The role of FEA in the design of advanced electric machines

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NRC·CNRC

The role of FEA in the design of advanced electric machines

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Canada

Outline

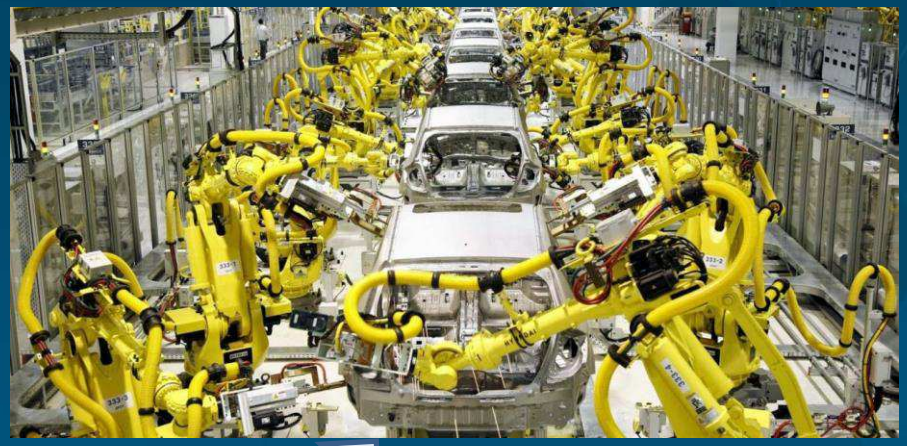
- Importance of FEA in electric machine design
- Variable flux motor
- Reduced rare-earth permanent magnet motor
- Electric motor development using additive manufacturing

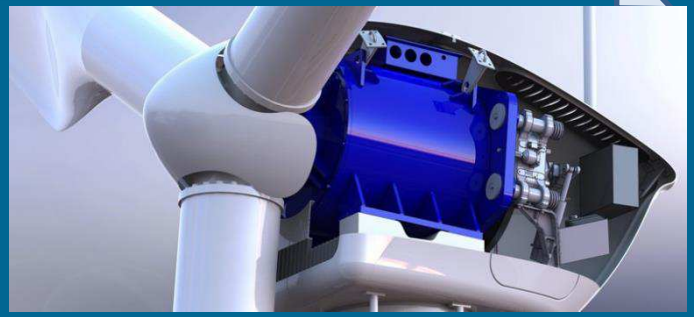
Applications of electric machines

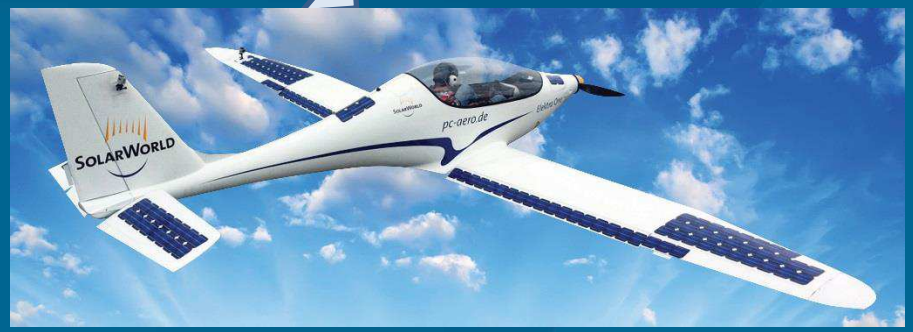
99% of all the electricity originates from an electric generator

50% of the generated electricity are utilized through electric motors

Applications of modern Electric machines



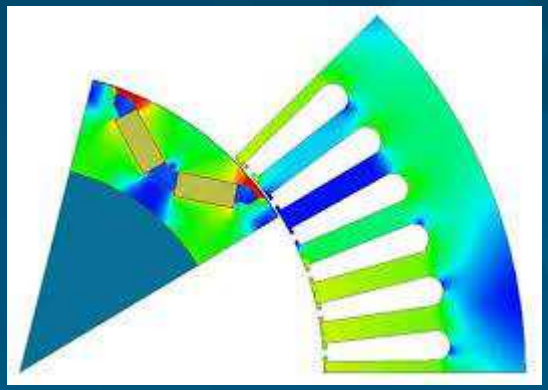


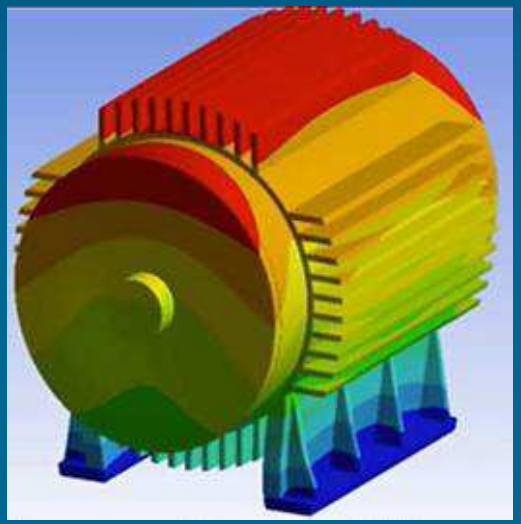


Modern electric machine design

Goals of a modern electric machine

- High efficiency and reliability
- Small size and weight
- Minimized noise and vibration
- Reduced cost

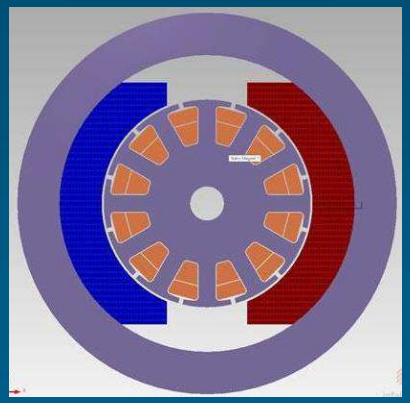
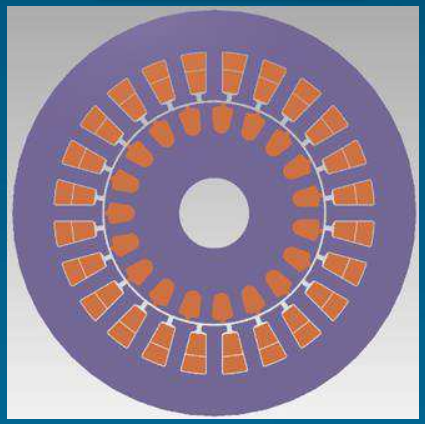
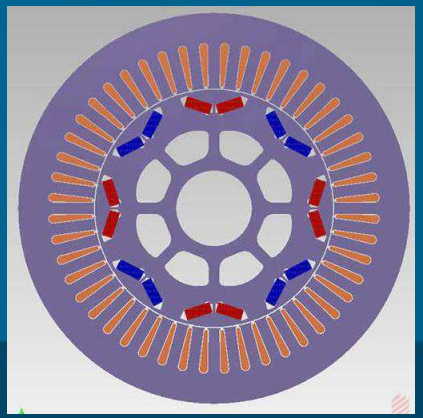
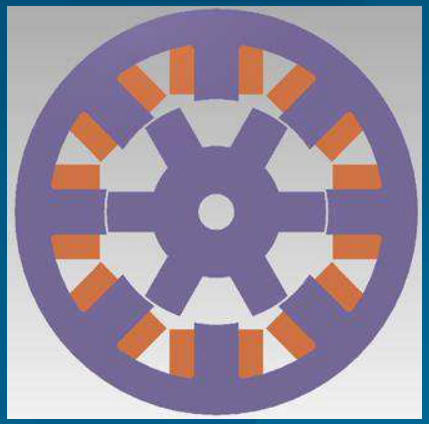




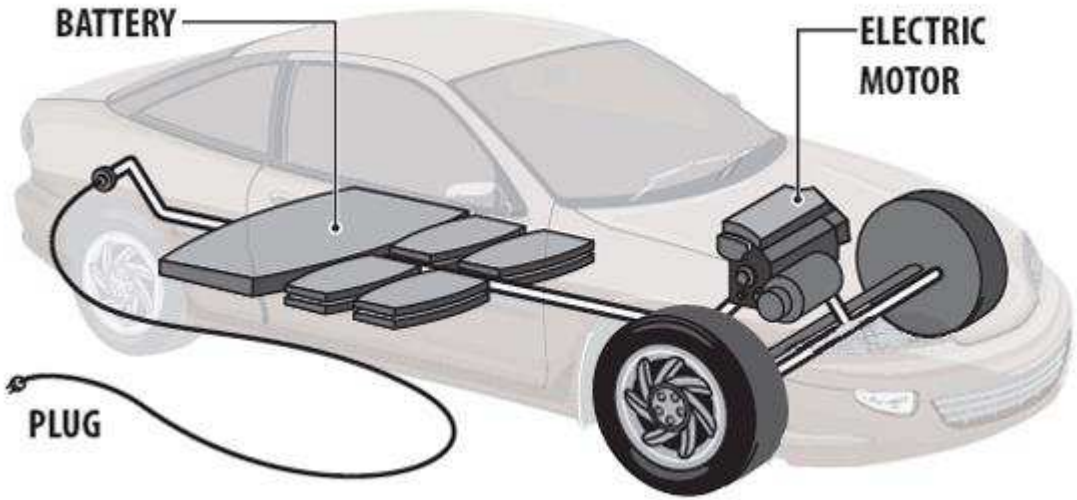
Role of FEA simulations

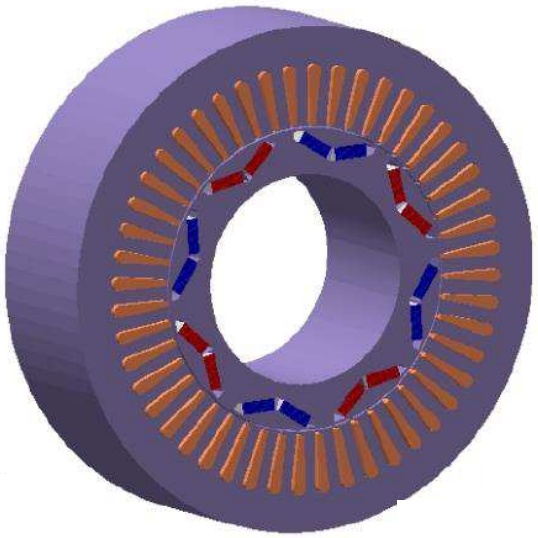
- Efficient electromagnetic design
- Accurate loss calculations
- Thermal analysis
- Structural integrity

