LUT University

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HIPO Summer School 24.5.2023 - jjp

ELECTRICAL MACHINES FOR EV PROPULSION APPLICATIONS

State of electrical vehicle propulsion motor development.

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Introduction

Setting new directions and targets for cost reduction in electrical vehicle traction drive production

- US Department of Energy: an electric traction drive system, at a cost of $6/kW for a 100 kW peak system
- European Commission: a new propulsion motor, 23 kW/kg and 7 kW/litre, with 60% reduced permanent magnet (PM) volume

Examples of R&D targets in the US

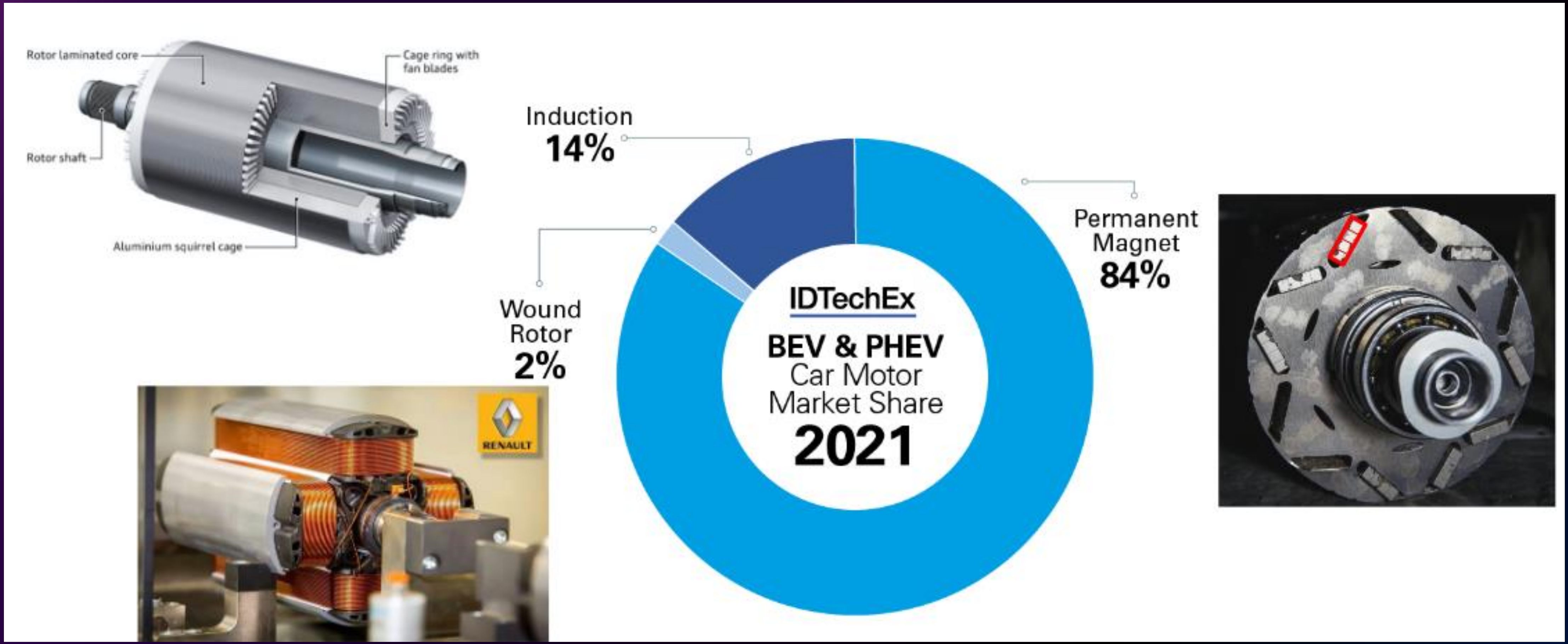
Electric Traction Drive Systems

Year	2020	2025	Change
Cost ($/kW)	8	6	25% cost reduction
Power Density (kW/l)	4	33	88% volume reduction

Power Electronics

Year	2020	2025	Change
Cost ($/kW)	3.3	2.7	18% cost reduction
Power Density (kW/l)	13.4	11	87% volume reduction

Market shares for EV car motors
-this will change in the future?



EVs, car propulsion motor data

Car and motor type	Max torque/Nm	Max speed/rpm	Specific torque Nm/kg	Torque density Nm/l	Peak power/kW	Peak specific power kW/kg	Peak power density kW/l	Cooling method
Prius 2010, IPMSM	205	13500	5.5	16.4	60	1.6	4.8	Housing jacket cool. with oil
Sonata 2011, PMSM	205	6000	7.5	20.5	30	1.1	3.0	Housing jacket cool. with oil
Tesla Roadster, 2012, IM	370	14000	7.0	-	215	4.05	-	Inner forced air + finned housing + outer fan
Nissan Leaf, 2012, IPMSM	280	10390	4.8	15.1	80	1.4	4.4	Housing jacket cool. with water ethylene glycol
Tesla S 60, IM	430	14800	-	-	225	-	-	Housing jacket cool. + shaft cool.
BMW i3, 2016, IPMSM	250	11400	6.0	18.2	125	3.0	9.1	Housing jacket cool. with oil
GE Global research, IPMSM	180	14000	5.1	18.6	55	1.5	5.7	Housing jacket + end winding spray + rotor cooling
Yasa 750, Axial Flux PMSM	800	-	21.6	-	180	4.86	-	Inner armature liquid cooling
Koenigsegg, Quark, Raxial Flux PMSM	600	9800	20	-	250	8.3	-	Inner armature liquid cooling

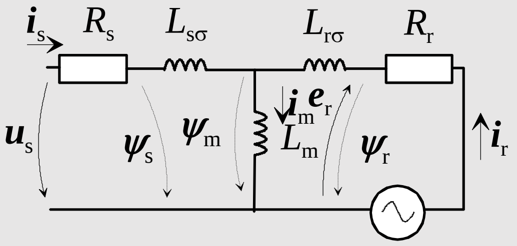
Electromagnetic basics

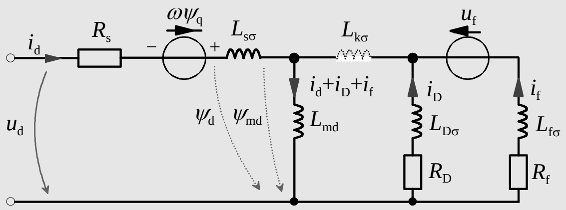
The main purpose of an electrical machine drive is to produce the torque needed at a desired speed

