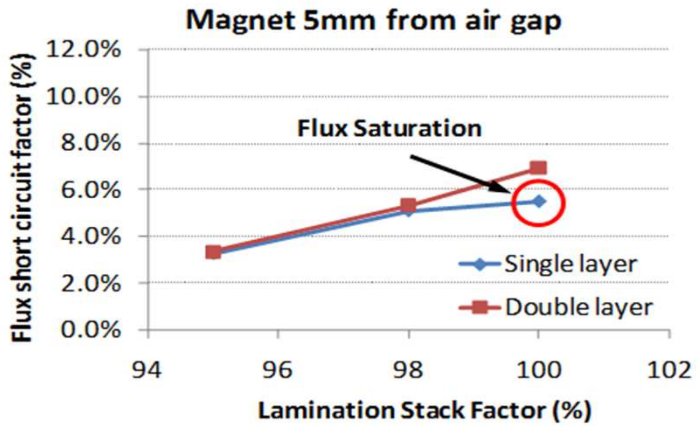
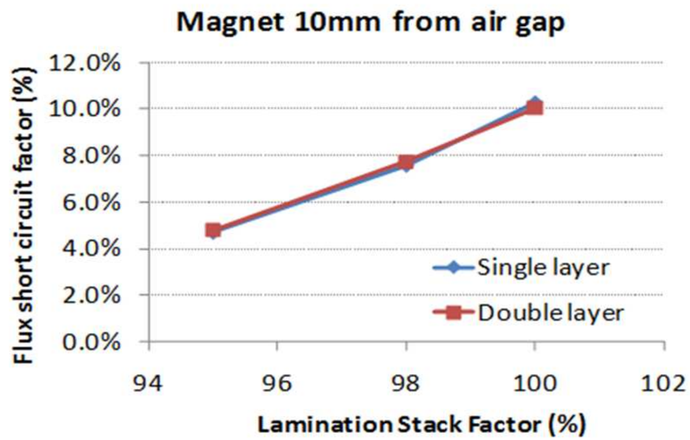
- Magnet layout investigated to find optimal topology







- Double layer design reduces risk of saturation in rotor, particularly at high stack factors
- Increased magnet depth in core improves short circuit plate performance

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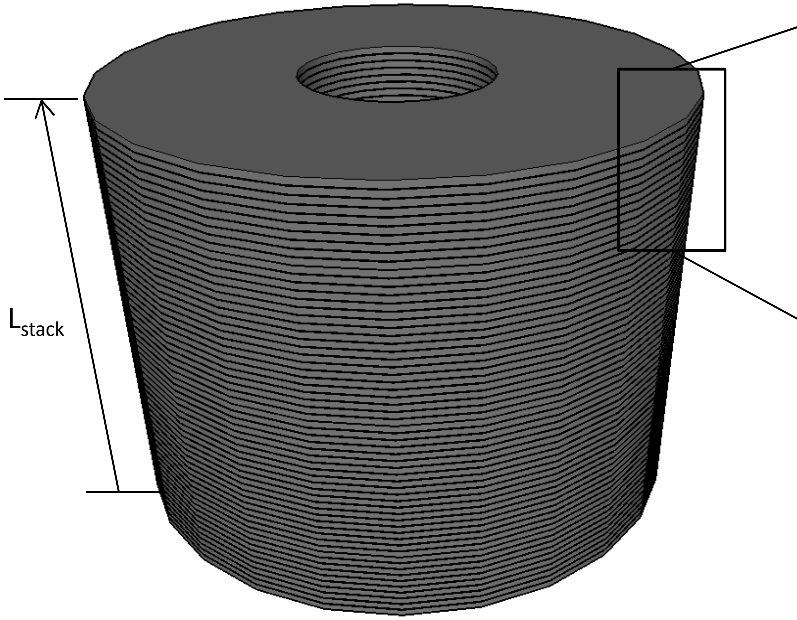

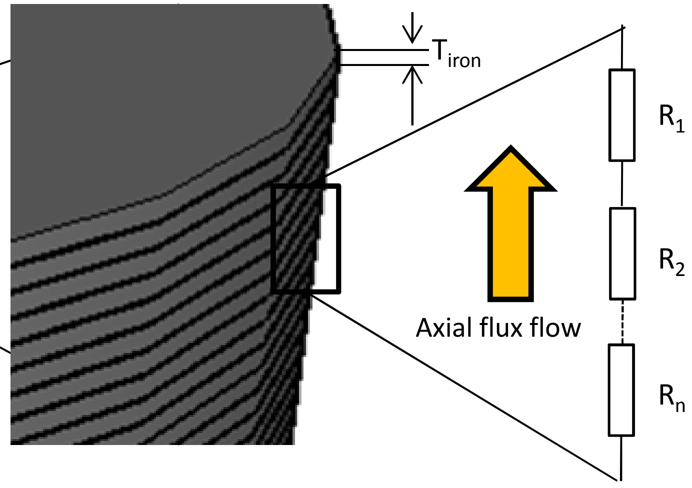

$$Stackfacto\ r = \frac{\sum T_{iron}}{L_{total}} \times 100\,\%$$

Axial reluctance increases proportionally to the number of plates (n) the flux has to pass through

$$\Re = \frac{\sum_{1}^{n} T_{insulation}}{\mu_0 A}$$

(Assume permeability of insulation material = $4\pi x10^{-7}$ (air))