Main Types of Electric Machines

- DC
  - 
  - Low efficiency
  - Short life-time
  - Easy to control
- AC
  - Induction
    - 
  - Synchronous
    - Wound-field
    - Reluctance
    - Permanent magnet
      - 
  - Switched Reluctance
    - 

Traction motors in electric vehicles

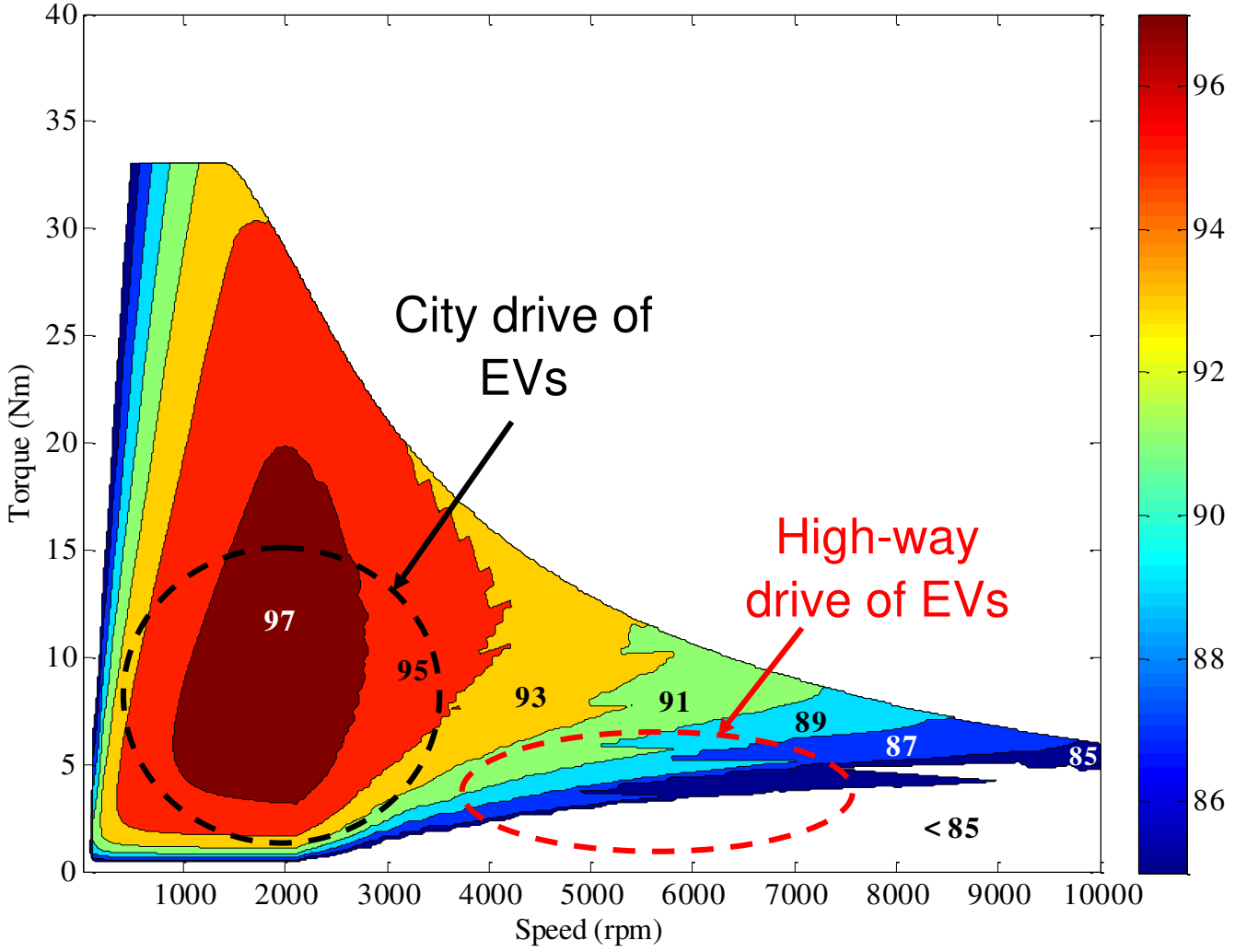




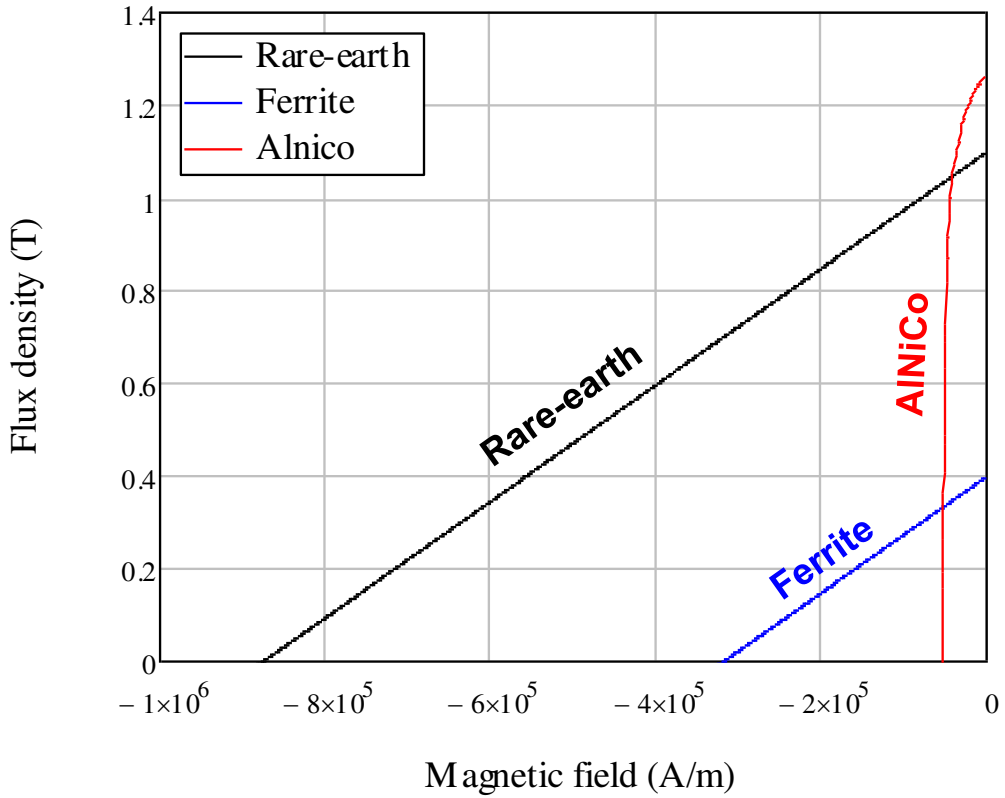
Toyota Prius motor

- Most commercial electric vehicles utilize rare-earth permanent magnet synchronous motors.
- Due to their highly concentrated production, rare-earth magnets may not be available in the future at economical prices.