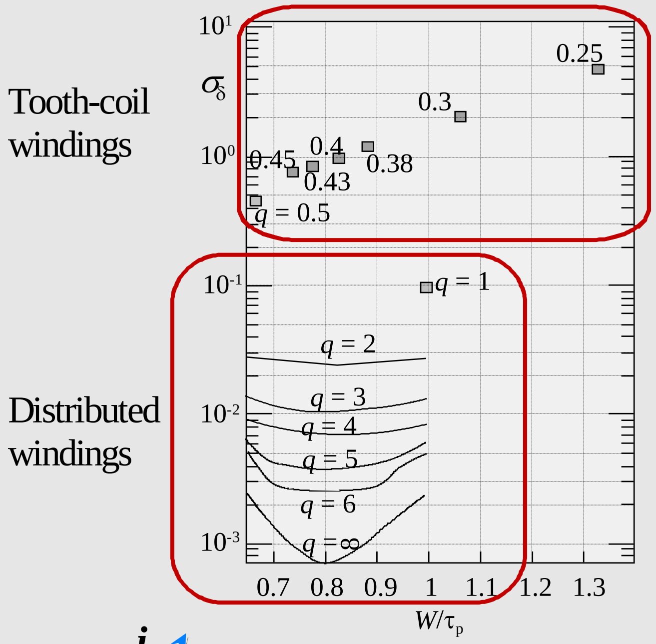
- Torque producing Maxwell stress
- Motor parameters
- Motor behaviour
- ICE vs. EM propulsion

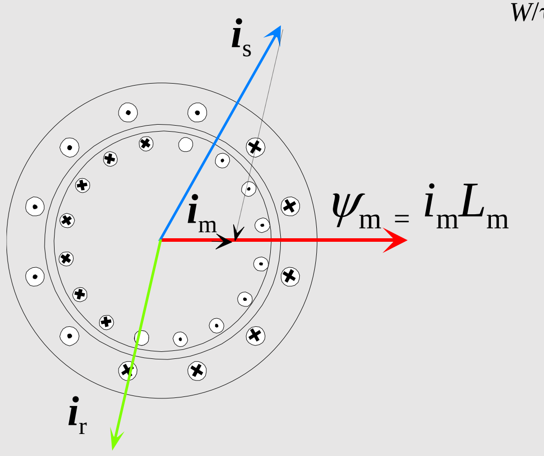
Electromagnetic basics

- $\sigma_{Ftan} \sim A \times B.$
- $T = 2\sigma_{Ftan} V_r$
- $C \sim T \sim V_r$
- $P = \Omega T$
- $L_m = \frac{mD_\delta}{\pi p^2 \delta_{ef}} \mu_0 l' (k_{ws1} N_s)^2$
- $f = pn$
- $T_e = \frac{3p}{2} \boldsymbol{\psi}_s \times \boldsymbol{i}_s = \frac{3p}{2} \boldsymbol{\psi}_m \times \boldsymbol{i}_s$
- $\eta_r \approx 1 - s$
- $P = 3\left(\frac{U_{sph} E_f}{\omega_s L_d} \sin\delta + U_{sph}^2 \frac{L_d - L_q}{2\,\omega_s L_d\, L_q} \sin 2\delta\right)$

