Comparison of axial-flux and radial-flux-machines for use in wheel-hub-drives

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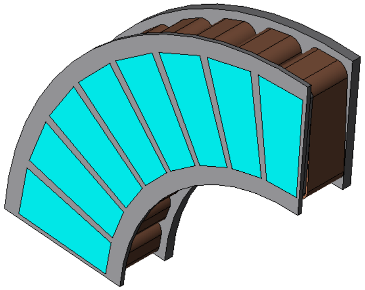
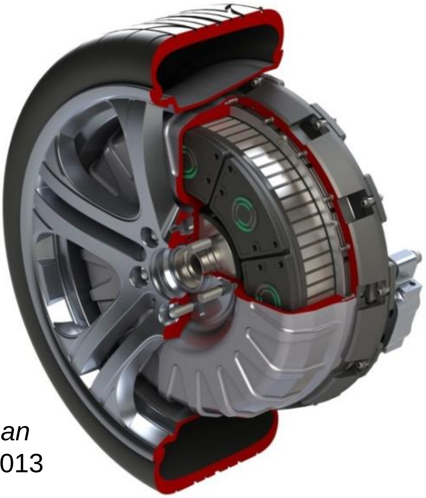


Content

Introduction
Wheel-hub-drives

Advantages

- No gear losses
- Low maintenance effort
- More space inside the vehicle
- Opportunity to use „Torque Vectoring“
- Improvement of driver assistance systems



Source: *Protean Electric Ltd*, 2013

Disadvantages

- Limited space → short axial length
- Protection against environmental influences and robust construction required
- Increase of unsprung mass
  → Highest power densities required
  → Usage of permanent magnets (PM)
  → High pole count necessary
- More expensive in comparison to central drive (at least two motors required)

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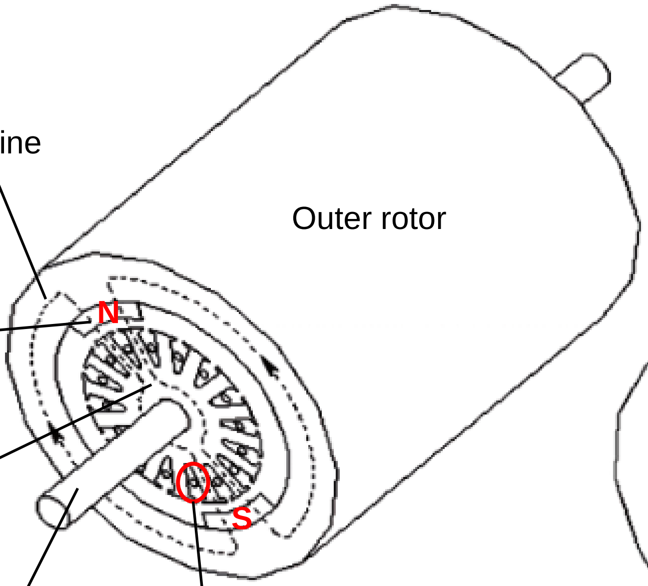
Structures and operation principles
Radial-flux vs. axial-flux-machine

Permanent magnet radial-flux-machine (RFM)



Field line

Outer rotor

Permanent magnet: 2-poles

N

S

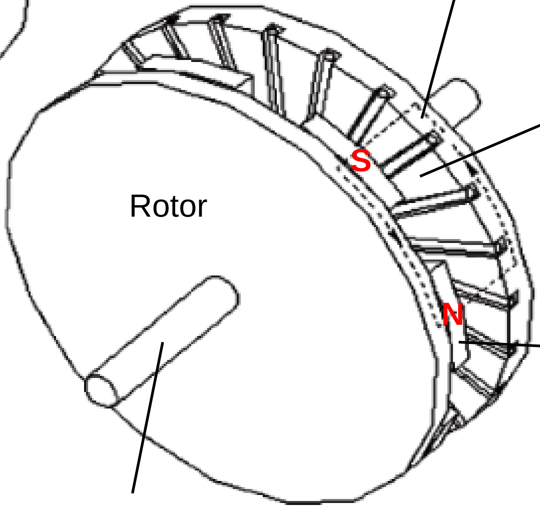
Inner stator

Shaft

Stator slot: Distributed winding

Permanent magnet axial-flux-machine (AFM)