High speed operation of rare-earth PMSM

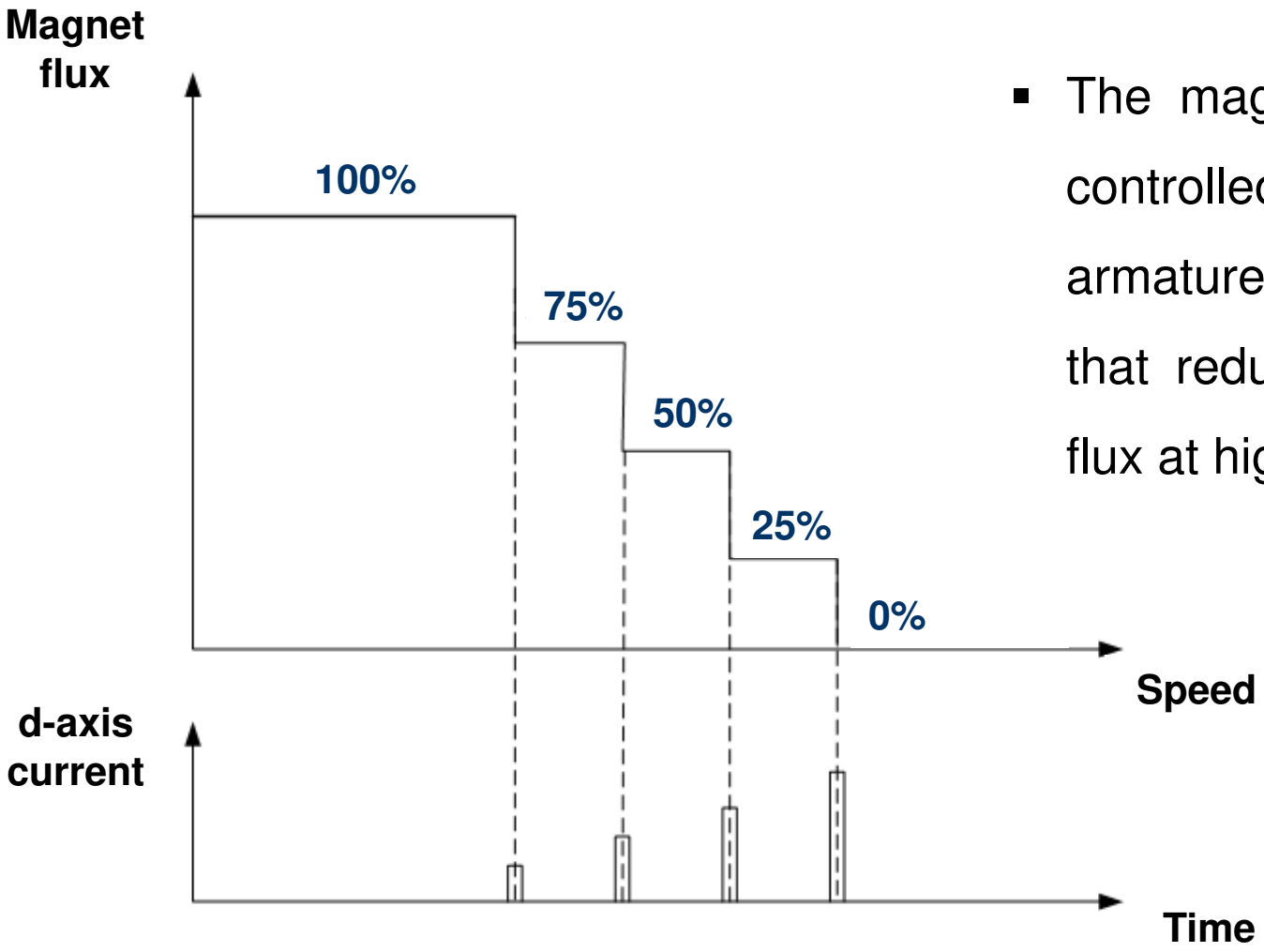


Alternative Permanent Magnets



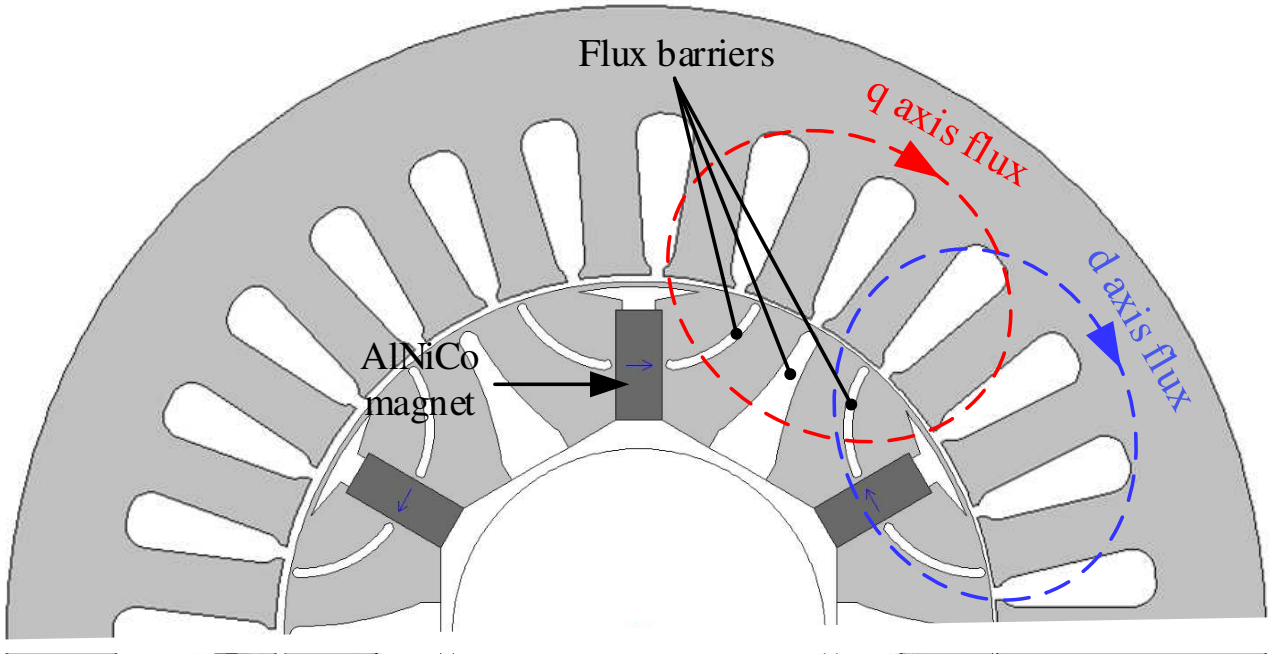
- If the demagnetization effects of AlNiCo magnet are controlled, an AlNiCo PMSM can provide performance comparable to rare-earth machines.

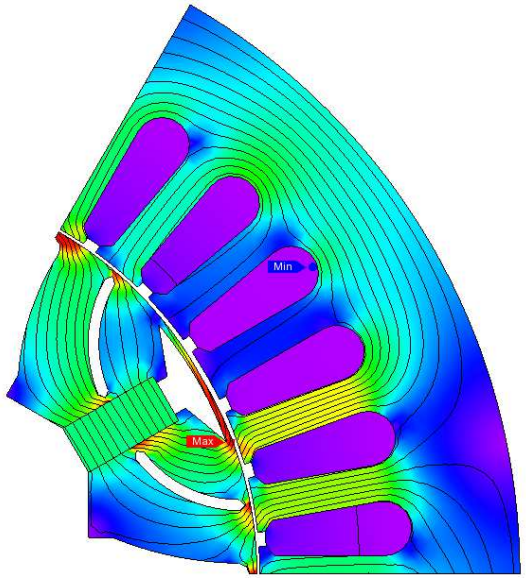
High-speed operation of an AlNiCo PMSM (variable flux machine)



- The magnet flux can be controlled by applying armature current pulses that reduces the magnet flux at high speed.

Developed AlNico PMSM



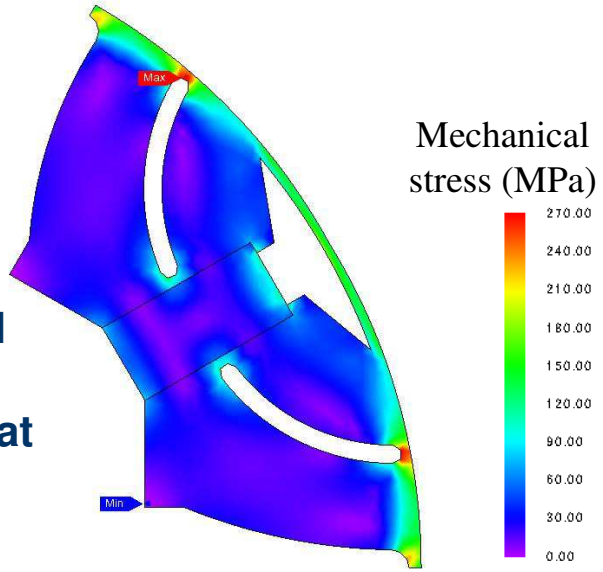


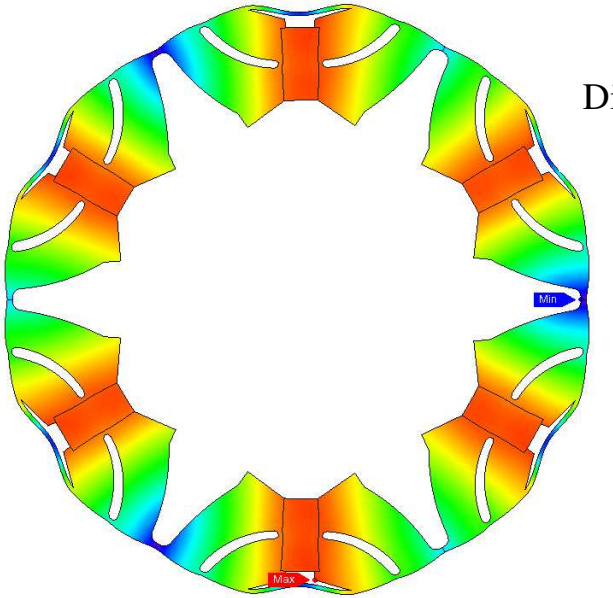
An AlNiCo PMSM is designed to have:

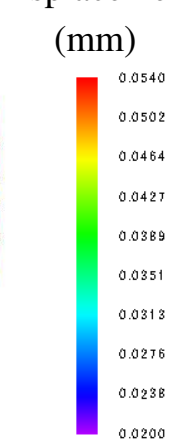
- High torque at low speeds
- Controllable magnet flux at high speeds