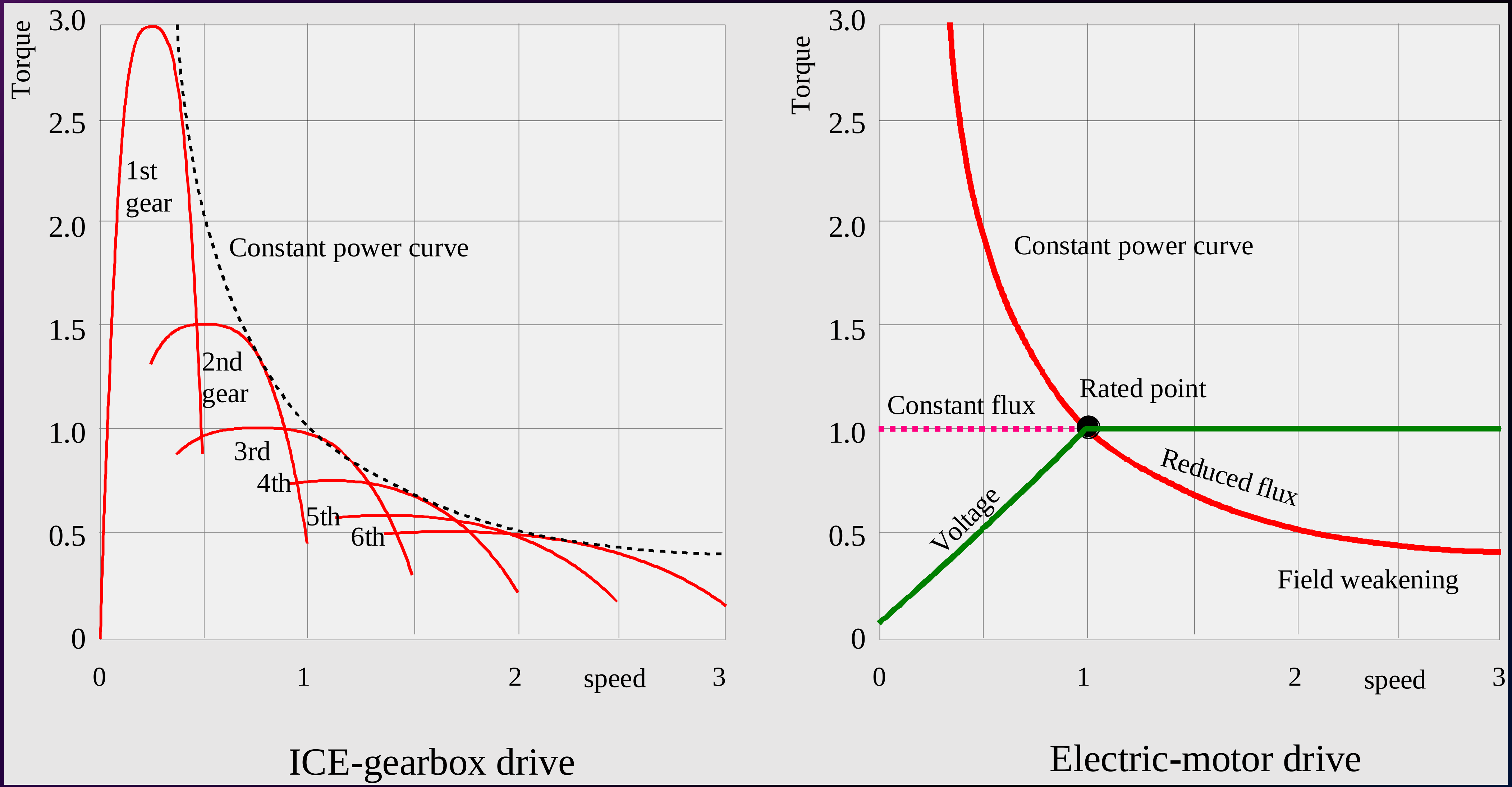




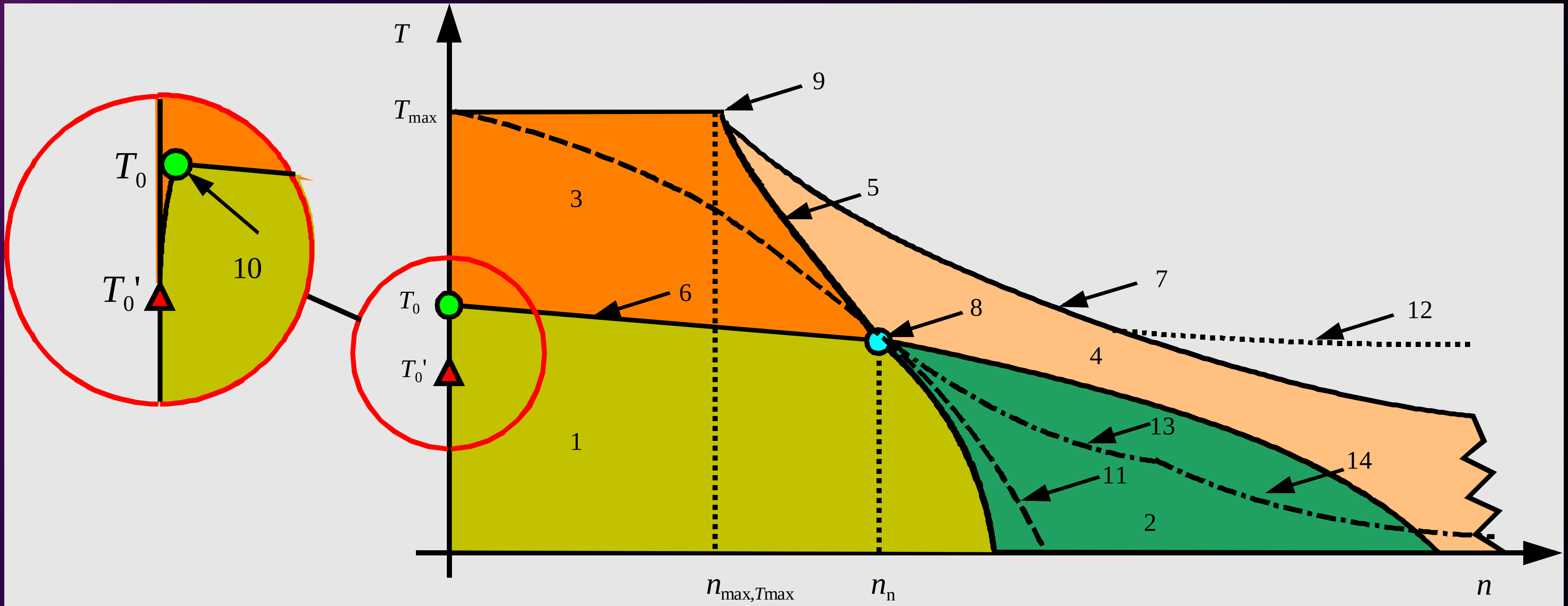




ICE vs. EM propulsion



In EVs field weakening is essential



1. PMSM, IM, SM: S1 duty
2. Moderate L_s PMSM: S1 duty with field weakening (green)
3. PMSM, IM and SM: S3 duty, cycle duration should not exceed 10% of the thermal time constant
4. Moderate L_s PMSM, SM: S3 duty with field weakening, cycle duration should not exceed 10% of the thermal time constant
5. PMSM: Voltage limit characteristic
6. PMSM, SM, IM: limit characteristic for S1 duty in constant flux range
7. Voltage limit characteristic with field weakening
8. Rated operating point at T_n, n_n, I_n
9. Operating point at T_{max}, I_{max}, $n_{max,Tmax}$
10. PMSM, SM: Torque T_0 at a low speed n (derating of power electronics close to DC)
11. Voltage limit of low synchronous inductance PMSM
12. Synchronous motor can deliver rated torque temporarily in the field weakening
13. Field weakening of IM with constant power
14. Field weakening if IM at high-speed area

Examples of current traction motor technologies

IMs and PMSMs with embedded magnets are the dominant motor technologies used in EV propulsion.

- Volkswagen ID4
- Mercedes Benz EQA
- Renault Zoe
- BMW iX M60

VW ID4 IM and VW ID4 PMSM

Rear-axle 8-pole PMSM

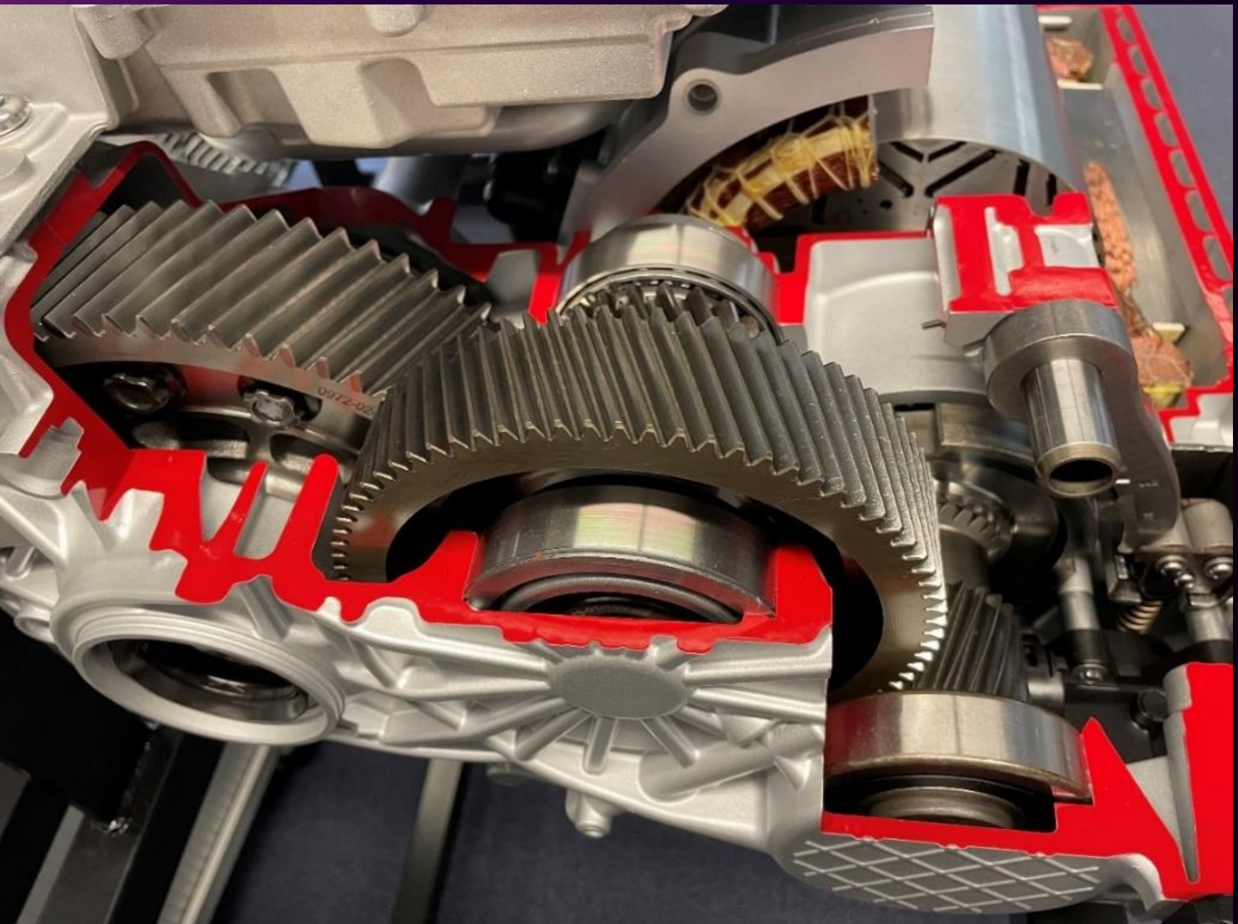
Front-axle 8-pole IM with 80 kW peak power

WHY 8-POLE VERSIONS?