Single sided AFM



Field line

Stator: Tooth coil winding

S

Rotor

N

Permanent magnet: 8-poles

Shaft

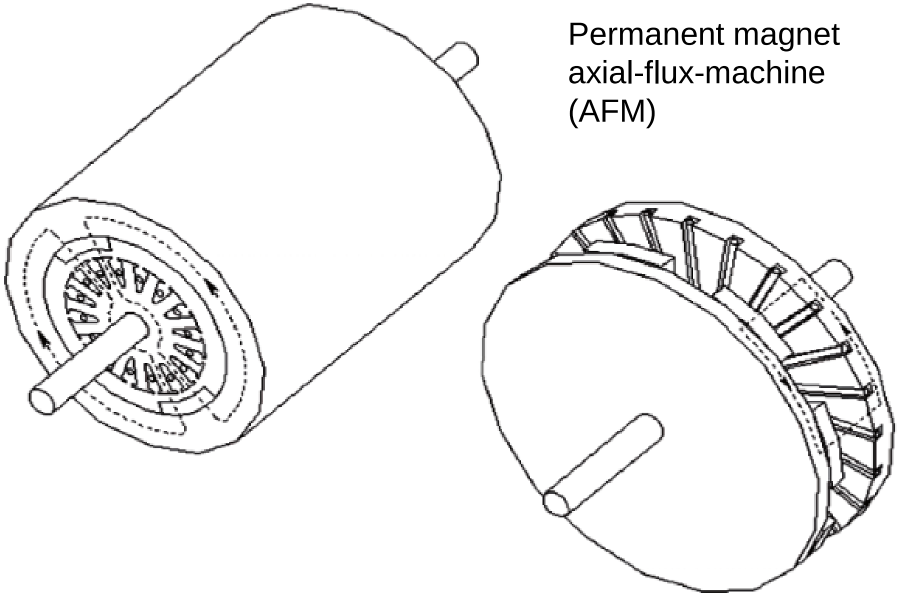
Source: *Gieras*, 2008

Structures and operation principles
Radial-flux vs. axial-flux-machine

- Direction of flux determines the machine type: radial-flux or axial-flux
- Different flux directions lead to different coil arrangements
  → different iron structures
- Radial-flux-machine:
  - Cylindrical motor structure
- Axial-flux-machine:
  - Disc-like motor shape
    → short axial length,
    ideal shape for wheel hub drive
  - Different axial-flux structures possible

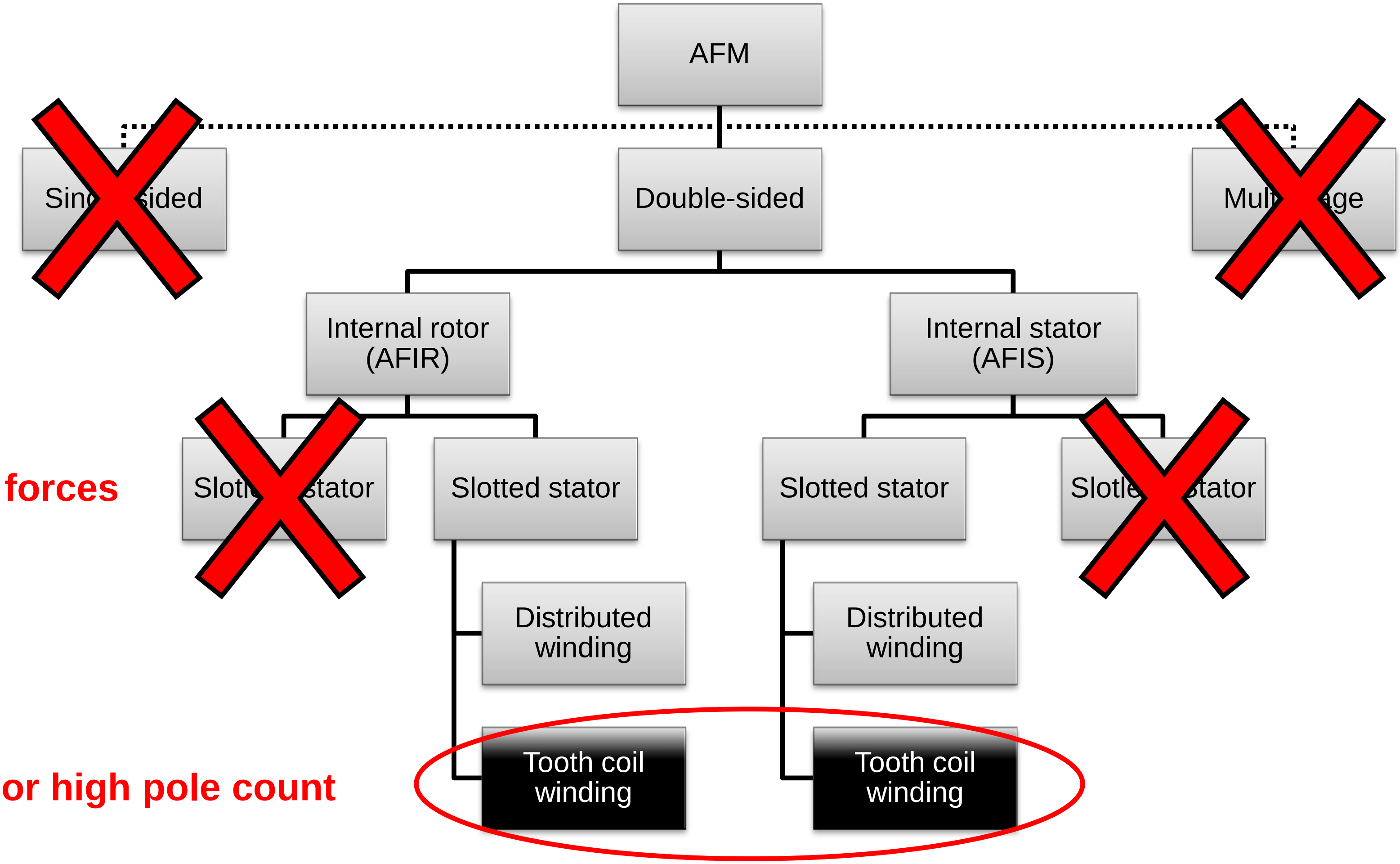
Permanent magnet
radial-flux-machine
(RFM)