Structural analysis

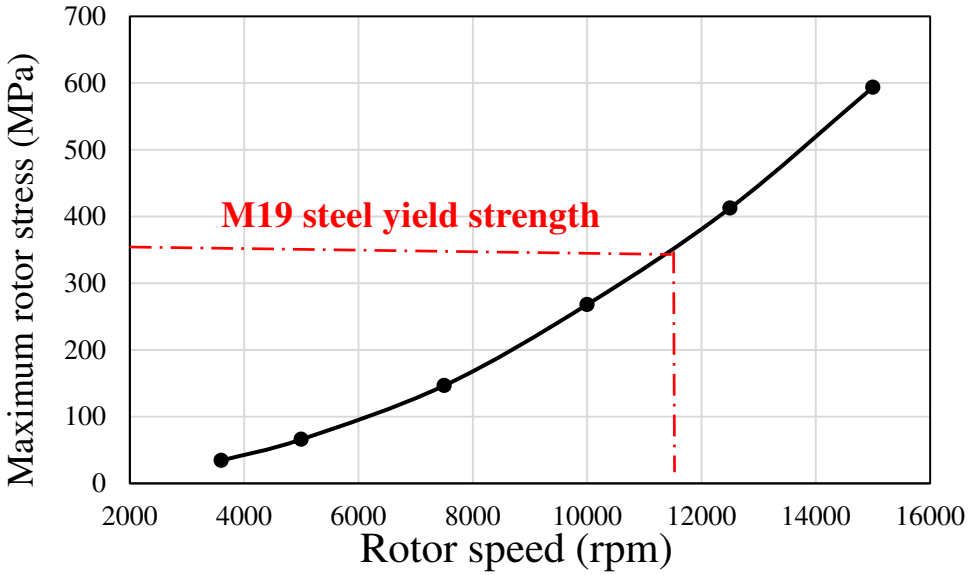
Mechanical stress distribution at 10,000 rpm





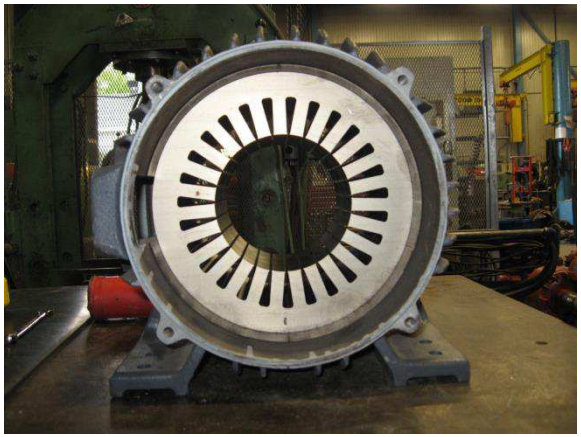


Scaled rotor deformation at maximum speed



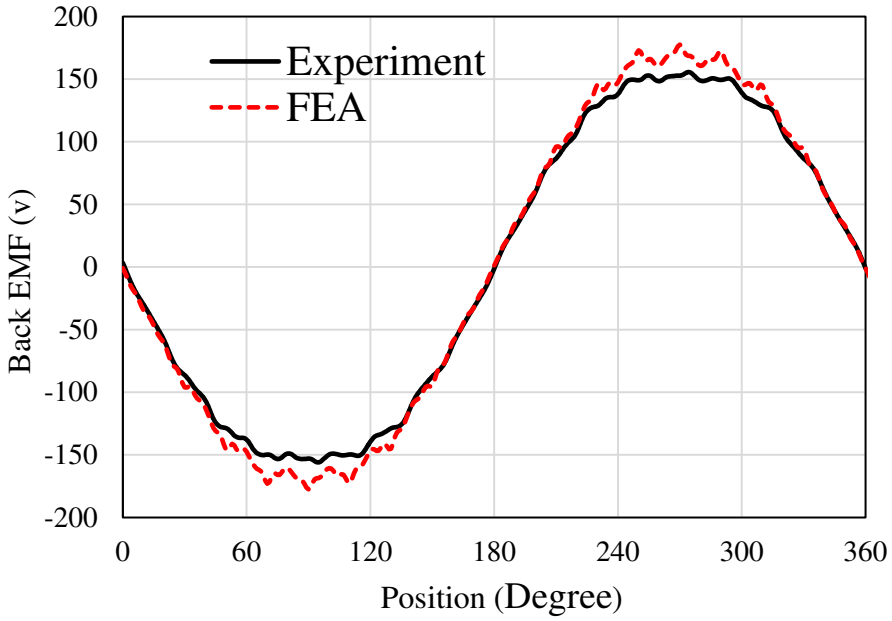
- The machine can operate safely for rotor speeds lower than 10,000 rpm.

Machine Prototyping

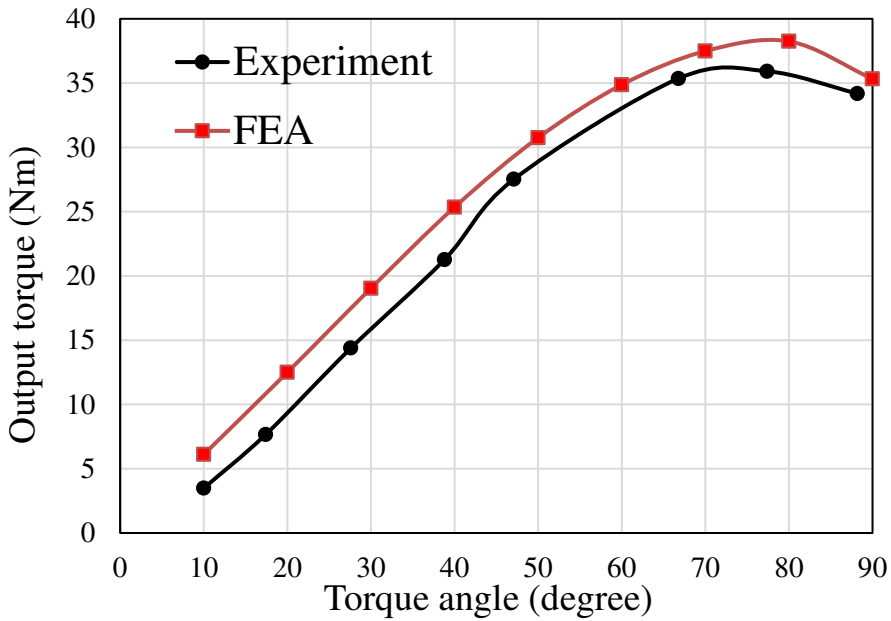


Experimental Results

Back EMF comparison at 1000 rpm



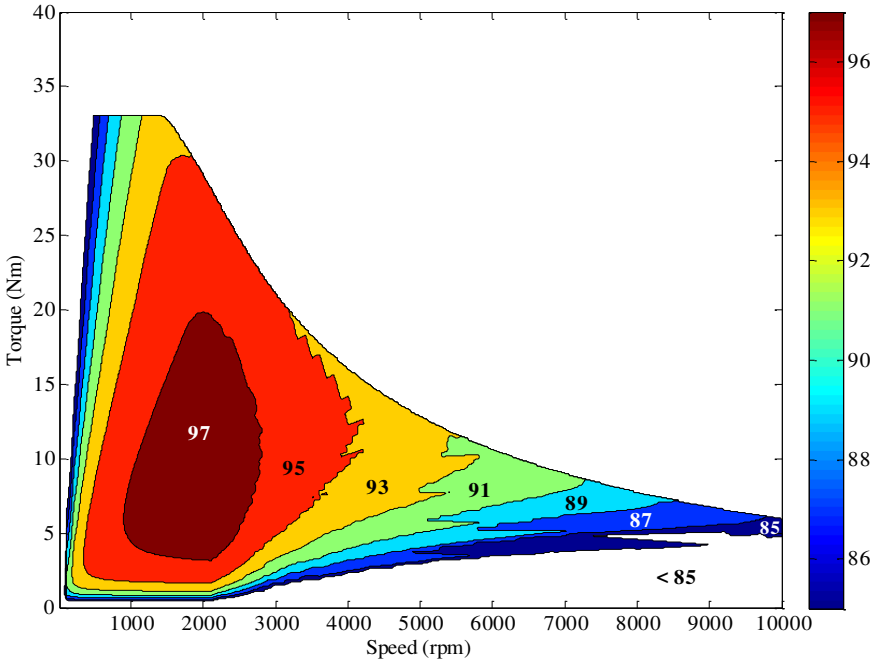
Output torque comparison at 10 A



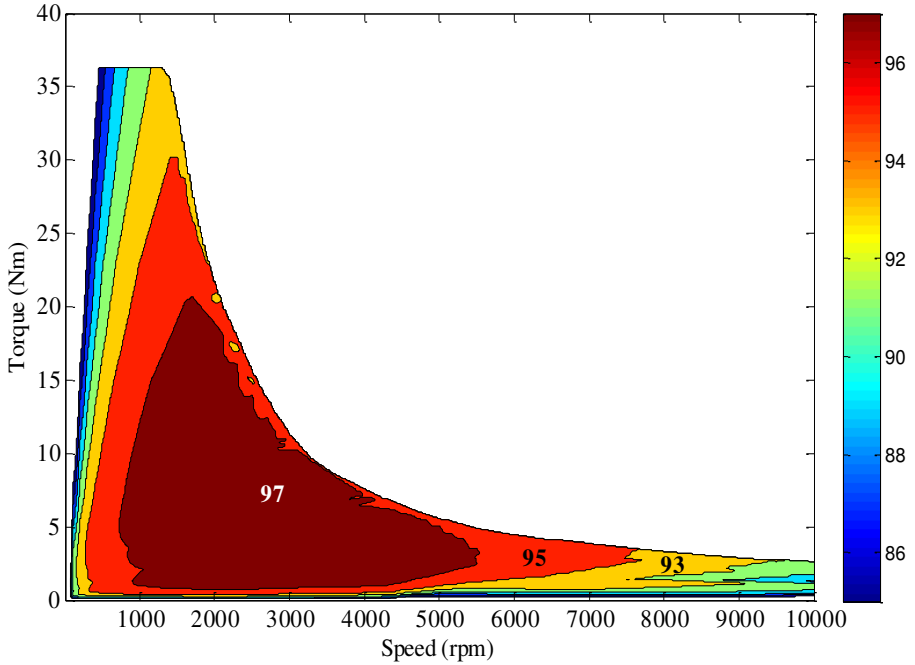
- The measured back EMF and torque at full magnetization is about 6% lower than the FEA simulation.