- Typical stack factor ~95% using standard rotor fabrication techniques (cleating, adhesive bonding etc)
- Study shows stack factor >98% required to maximise level of axial flux flow
- Stack factor of 98.4% can be achieve by welding inner bore and press fitting end caps on to core when fitted to shaft to minimise splay
- This technique allows the flux to be reduced by 7.5% per end cap = 15% reduction overall

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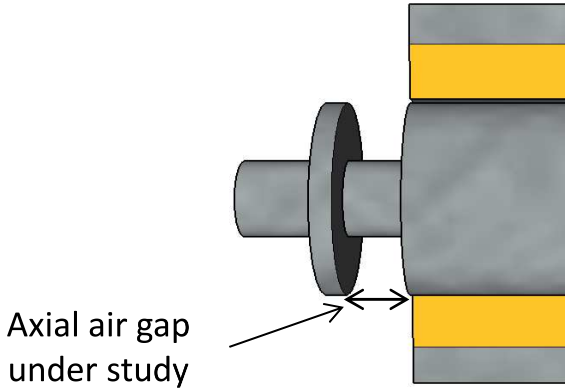
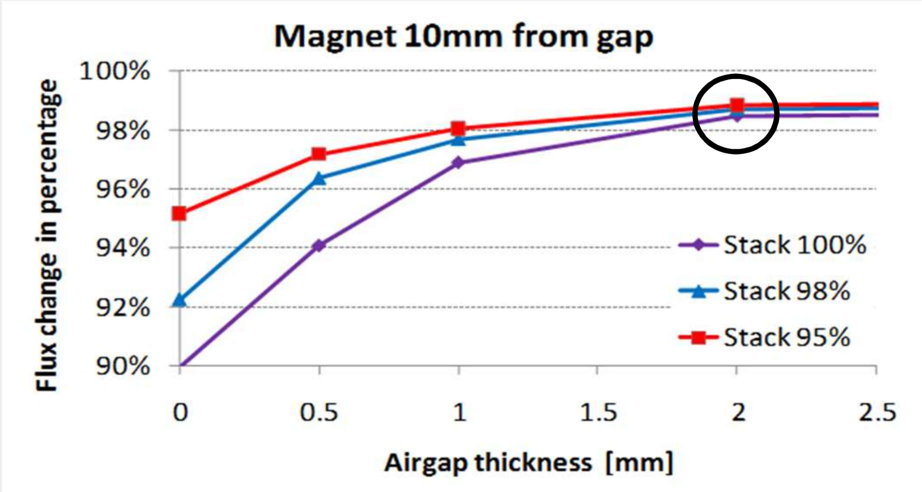
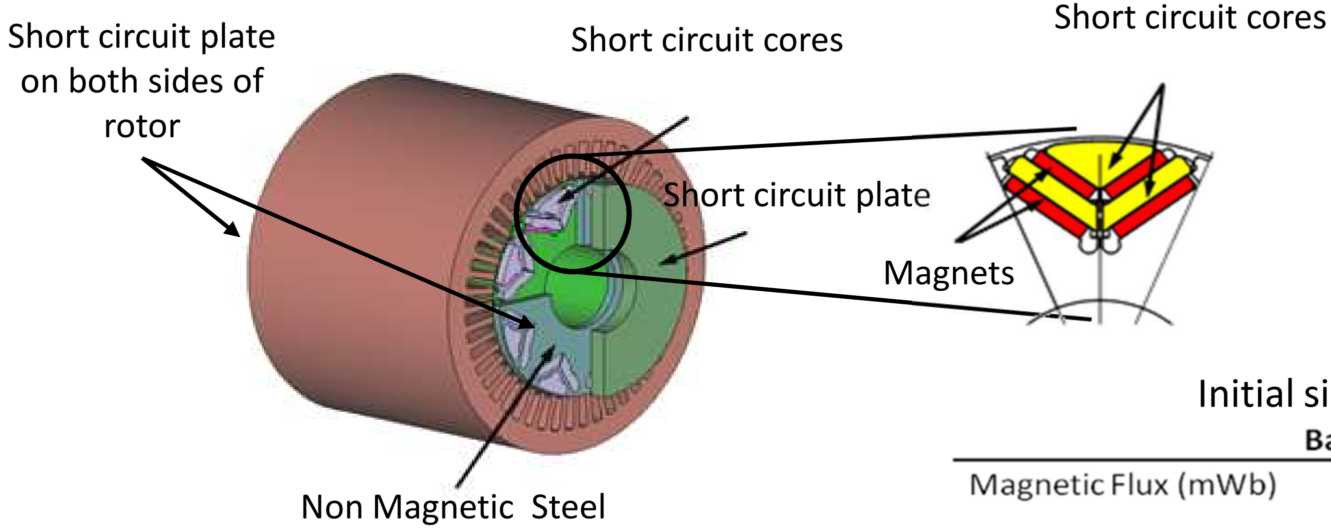
- The high forces involved during plate actuation risks damaging the magnets in the core; end cap is required to protect the magnets
- This creates a gap between the plates and the magnet, the influence of this gap must be understood