Permanent magnet
axial-flux-machine
(AFM)



Source: *Gieras*, 2008

Structures and operation principles
Axial-flux PM machines (AFM)

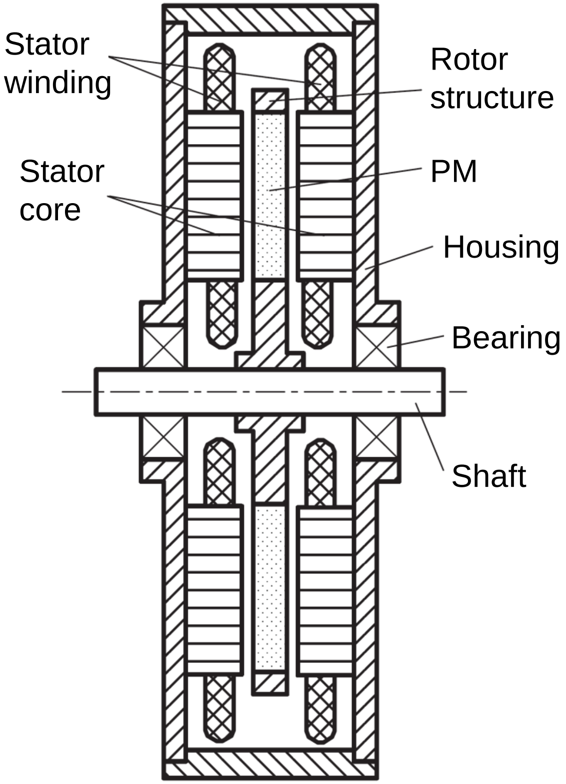


Low forces

For high pole count

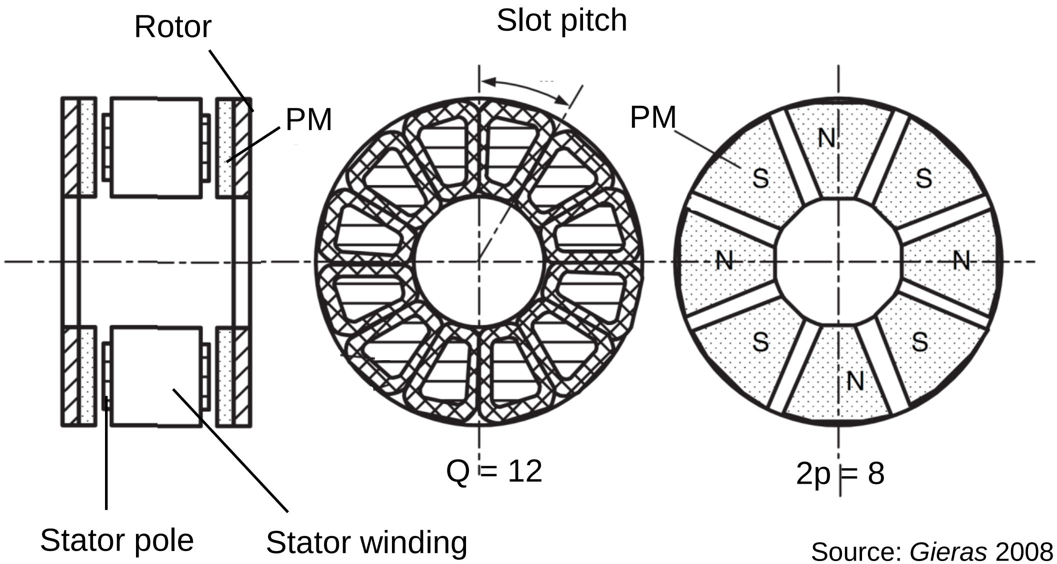
Structures and operation principles
Axial-flux PM machines (AFPM)

Internal rotor with tooth coil windings



Source: *Gieras* 2008

Internal stator with tooth coil windings



Source: *Gieras* 2008

Tooth coil winding

PM – Permanent magnet

Number of slots per pole and phase

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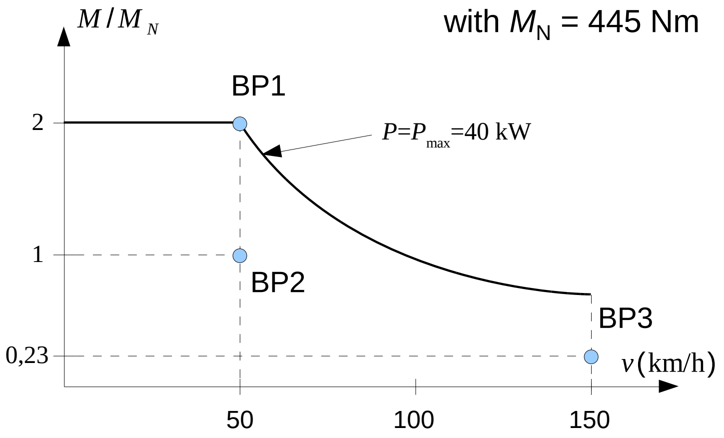
Electromagnetic design
Requirements