109–150 kW power, 310 N·m max torque, 16,000 rpm max speed

MB EQS

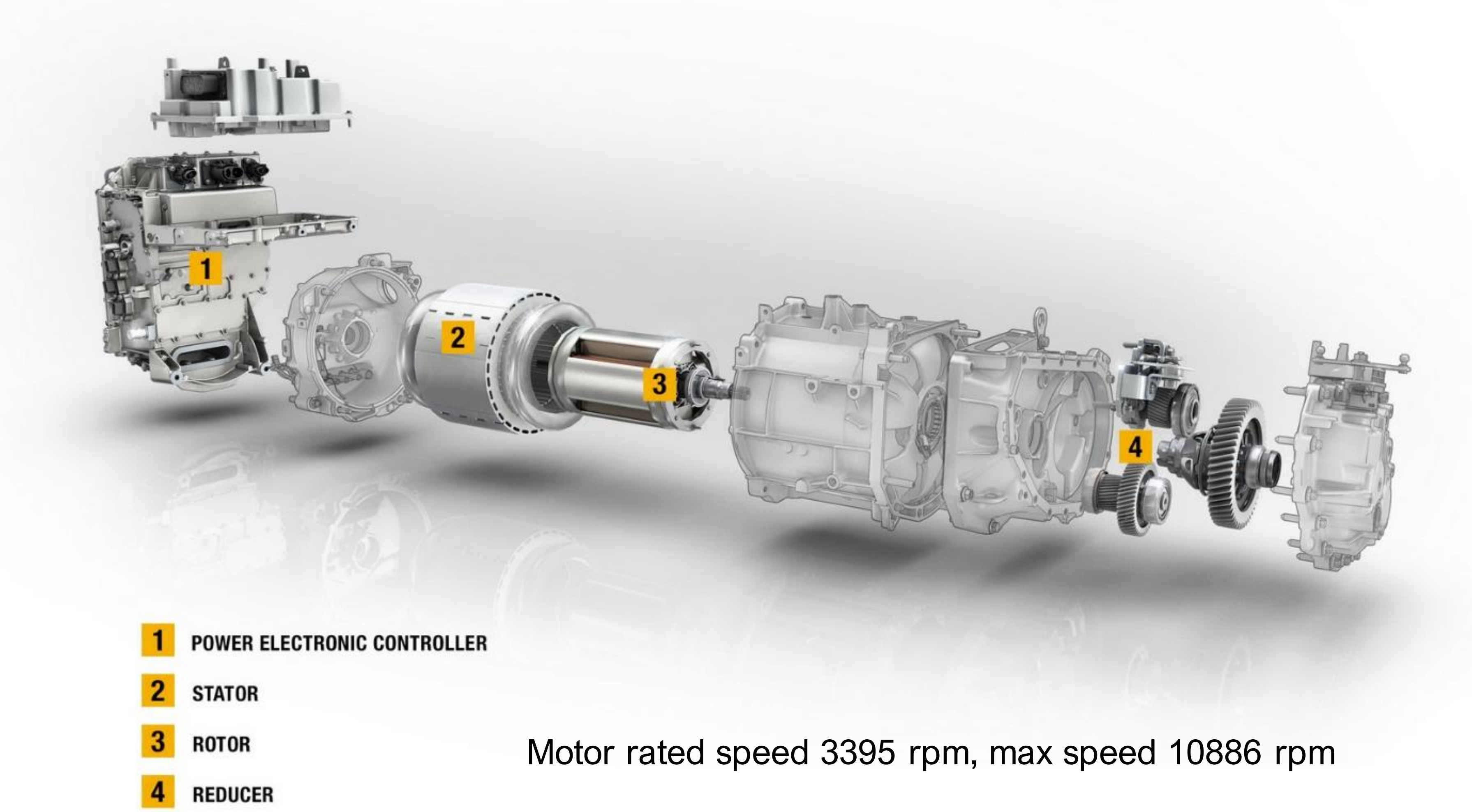
Rear-axle 8-pole 245 kW peak PMSM with embedded magnets