Efficiency Comparison

Rare-earth PMSM



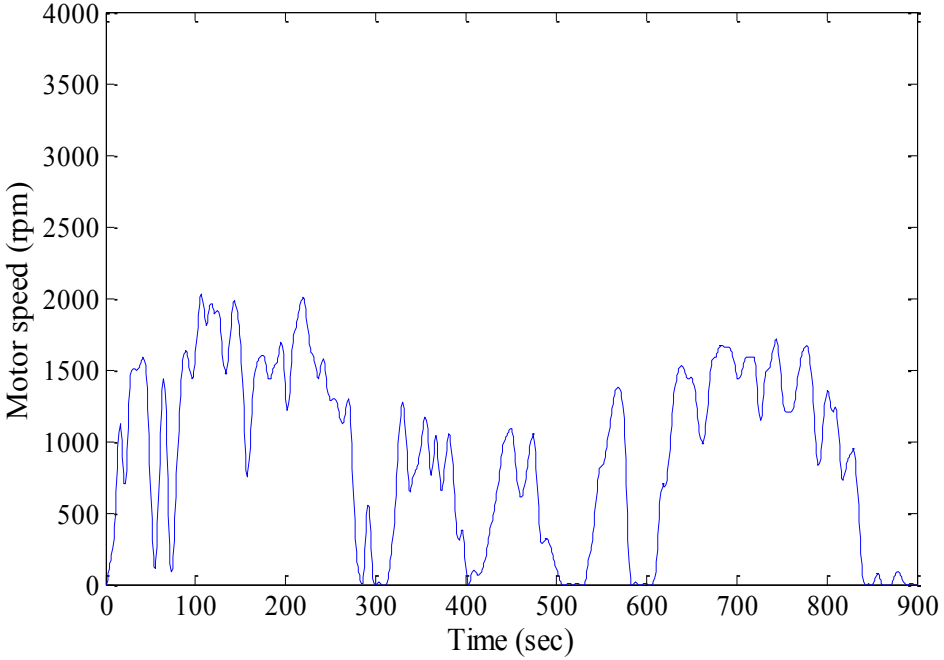
Variable Flux PMSM



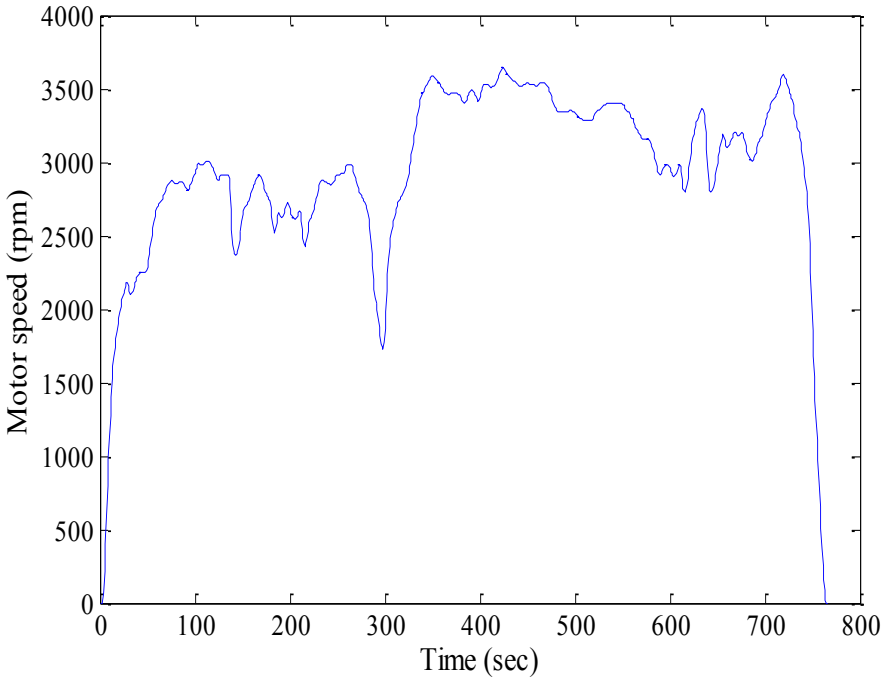
- The variable flux machine has higher efficiency at the high speed region, but it also has lower power capability at high speeds.