Motor specifications with three operating points:

BP1: Overload: 200% acceleration,
shortime S2-30s
BP2: Rated point, S2-30 min (15% climbing)
BP3: Maximum speed, field weakening 1:3
S2-30 min



with M_N = 445 Nm

	BP1	BP2	BP3
	Overload	Rated point	Maximum speed
Power *P*	40 kW	20 kW	13.5 kW
Speed *v*	50 km/h	50 km/h	150 km/h
Torque *M*	$2 \cdot M_N$	M_N	$0.23 \cdot M_N$

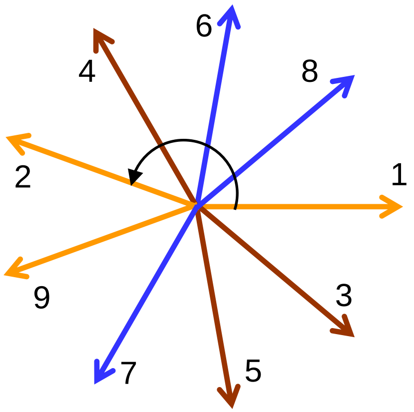
Car type:
Compact class mass ≈ 1.5 t

Electromagnetic design
Tooth coil winding

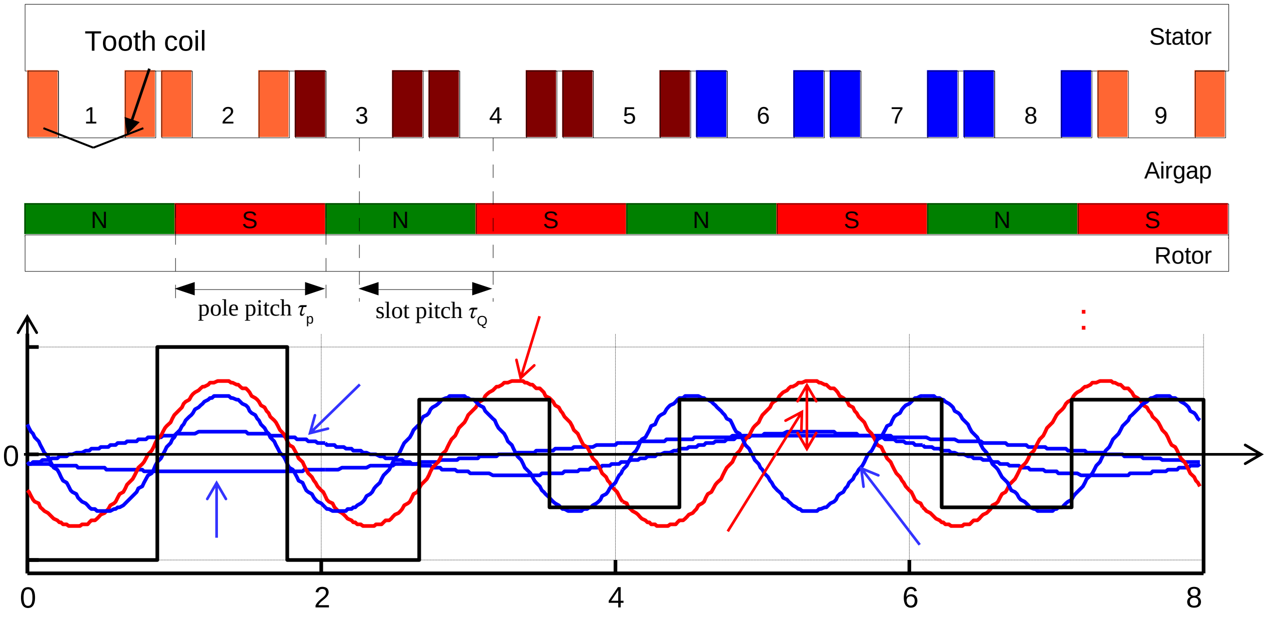
Tooth coil winding $q = 3/8$

- Number of phases $m = 3$
- Number of slots per basic period $Q_U = 9$
- Pole count per basic period $2p_U = 8$

Voltage phasors per coil:



One basic winding period:



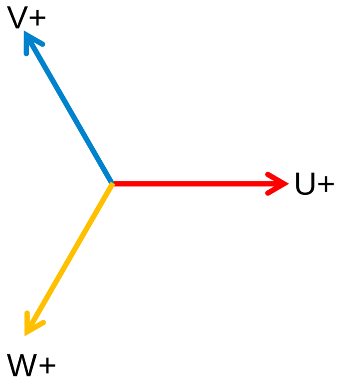
Number of slots per pole and phase:

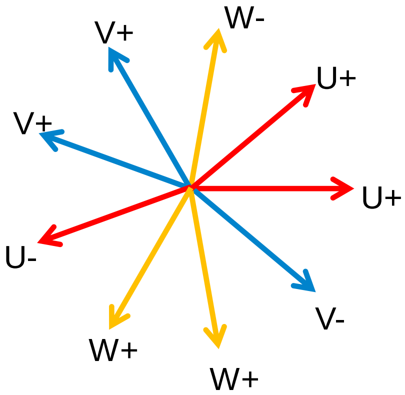
Phase shift between the voltages of neighbouring coils:

Electromagnetic design

Different slot numbers per pole and phase

Winding A: $q = 1/2$	Winding B: $q = 3/8$
Operating wave :	Operating wave : (+9%)
Harmonic content:	Harmonic content: (+157%)
(No Sub-harmonics)	(Two Sub-harmonics)





Main inductance of operating wave:

Total winding inductance:

Winding factor of operating wave:

harmonic leakage factor:

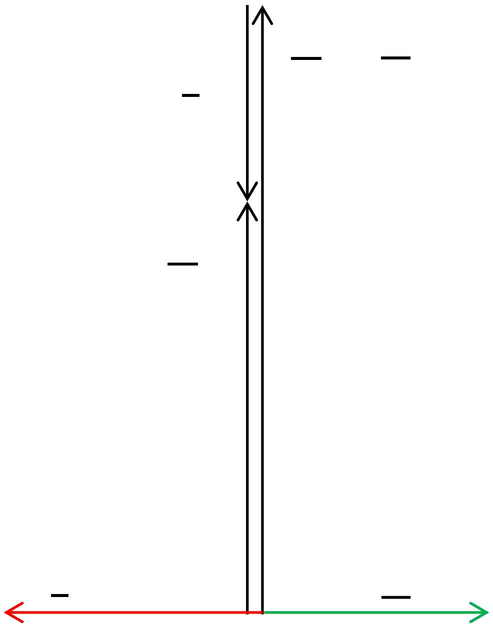
Electromagnetic design

Estimation of winding losses

P_{cu} in BP3 for pure *d*-current operation (=no torque):

	Winding A		Winding B
q	1/2		3/8
	0.46		1.18
	0.866		0.945
	1.78		
	1.78		
	3.20		

U_p: back-EMF
U_s: stator voltage
ω_s: stator frequency
I_s: stator current
B_{PM}: PM flux density



Conclusion: For dominating ohmic losses the efficiency of motor B in BP3 should be higher than for motor A due to the higher winding factor and the higher harmonic stray flux.

Disadvantage for Winding B: Due to big reduced power factor in the base speed range.

Electromagnetic design

Specific electromagnetic thrust

- Specific thrust τ for electric machines is defined as tangential electromagnetic force *F* per air-gap area :

—

- Specific thrust τ depends on current *I* and magnetic flux density B_δ in the air gap
- Current and flux density can be chosen identical for AFM- and RFM-machine

→ Identical thrust leads to a higher force for the AFM-machine and therefore to a higher power density

- For machines with short axial length (wheel-hub-drive) and ——— > 1 AFM-machines have benefits compared to RFM-machines

Electromagnetic design
Air-gap area

Area of the air-gap A_δ is different for RFM- and AFM-machines (double-sided):

$$(\qquad)$$

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With :

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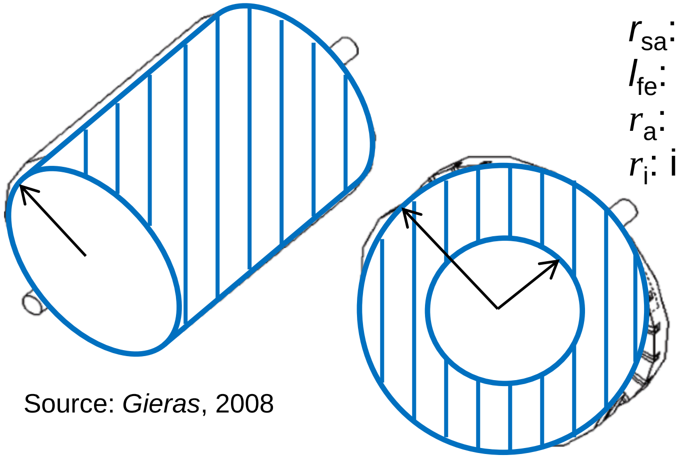
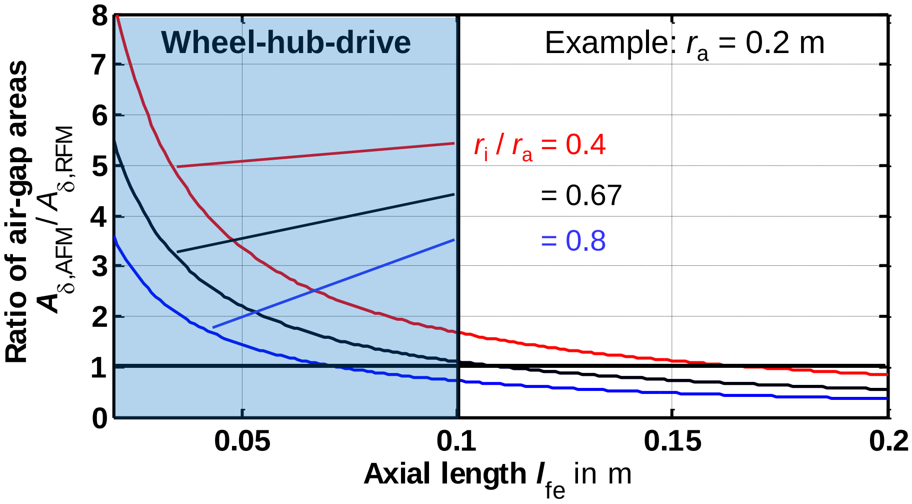