Front-axle IM with 140 kW peak power

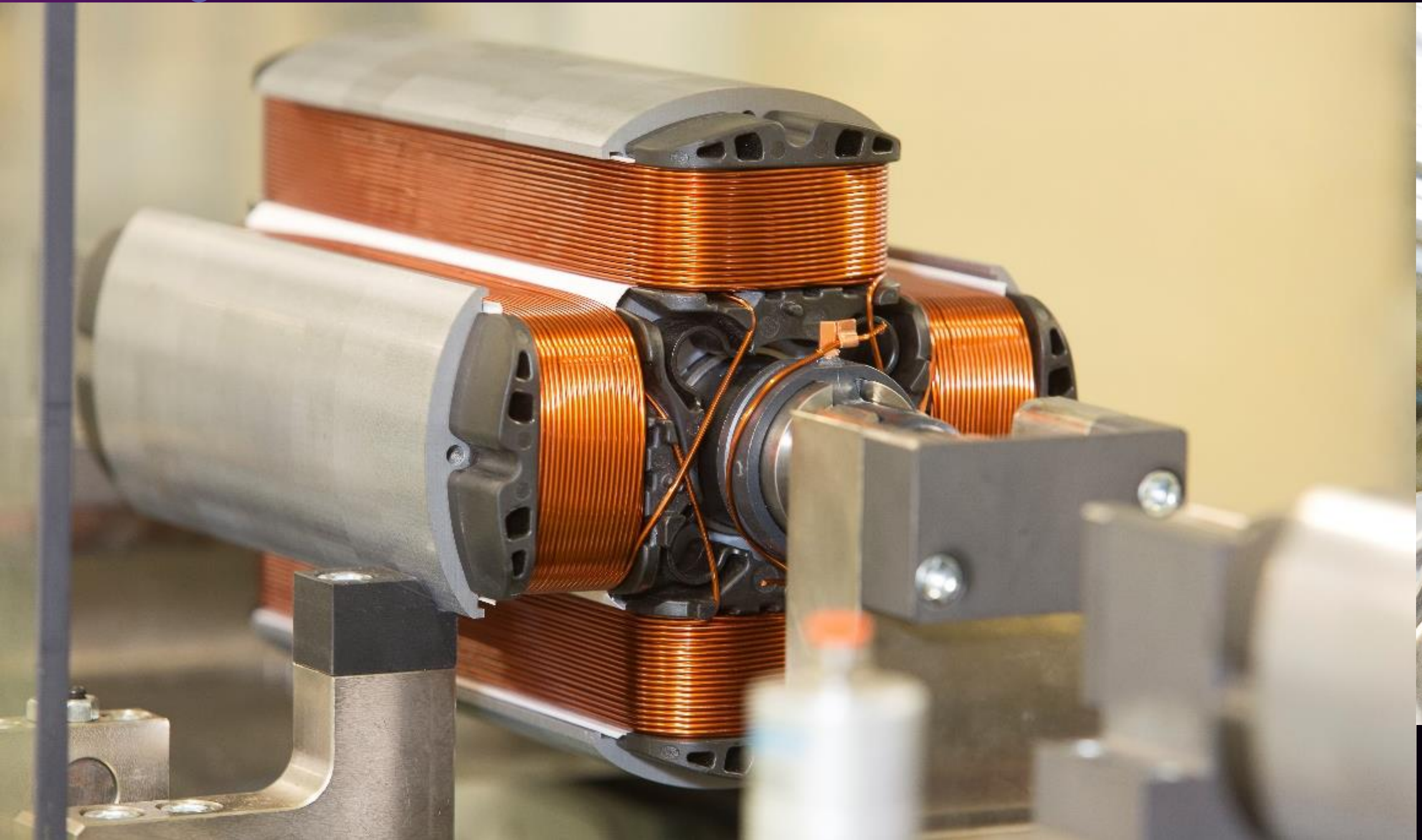
Renault Zoe – early different thinking

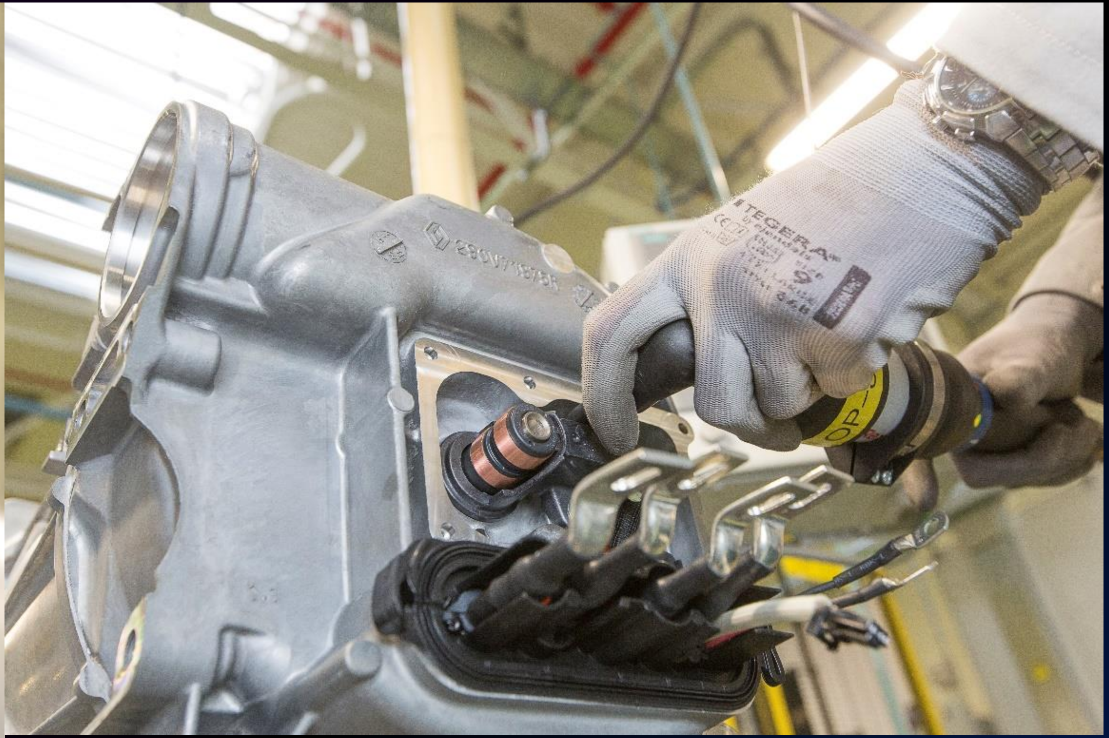
Synchronous motor with 80 kW or 100 kW power