- To counter this concern low reluctance material such as iron can be inserted into the end cap such that the short circuit flux can be maximised whilst ensuring the magnets are protected during plate actuation

- Output of parameter study allowed initial machine design to be realised



Initial simulation results

	Base Motor	Variable flux V1	
Magnetic Flux (mWb)	76.13	67.36	-11.5%

- Initial simulation results show 11.5% reduction in flux linkage
- This result is much lower than the 15% indicated in the initial study, further optimisation is required

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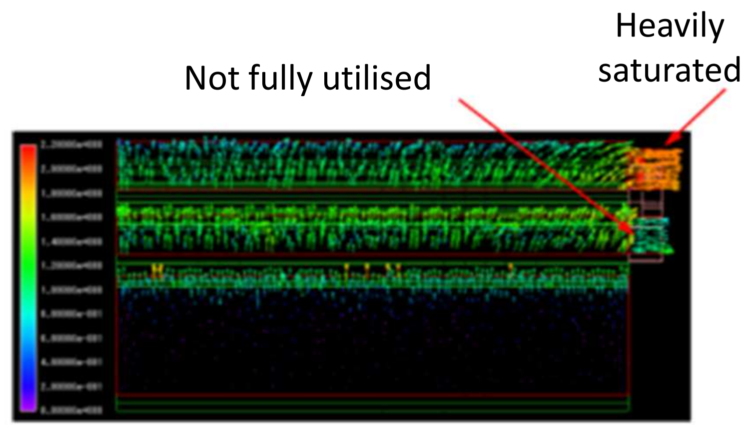
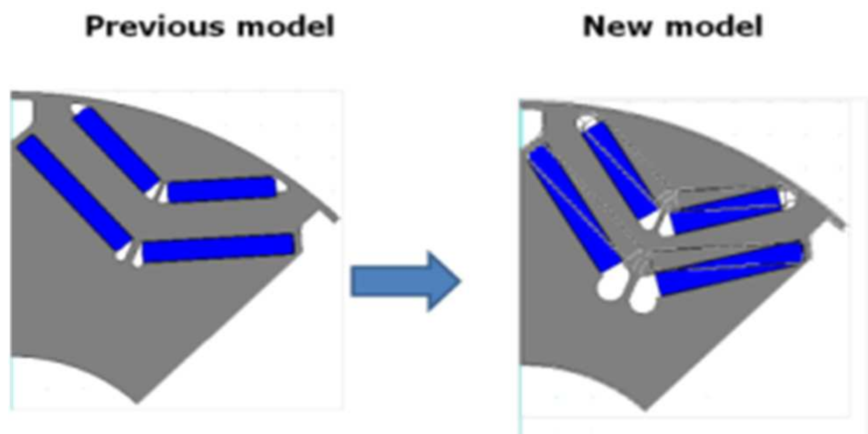
- 3D FEA shows initial ‘V’ design has high saturation in the upper region of the rotor core reducing the effectiveness of the design
- ‘V’ Shape design optimised to improve distribution such that it provides optimal balance between requirement to maximise axial flux distribution whilst minimising stress concentrations on rotor structure