Source: *Gieras*, 2008

r_{sa}: stator outer radius
l_{fe}: iron length
r_a: outer radius
r_i: inner radius

Air-gap area A_δ

Ratio of air-gap areas over axial length



Electromagnetic design

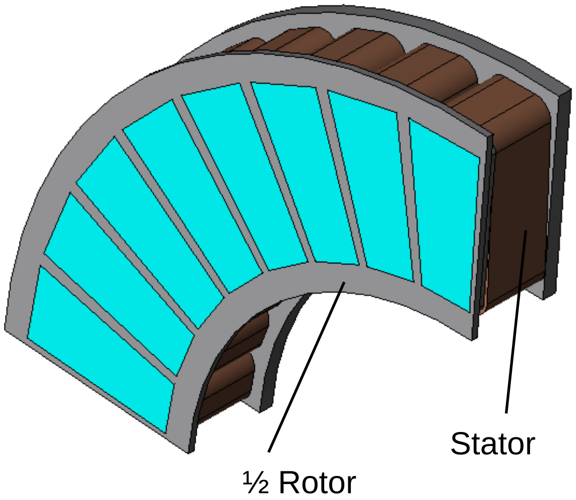
Axial-flux- vs. radial-flux-machines

- Electromagnetic designs of RFM- and AFM-machines with same basic parameters
- But: Double-sided AFM-machines → two air-gaps → double magnet height to keep fundamental air-gap flux density constant ( )
- For same torque of RFM- and AFM-machines current I_s can be reduced for the AFM-machine due to higher air-gap area A_δ → Higher efficiencies in BP1 and BP2
- But: Comparison of magnet masses m_M shows:
- Fair comparison for same magnet masses → Magnet height of AFM-machine is reduced ( )
- Lower magnet height leads to higher inductance

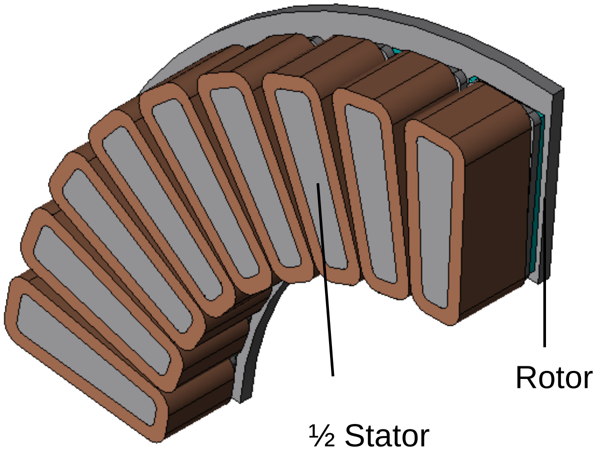
Electromagnetic design

Electromagnetic comparison

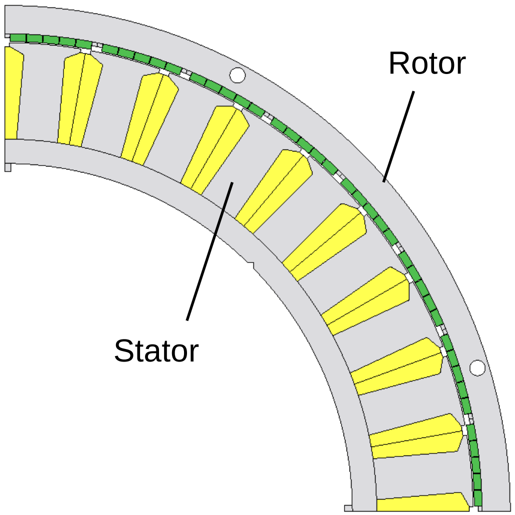
Axial-flux internal rotor



Axial-flux internal stator



Radial-flux outer rotor



Variant	Efficiency* η_{BP1}	Efficiency* η_{BP2}	Efficiency* η_{BP3}	Active mass m
AFIS	86.5 %	93.9 %	89.7 %	32.5 kg
AFIR	86.6 %	93.8 %	90.4 %	32.0 kg
RFPM	86.4%	93.9%	88.3%	32.6 kg