Motor rated speed 3395 rpm, max speed 10886 rpm

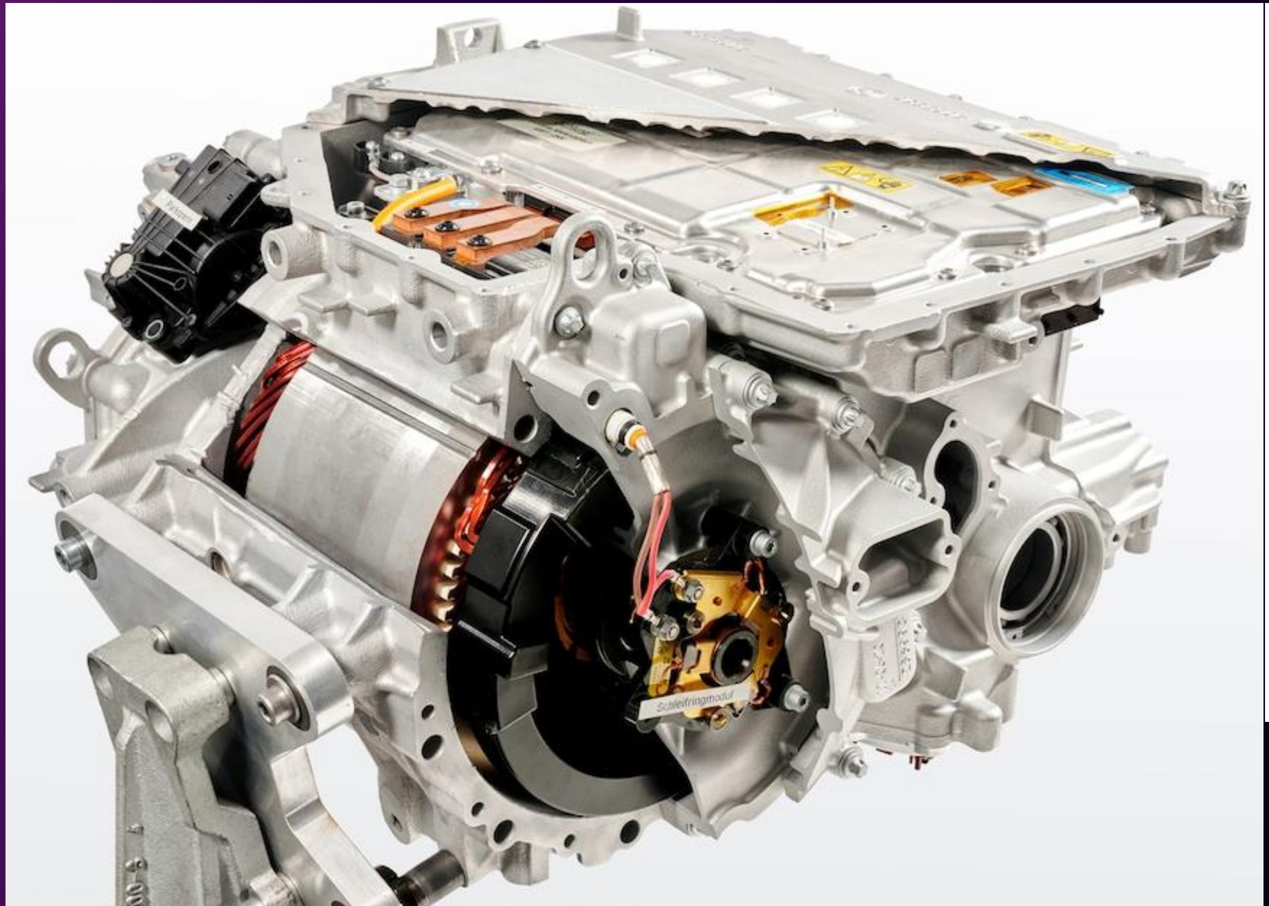
Renault Zoe

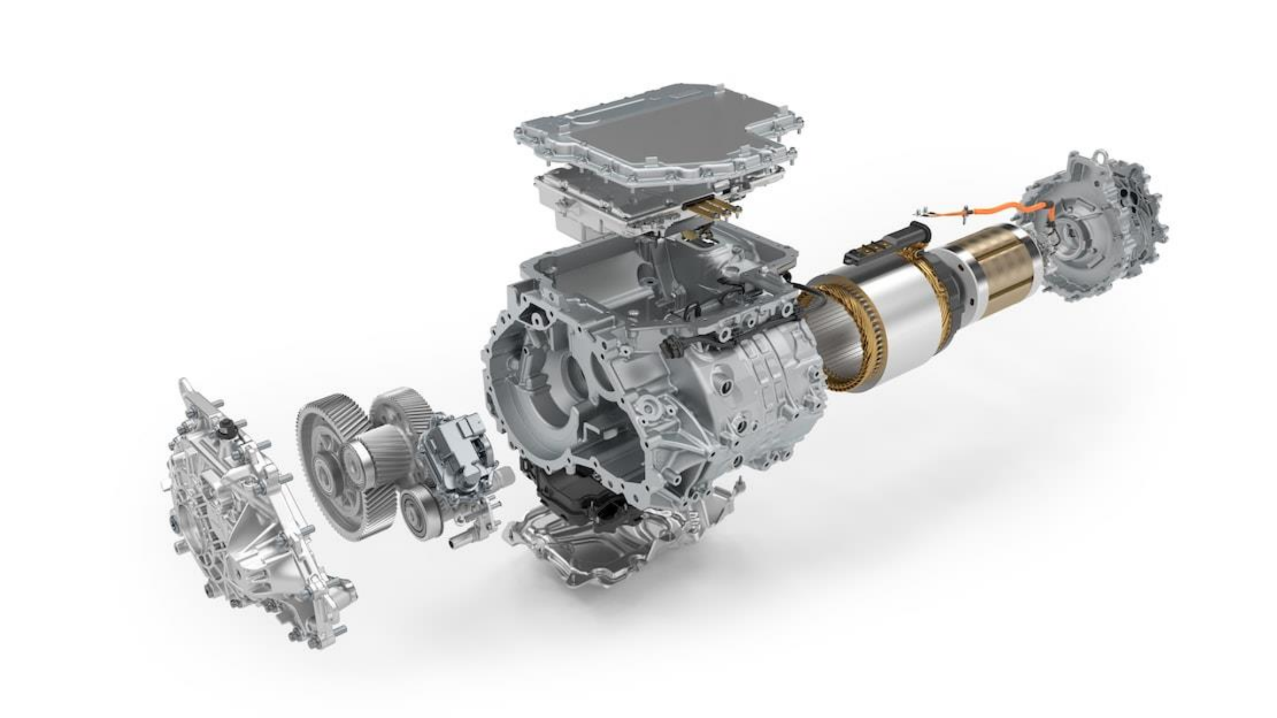




BMW iX M60 with SM

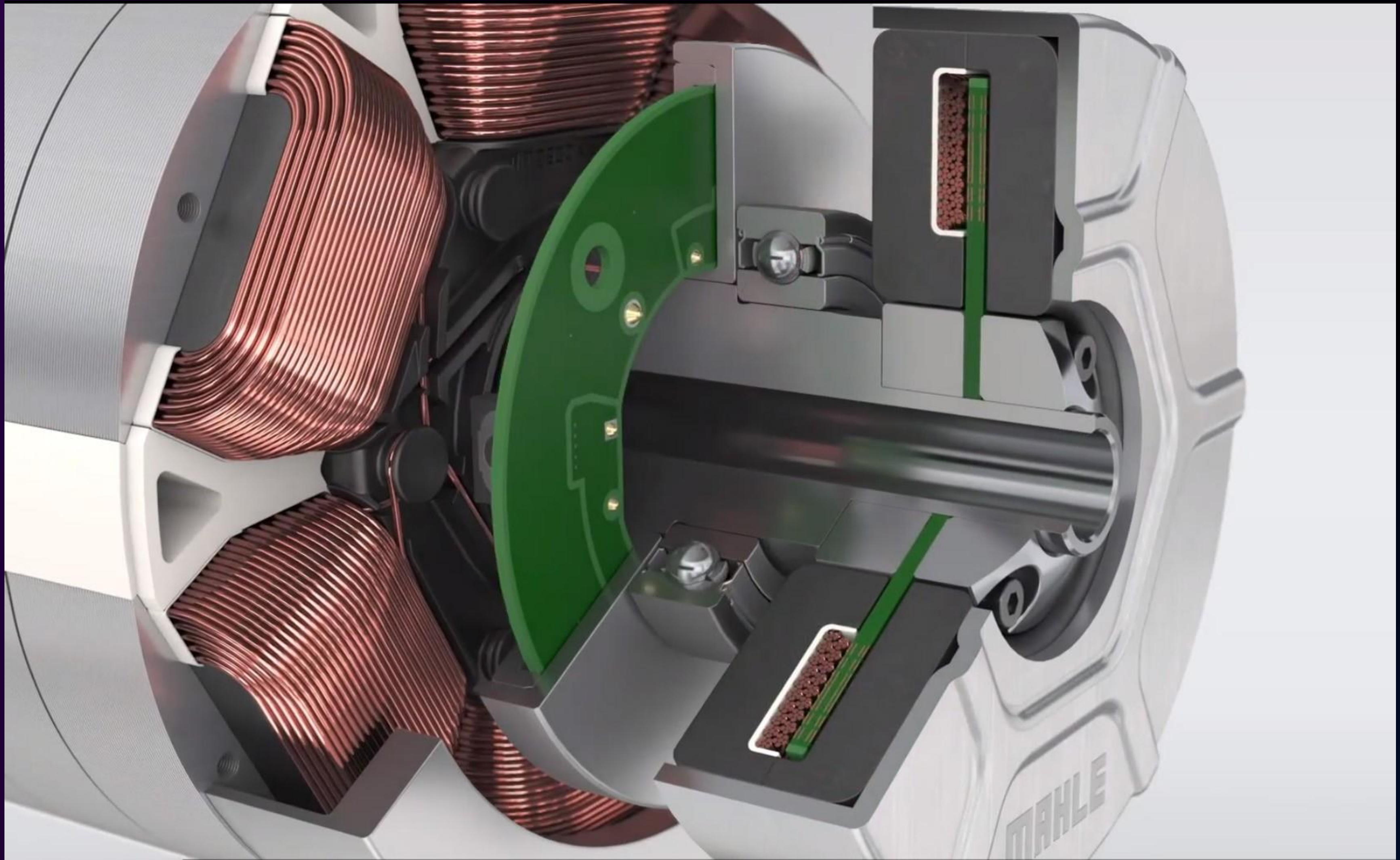
”It's clear that the battle for magnet-less motor supremacy is only just getting started, and BMW is answering a key criticism frequently leveled against EVs: **relying on rare, sometimes unethically mined materials makes EVs worse for the planet**. We're truly stepping into an interesting time in electric motor development.”