	Base Motor	Variable flux V2	
Magnetic Flux (mWb)	76.27	64.85	-15.0%



- Performance improved to provide 15% reduction in flux linkage

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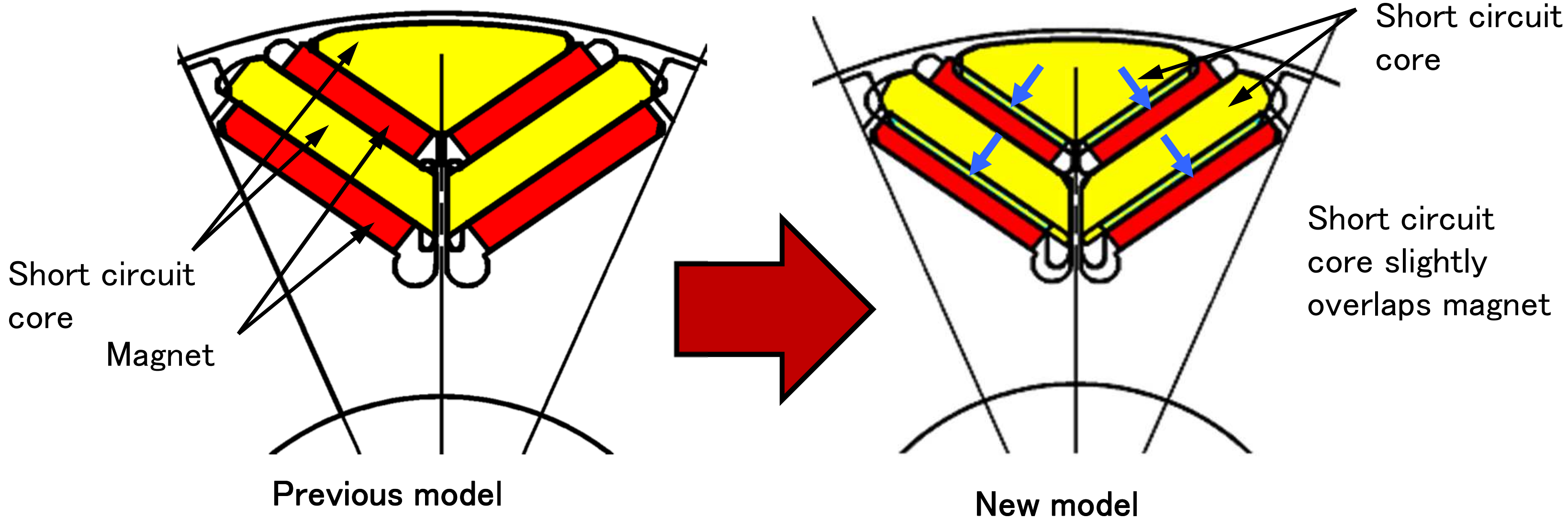
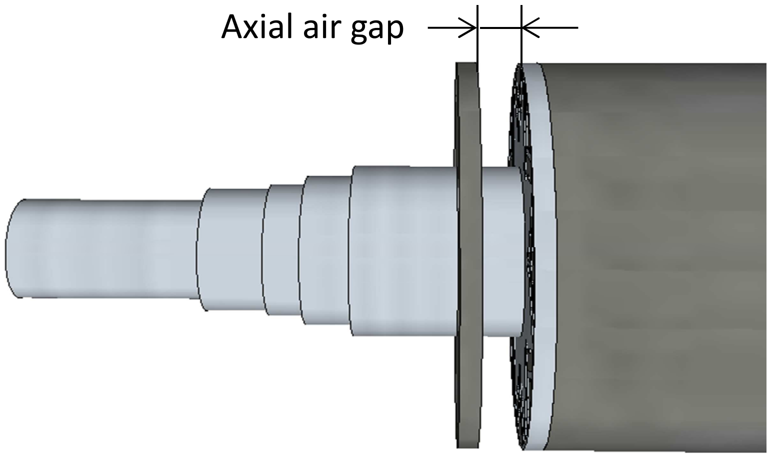
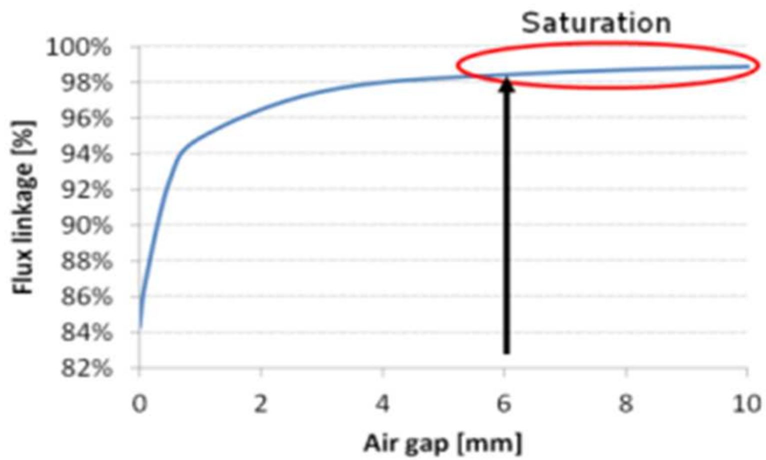
- Optimisation of solid steel insert geometry in the end cap assembly provides further improvements in performance



	Base Motor	Variable flux V3	
Magnetic Flux (mWb)	76.35	64.34	-15.7%

- Final stage must consider the optimal air gap between the short circuit plate and the end cap





- 6mm gap is optimum distance, saturation effects means limited benefit in moving plate beyond this distance