* Included losses: Ohmic losses, Iron losses in stator and rotor

Simulation with JMAG Designer 13.0

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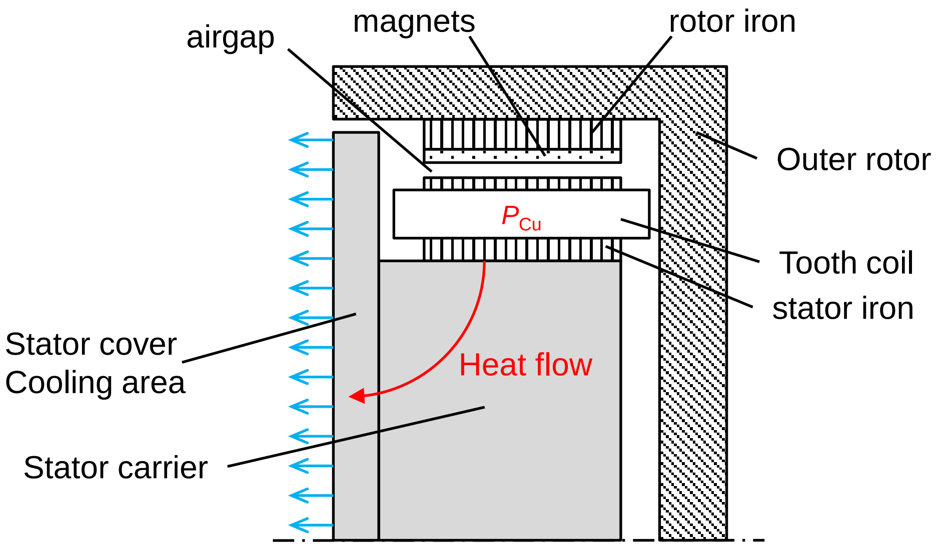
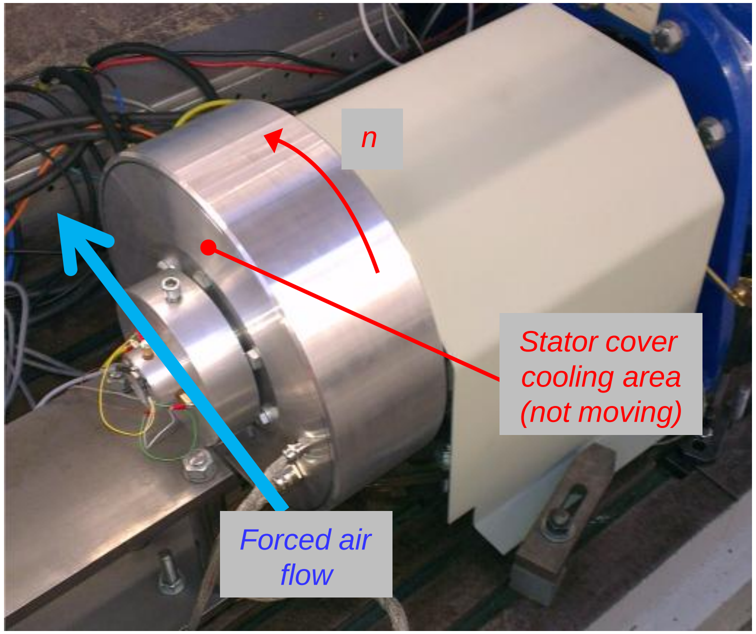
Thermal considerations and studies

Cooling concept for RFM

- Air-cooling by the natural airflow because of the moving vehicle (v_N = 50 km/h)
- Totally enclosed machine

  → Stator-cooling mainly on one side
- Heat transfer coefficient for moving air on metallic surface (heat convection):