front motor 185 kW rear motor 355 kW

Mahle's 6-pole brushless SM



Trends in traction motor technology development – reducing the use of PM materials but wannabes still play on PMs

In addition to wound-rotor synchronous machines SynRMs and PM-assisted SynRMs are emerging options for traction motor applications.

- SynRM
- PMaSynRM
- Axial-flux machine
- Raxial flux machine

SynRM by Univ. of L'Aquila

Highly tuned laminated rotor mechanical construction.

Radial and tangential steel supports weaken the construction and make it mechanically vulnerable

Different SynRM Construction by LUT

- 3D Syn RM rotor modules with thin non-magnetic support plates
- Improved strength → High speed, high power density and high specific power available
- Improved saliency with no steel bridges and ribs → Improved performance
- Supports also a PMASynRM

Yasa – axial-flux PMSM

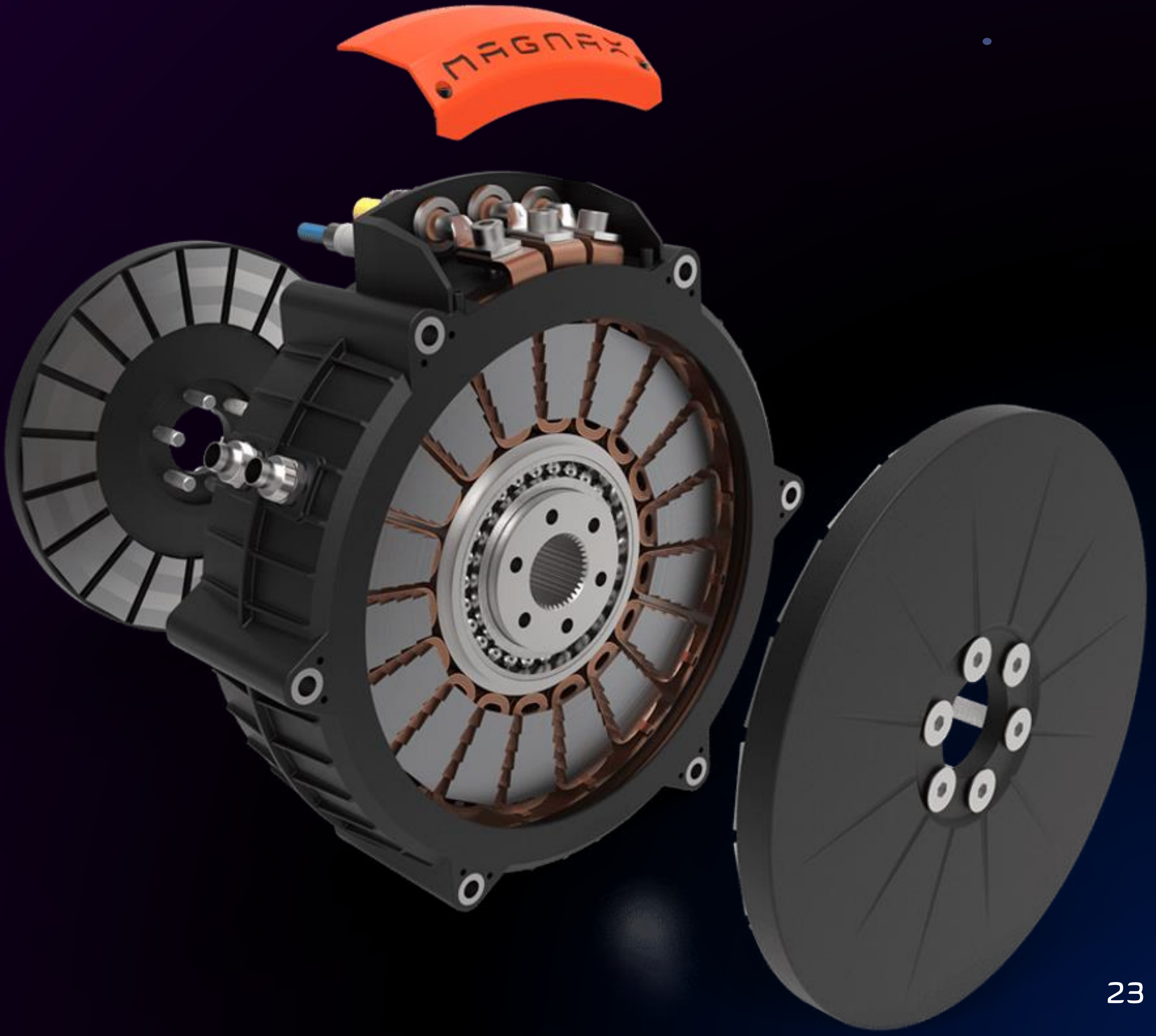
Axial-flux PMSM with two rotors and single liquid-cooled stator