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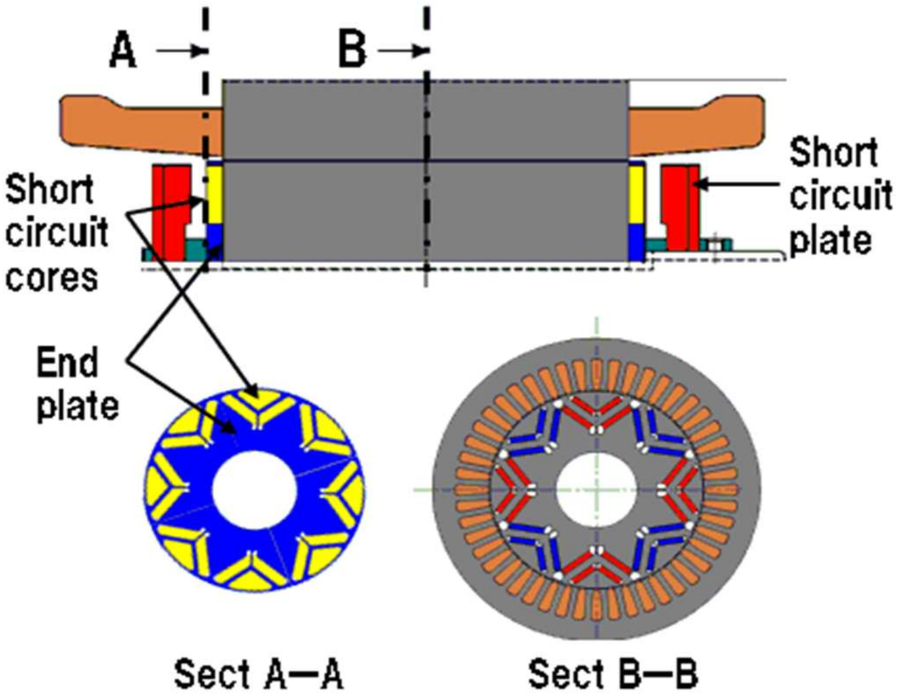
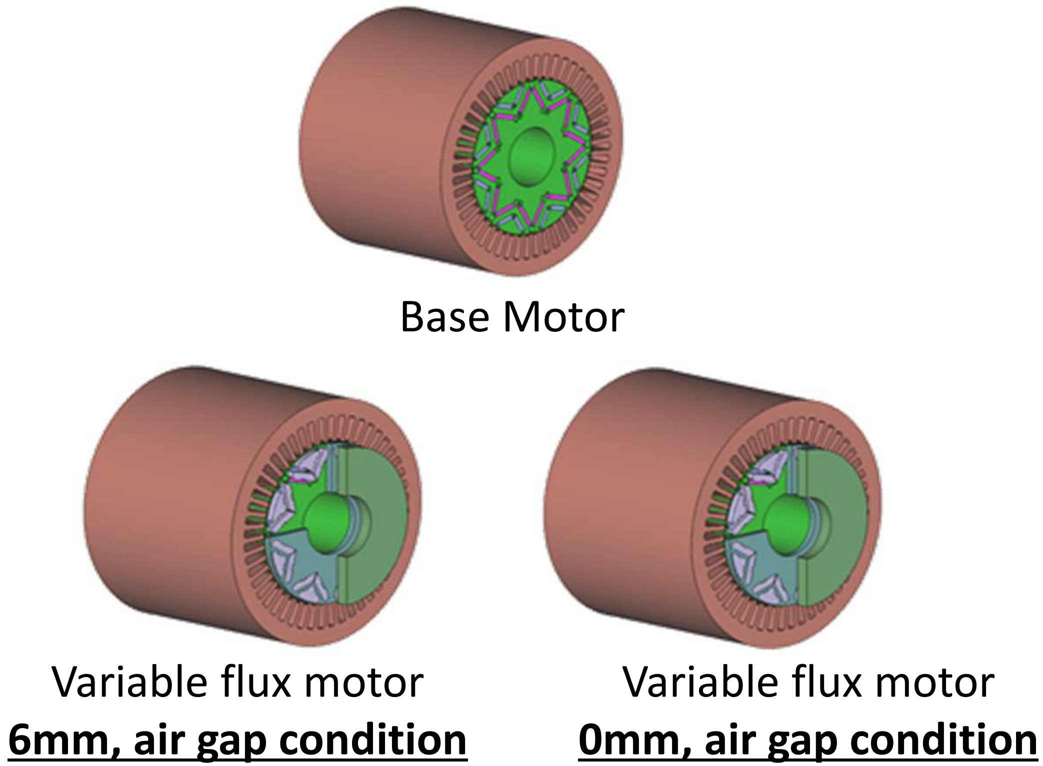
- Final Machine structure