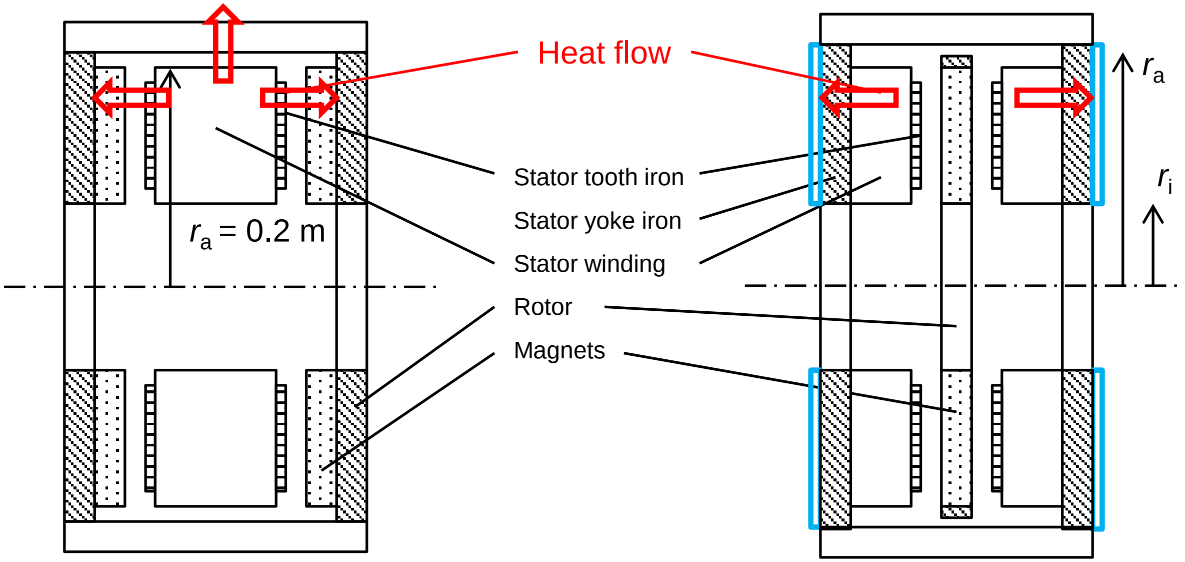
Thermal considerations and studies

Cooling surfaces of axial-flux-machines

Cooling capabilities of axial-flux internal stator- and axial-flux internal rotor machines:

Axial-flux internal stator

Axial-flux internal rotor



direct stator cooling surface A_{cool}

(——

For the axial-flux internal stator machine no direct stator cooling surface exists

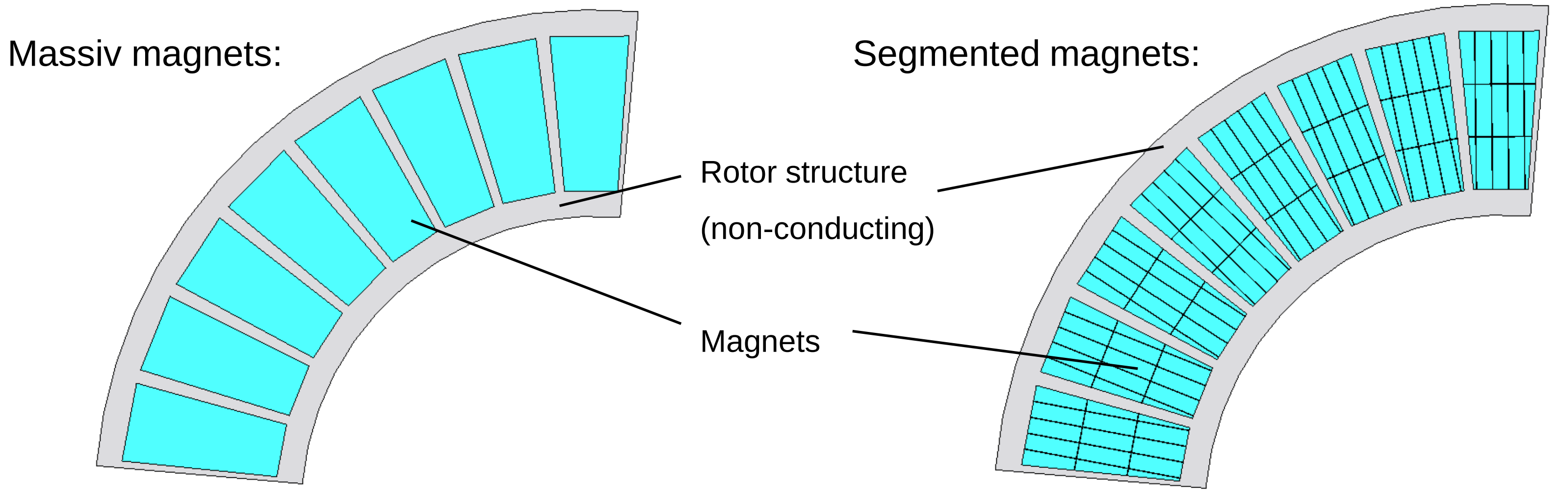
- Axial-flux internal rotor: winding temperature rise
- Axial-flux internal stator: winding temperature rise !!!

Thermal considerations and studies

Losses in magnets in AFIR-machine

Highest losses in the magnets occur in BP3 due to high speed and therefore high rotor tooth ripple frequencies

→ FE-Study of losses in magnets $P_{d,M}$ via time-step non-linear simulation with sinusoidal stator currents for segmented and unsegmented magnets



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Conclusion

- Permanent magnet synchronous machines as
  a) Radial-flux outer rotor-, b) axial-flux internal rotor- and c) axial-flux internal stator-machine have been electromagnetically designed for use in wheel-hub-drives for compact class E-cars
- Special focus was given on number of slots per pole and phase *q* in the stator
- Efficiency and mass were compared
  → The designed axial-flux-machines show slight advantages in comparison the radial-flux-machine especially at high speed (BP3)
- The AFIS-machine requires expensive thermal class and is therefore not appropriate for air-cooling!
- Temperature rise in winding of AFIR-machine is satisfactory, but
  → Magnets should be segmented to reduce the losses and the temperature in the magnets

Thank you for your attention!!!