Electric Vehicle Simulation

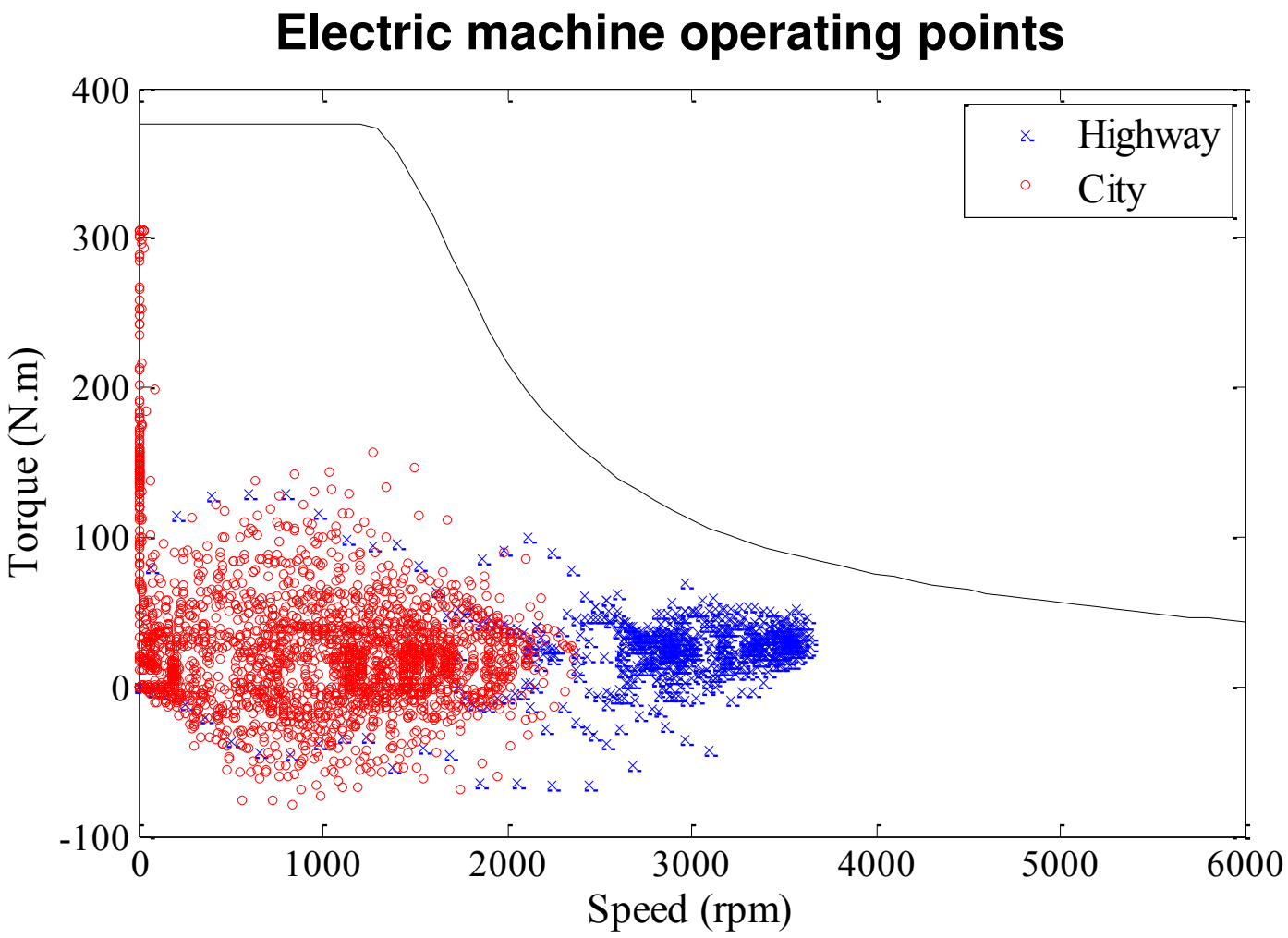
City driving cycle



Highway driving cycle

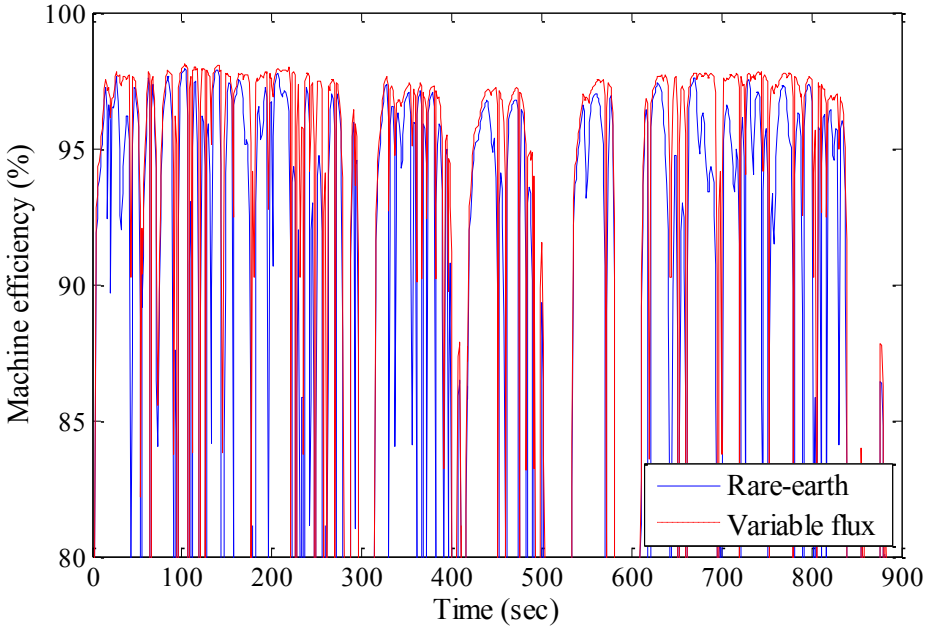


Electric Vehicle Simulation

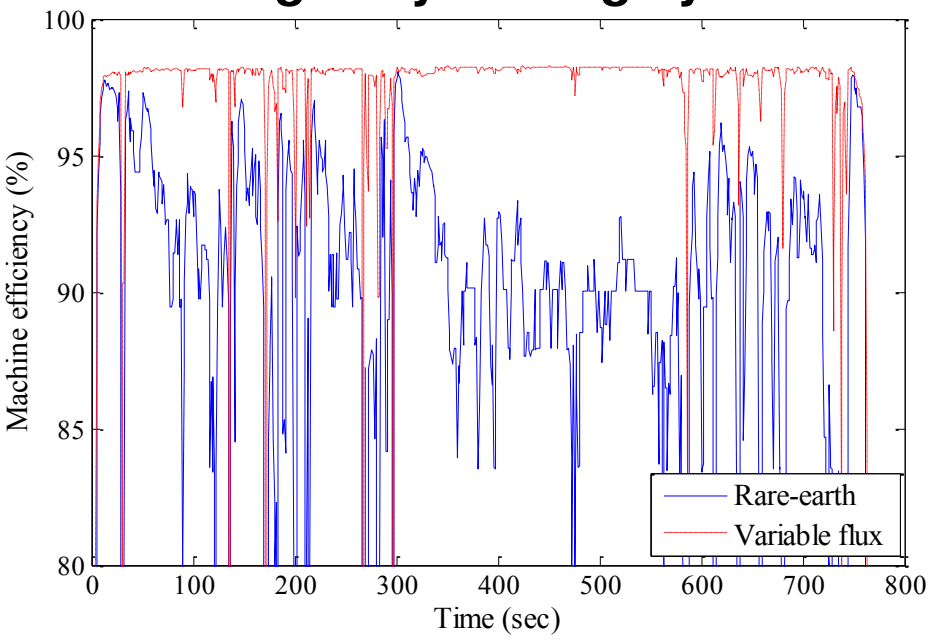


Efficiency Comparison

City driving cycle



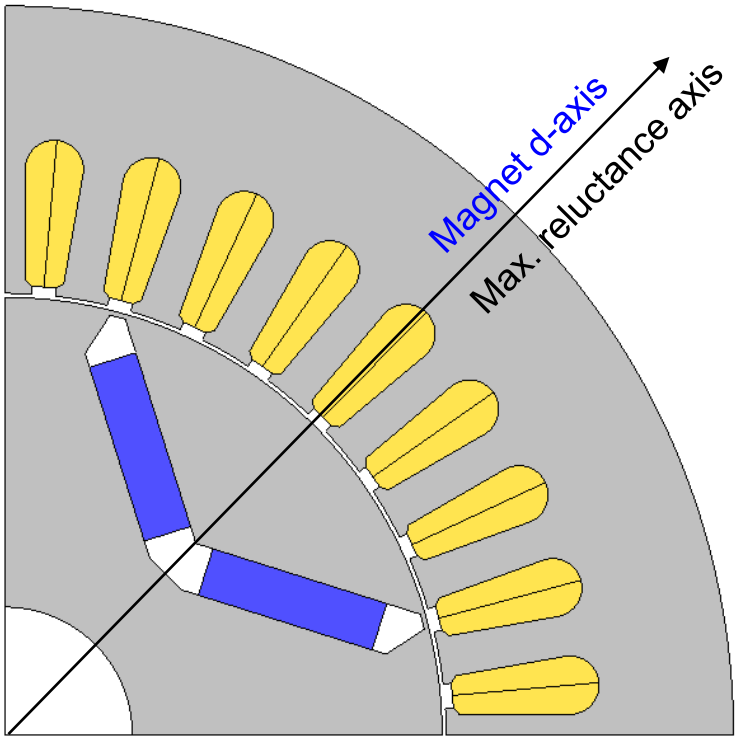
Highway driving cycle



- An average loss reduction capability of more than **35%** can be achieved by the variable flux machine.

Reduced Rare-earth PMSM

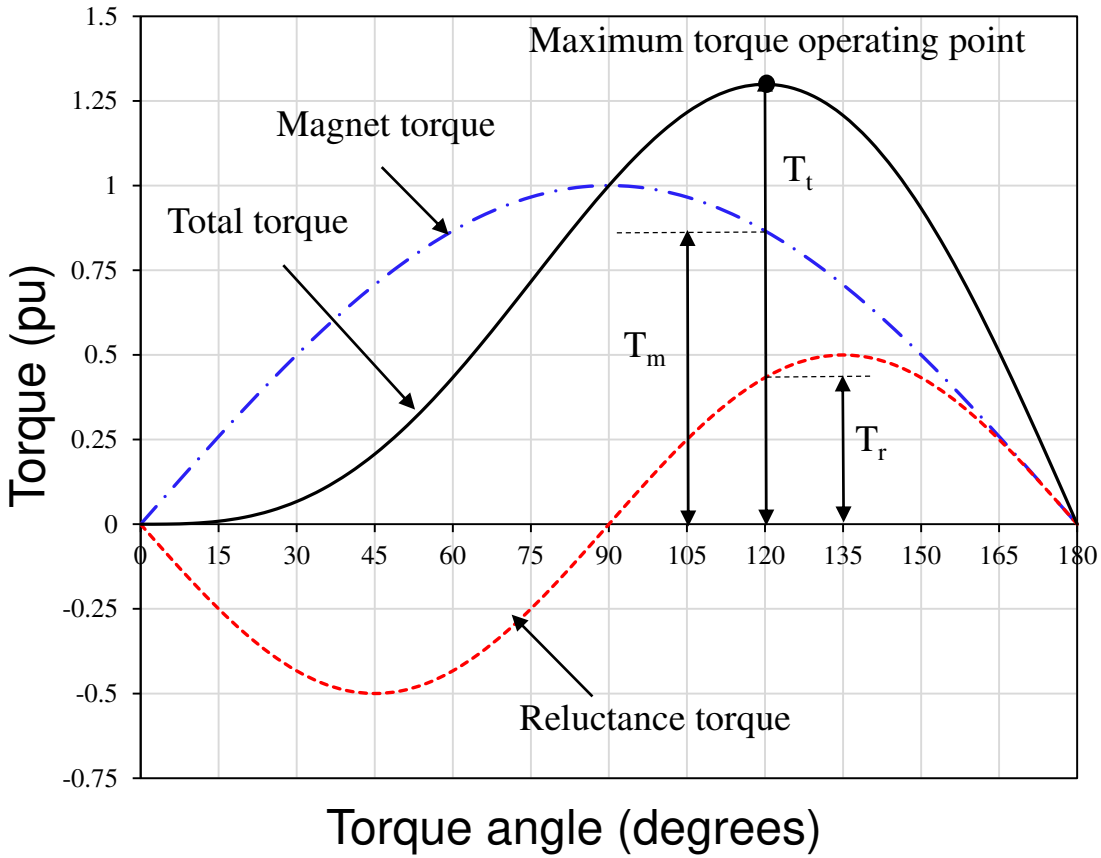
Torque Components of Interior PMSMs



- The interior PMSM can provide high torque density, as the machine can utilize both the magnet and reluctance torque components,