Final machine structure



3D FEA Models for Performance Verification

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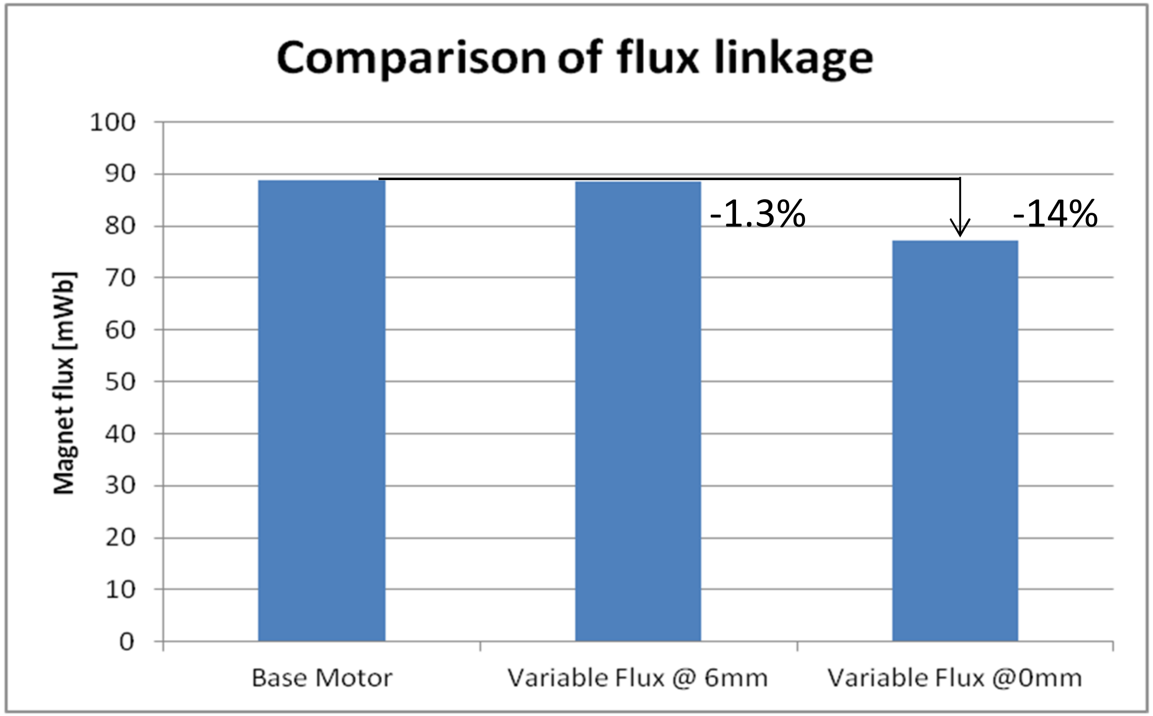
Mechanically Actuated Variable Flux IPMSM for EV and HEV applications

- Base motor and variable flux machine in maximum and minimum flux conditions evaluated using 3D FEA



- Slight reduction in linkage between base and variable flux @ 6mm
- **14%** reduction between base motor and minimum flux condition

Simulation	Magnetic Flux (Ψa) (mWb)
Base Motor	89.7
Variable flux @ 6mm	88.5
Variable flux @ 0mm	77.2

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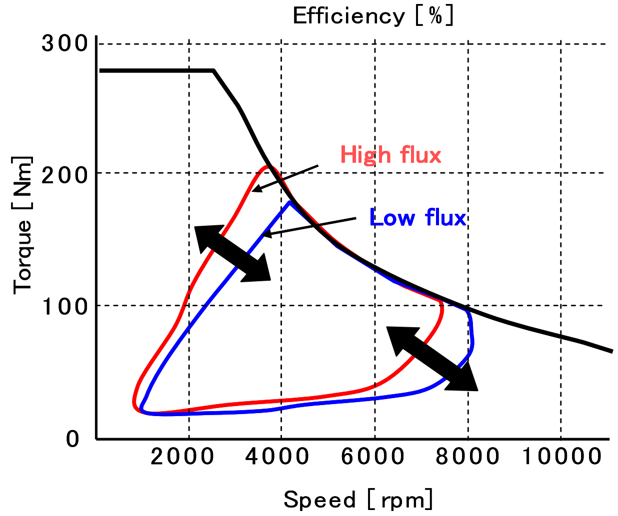
- Benefits of system become clear in the high speed/low torque operating region

50Nm@9000rpm	Base motor	Variable flux	Ratio
Copper loss [kw]	1.33	0.64	-52.0%
Iron loss [kw]	2.42	1.95	-19.2%
Total loss [kw]	3.75	2.60	**-30.9%**



Expansion of efficiency band

- Reduced requirement for flux weakening current and reduced flux density in the stator mean copper loss and iron loss are reduced 52% and 19.2% respectively