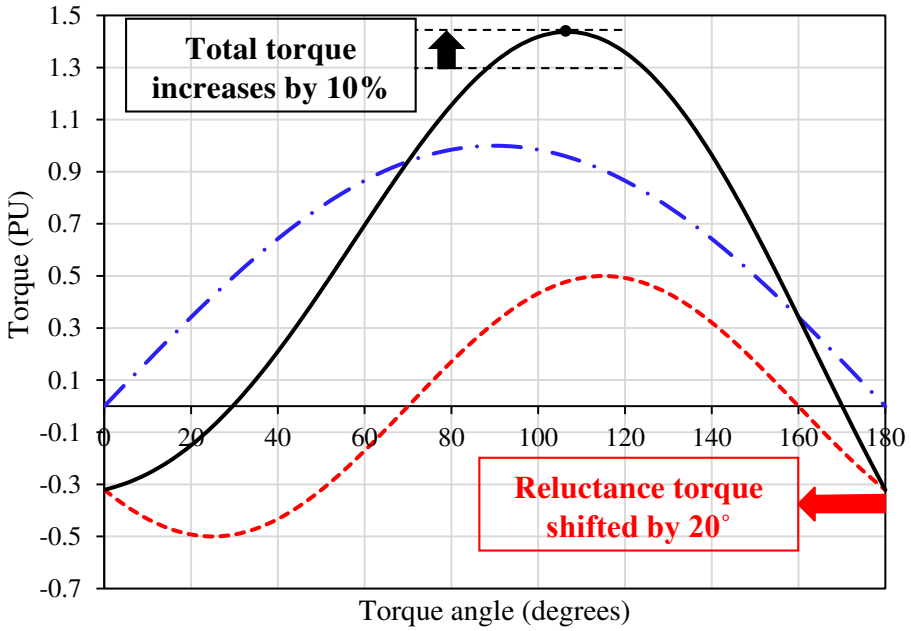
$$T_t = T_m + T_r = \frac{3P}{2}\left[\lambda I_s \sin(\delta) + \frac{1}{2}(L_d - L_q) I_s^2 \sin(2\delta)\right]$$

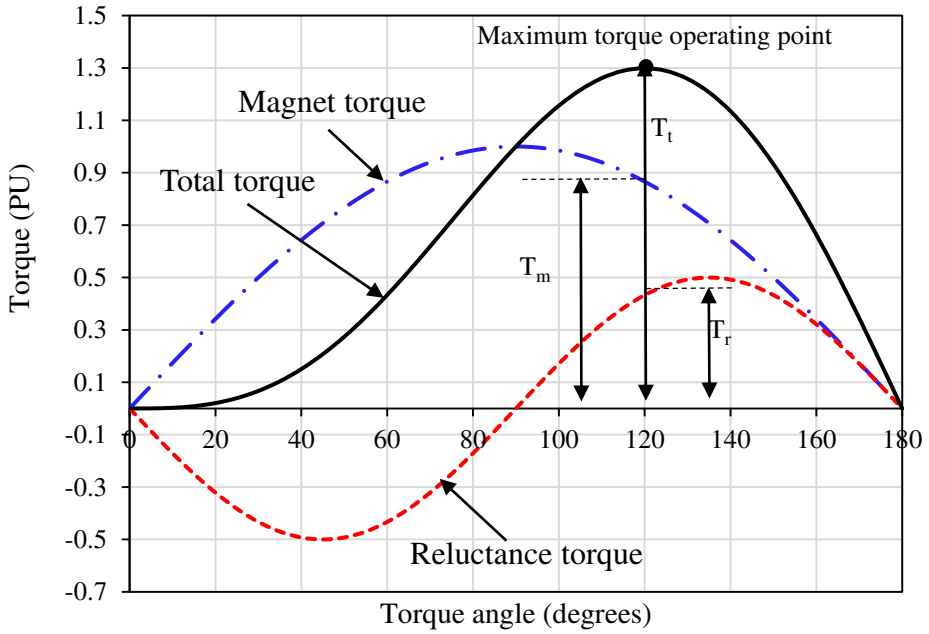
Torque Components of Interior PMSMs



- The conventional interior PMSMs can not fully utilize their torque components because of the 45˚ phase shift.

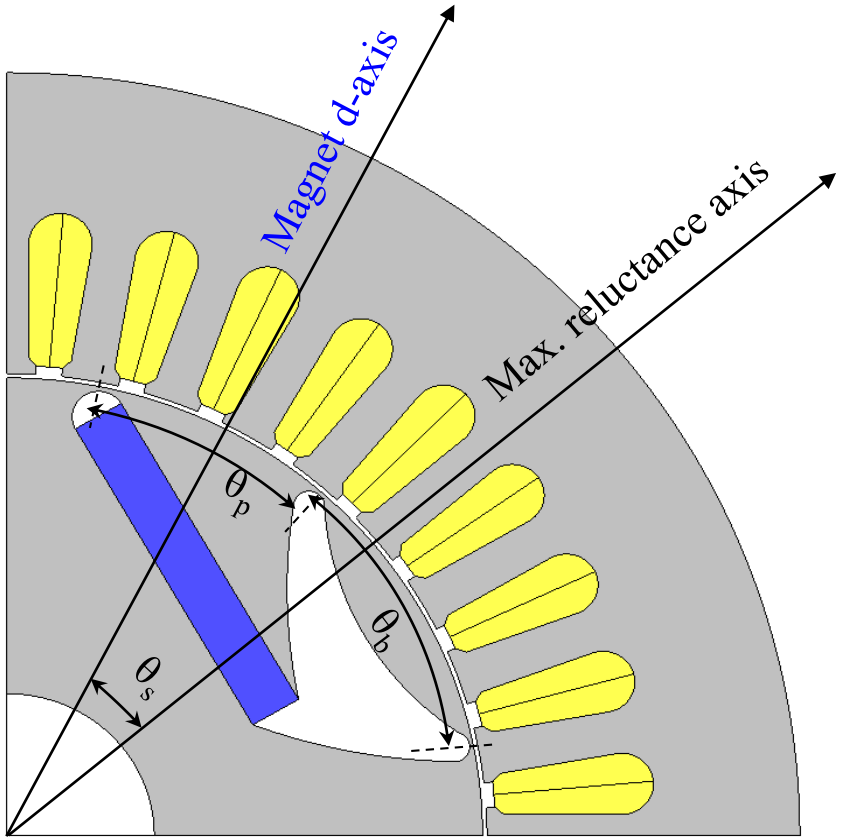
Effect of Shifting the Reluctance Torque





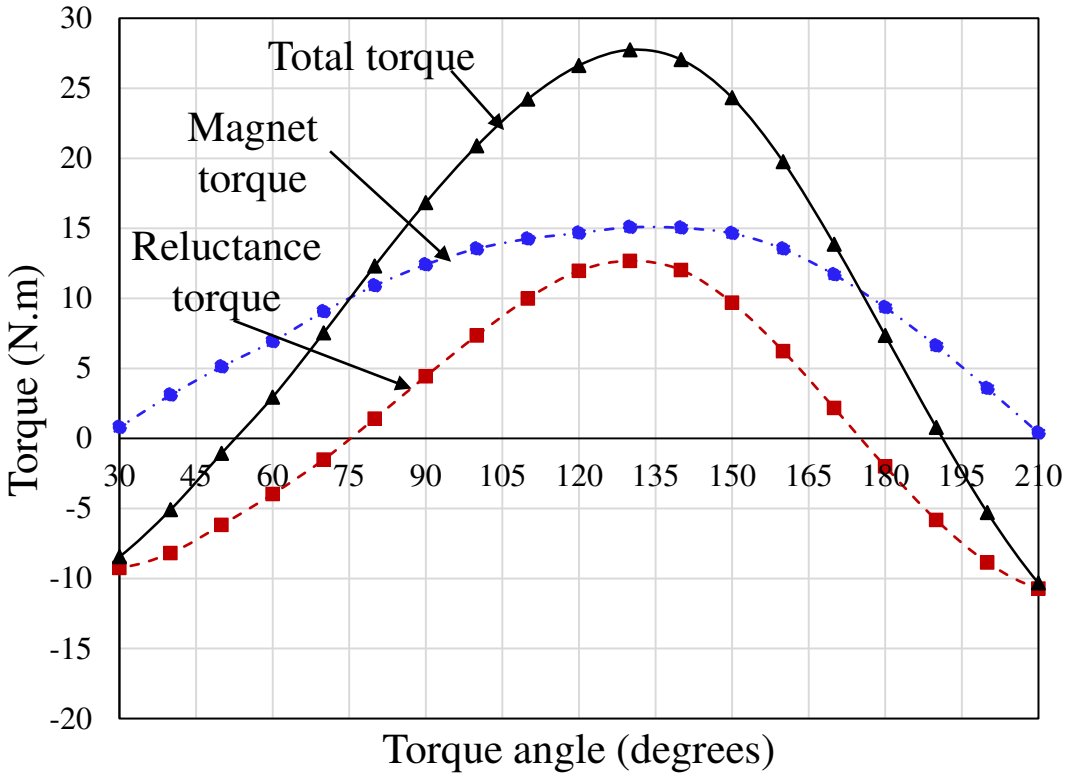
- Theoretically, if one of the torque components is shifted towards the other, the machine torque utilization will be improved.

Proposed machine design



- A PMSM is designed to shift the reluctance axis away from the magnet d-axis.
- FEA simulations are performed to optimize the shift angle

FEA simulation results



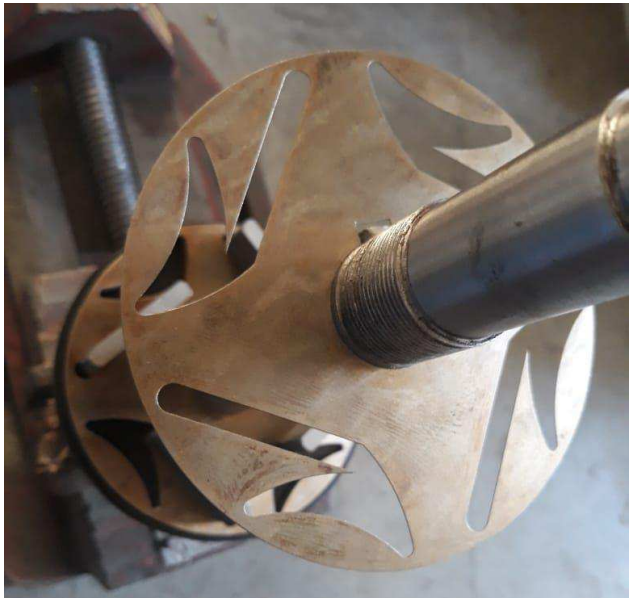
- The magnet and reluctance torques reach their maximum values at the same angle, so the machine can fully utilize its torque components.

Comparison with other PMSM configurations

	Surface PMSM	Inset PMSM	Conventional IPMSM	Proposed IPMSM
Number of poles	4			
Number of slots	36			
Stator outer diameter (mm)	180			
Axial length (mm)	125			
Magnet volume (mm^3)	**54266**	**40906**	**36750**	**30225**
Stator winding	5/6 double layer lap winding			
Rated current (A)	14.14			
Maximum total torque (N.m)	27.5			
Maximum magnet torque (N.m)	27.50	22.04	**17.04**	**14.39**
Maximum reluctance torque (N.m)	0	9.13	**14.12**	**14.42**
Torque ripple (%)	5.5	4.8	4.8	5.4
Iron loss (Watt)	45.00	82.58	59.69	61.78
Efficiency (%)	96.9	96.2	96.7	96.6

- The proposed design can reduce the magnet size by at least **20%.**

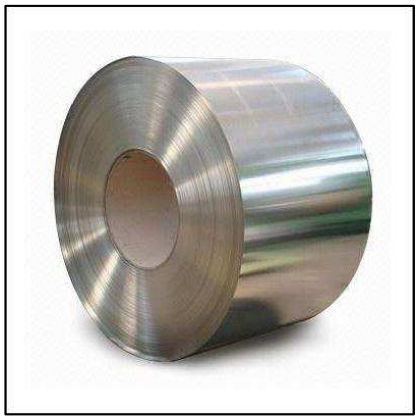
Machine Prototyping



Advanced motor design using additive manufacturing

Conventional motor manufacturing techniques

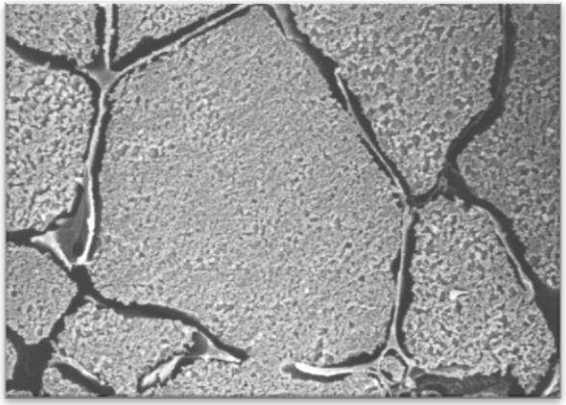
- Cold rolling Fe-Si sheets
- Applying insulating material on the sheets
- Stamping each lamination on core geometry
- Stacking lamination
- Core bonding



- The conventional motor assembly techniques are complex and lead to altering the steel magnetic properties.
- The steel laminations also limits motor designers to **2-D flux path designs**.

Magnetic materials at NRC

1. Compaction of Soft Magnetic Composite (SMC)



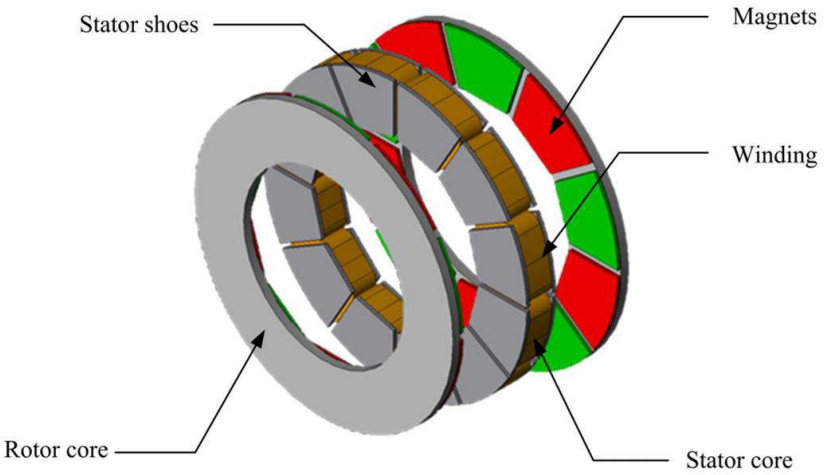
- Isotropic 3-D magnetic properties
- Ease of complex shape manufacturing
- Low cost mass production

2. Cold spray additive manufacturing of permanent magnet and SMC

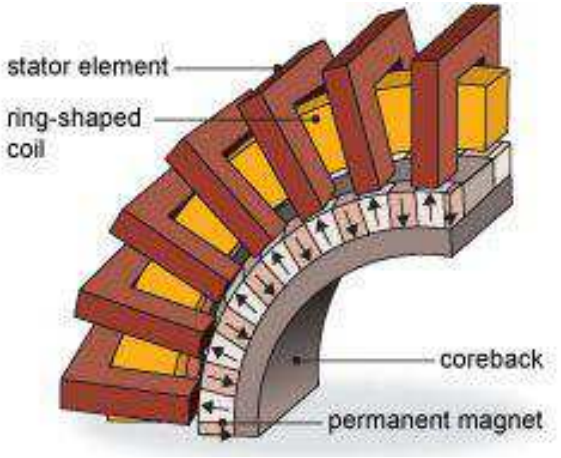
- No assembly
- Flexibility in magnet shape
- Increased thermal conductivity

Electric machine designs with 3-D flux paths

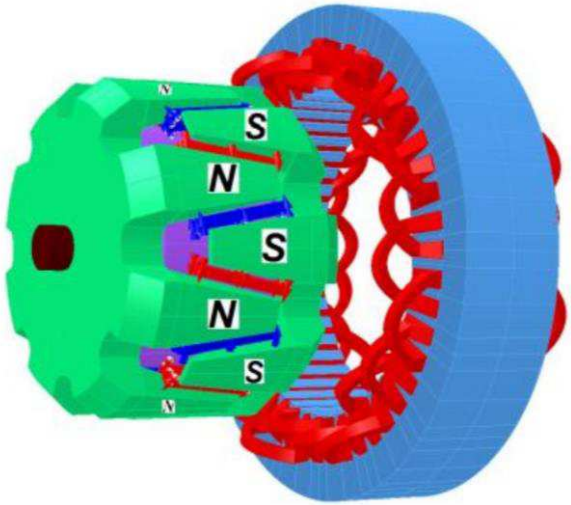
Axial flux



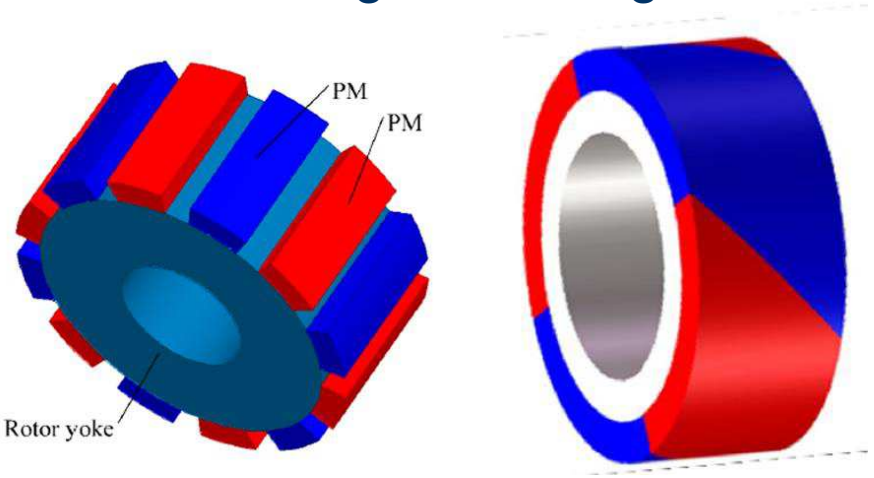
Transverse flux



Claw-pole



Magnet skewing



Conclusions

- FEA requirements for advanced motor design include;
  - Demagnetization/magnetization analysis
  - Accurate loss calculations
  - Accurate modeling of material magnetic properties
  - Structural and thermal analysis
- An efficient 3-D FEA simulation is required for optimizing complex motor structures.

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Thank you

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