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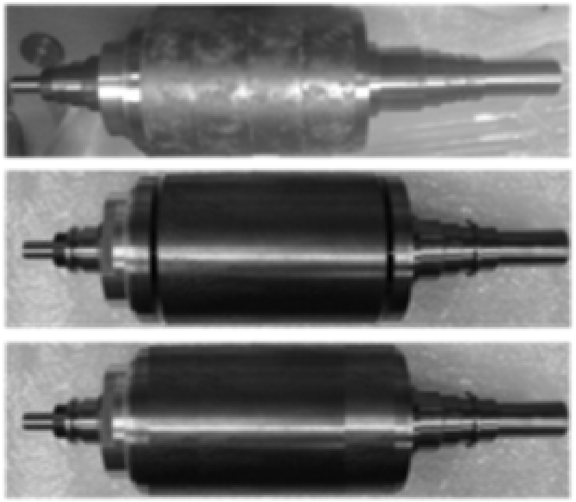
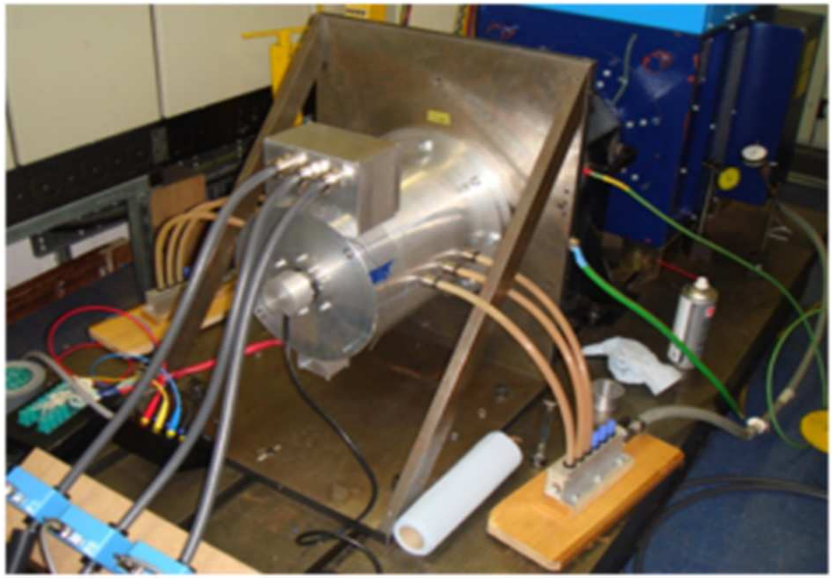
- Prototype machine fabricated to validate concept
- 3 rotor variants tested:
  - Base Rotor
  - Variable flux with end plates fixed 6mm from core (maximum flux condition)
  - Variable flux rotor with end plates fully engaged (minimum flux condition)



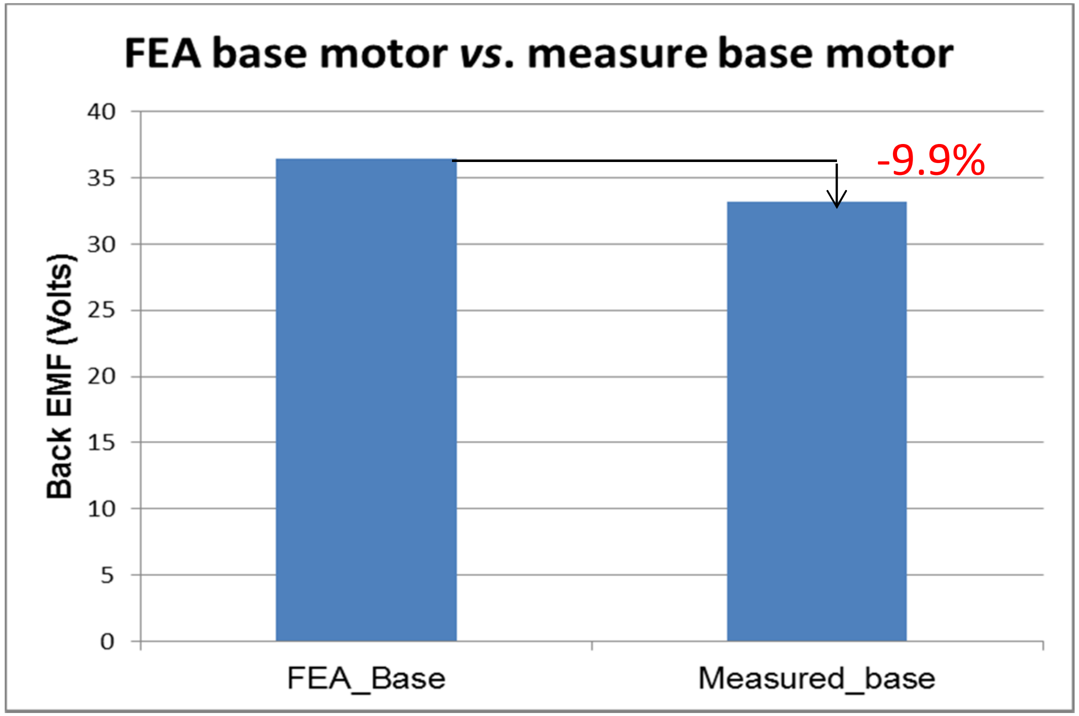
Base Rotor

V_flux @ 6mm

V_flux @ 0mm



- Initial test compared fabricated base motor with 3D FEA results



- Results show 9.9% drop in flux between physical machine and FEA
- Investigation found two primary sources of discrepancy
  - Rotor and stator core material grade
  - Additional air gaps in magnetic circuit due to tolerance stack up in machine

Component	Change Item	Contribution
Core Magnetic Steel	FEA = 35H210 Prototype = M250-35A	2.5%
Magnet Slot Width	FEA = 7mm Prototype = 7.2mm	6.7%
	TOTAL:	9.2%

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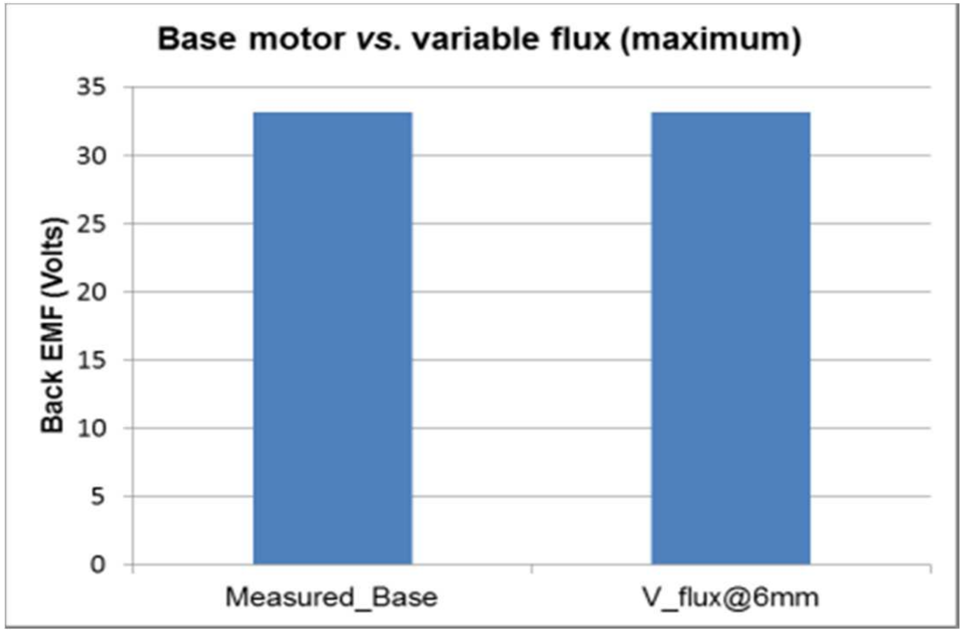
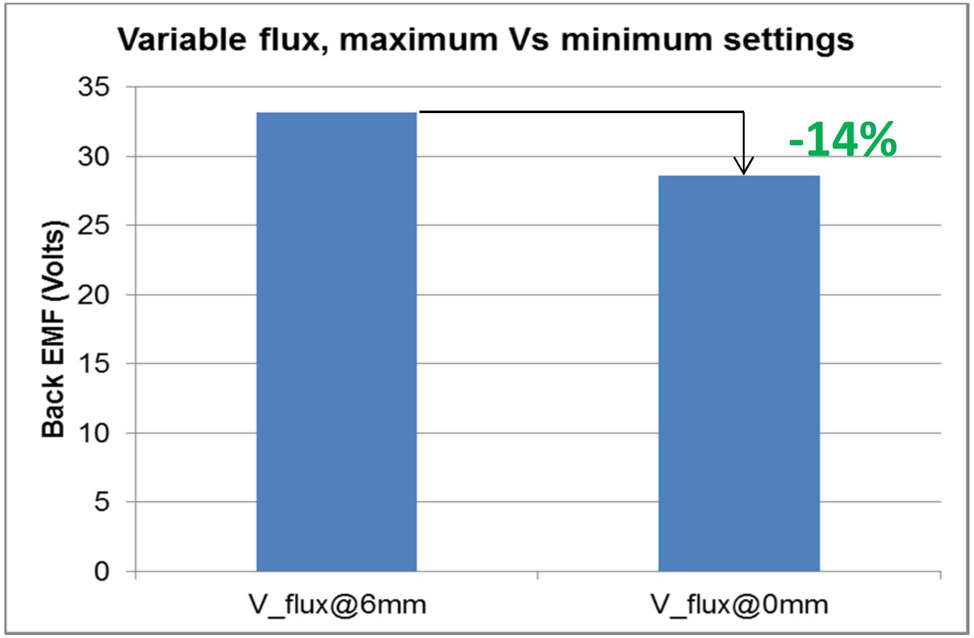
- Variable flux in maximum and minimum flux settings compared with Base motor





- Flux drop between base motor and maximum flux condition negligible
- 14% drop between maximum and minimum flux settings achieved

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- Novel mechanically actuated variable flux IPMSM presented
- Mechanism allows expansion of motor efficiency band whilst minimising impact on cost and packaging
- Fabricated prototype machine achieved predicted 14% reduction in flux reduction
- Design allows for a 30% reduction in loss within high speed/low torque region, reducing drive train energy consumption

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THANK YOU FOR LISTENING!