Emrax – another axial-flux PMSM

Axial-flux PMSM with “two rotors” and single stator

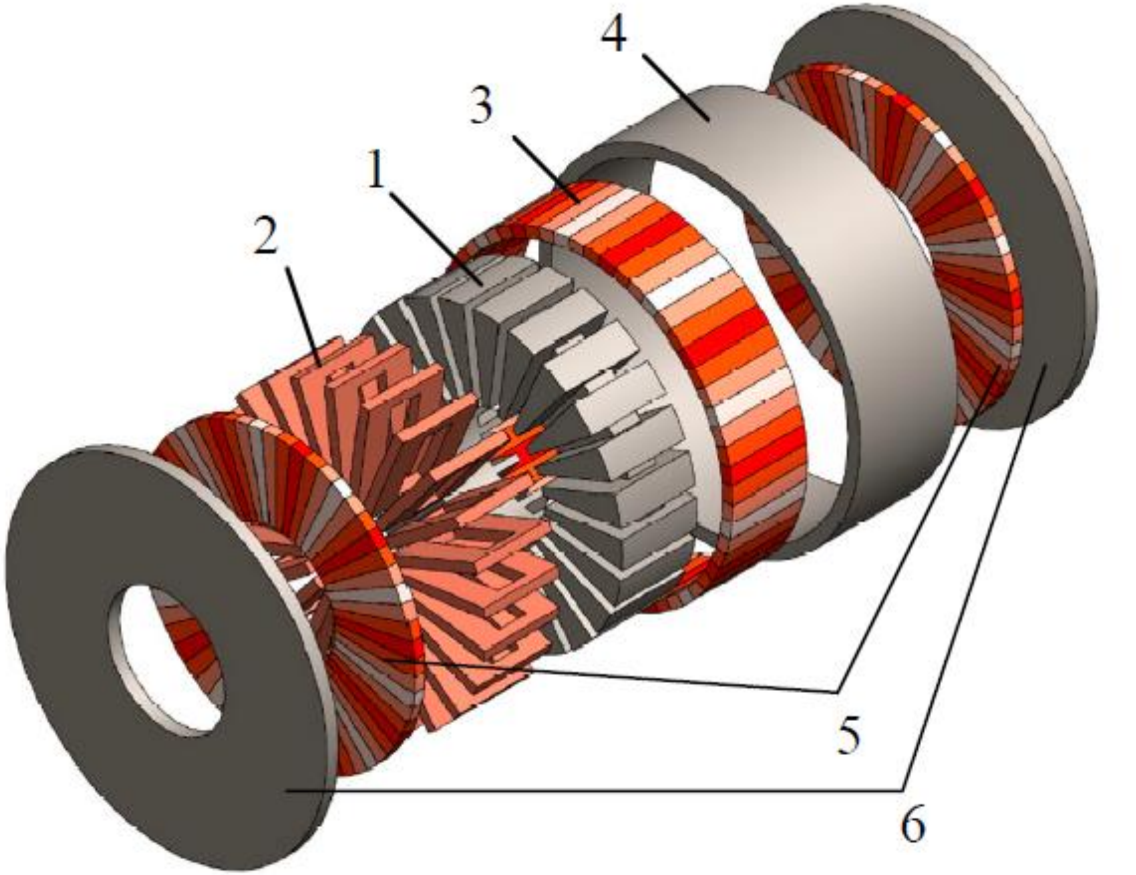
Magnax – and another PMSM

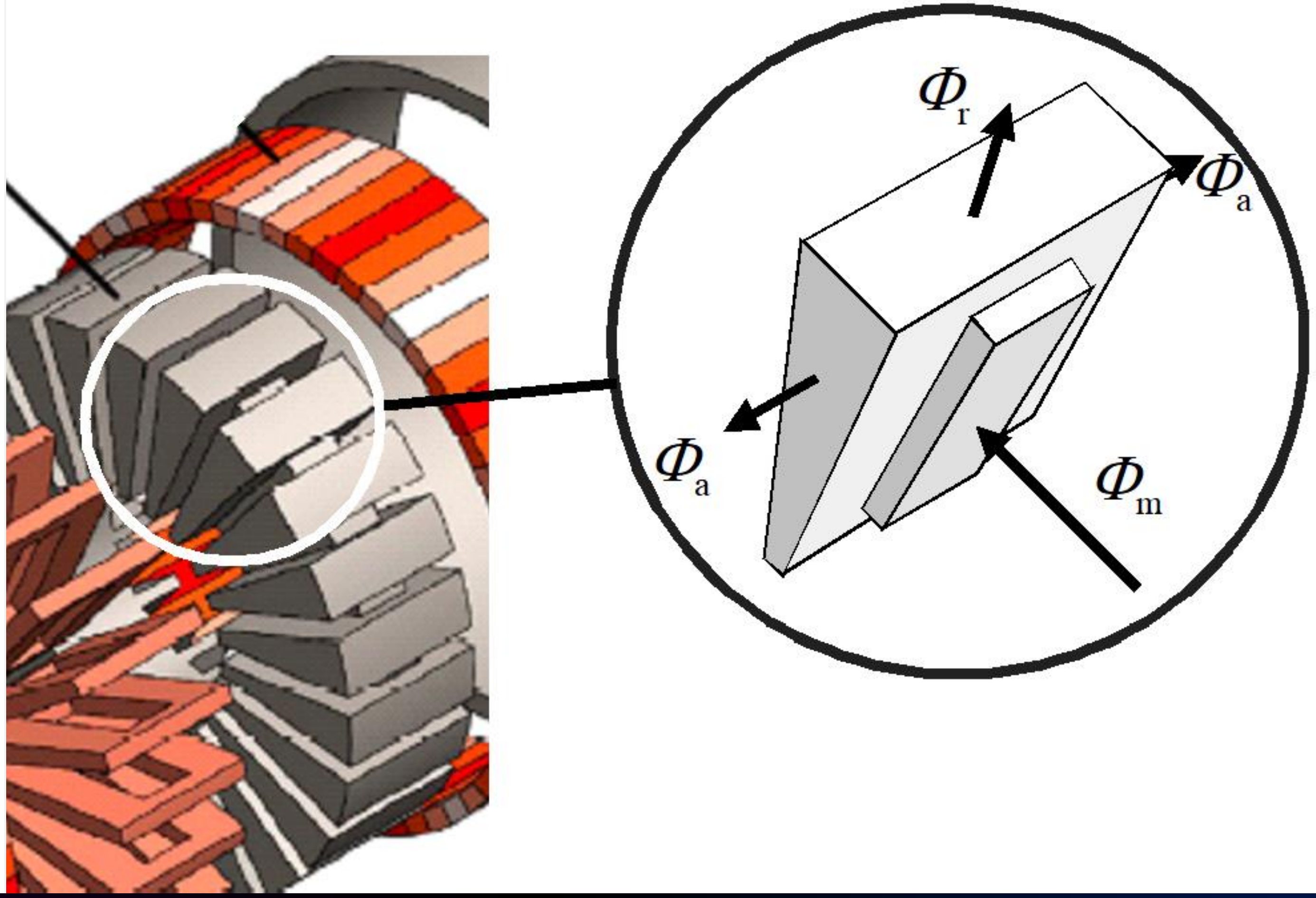
Axial-flux PMSM with two rotors and single stator
Rectangular winding strands to improve radial heat-transfer



Raxial-flux machine – 3D flux path high specific power

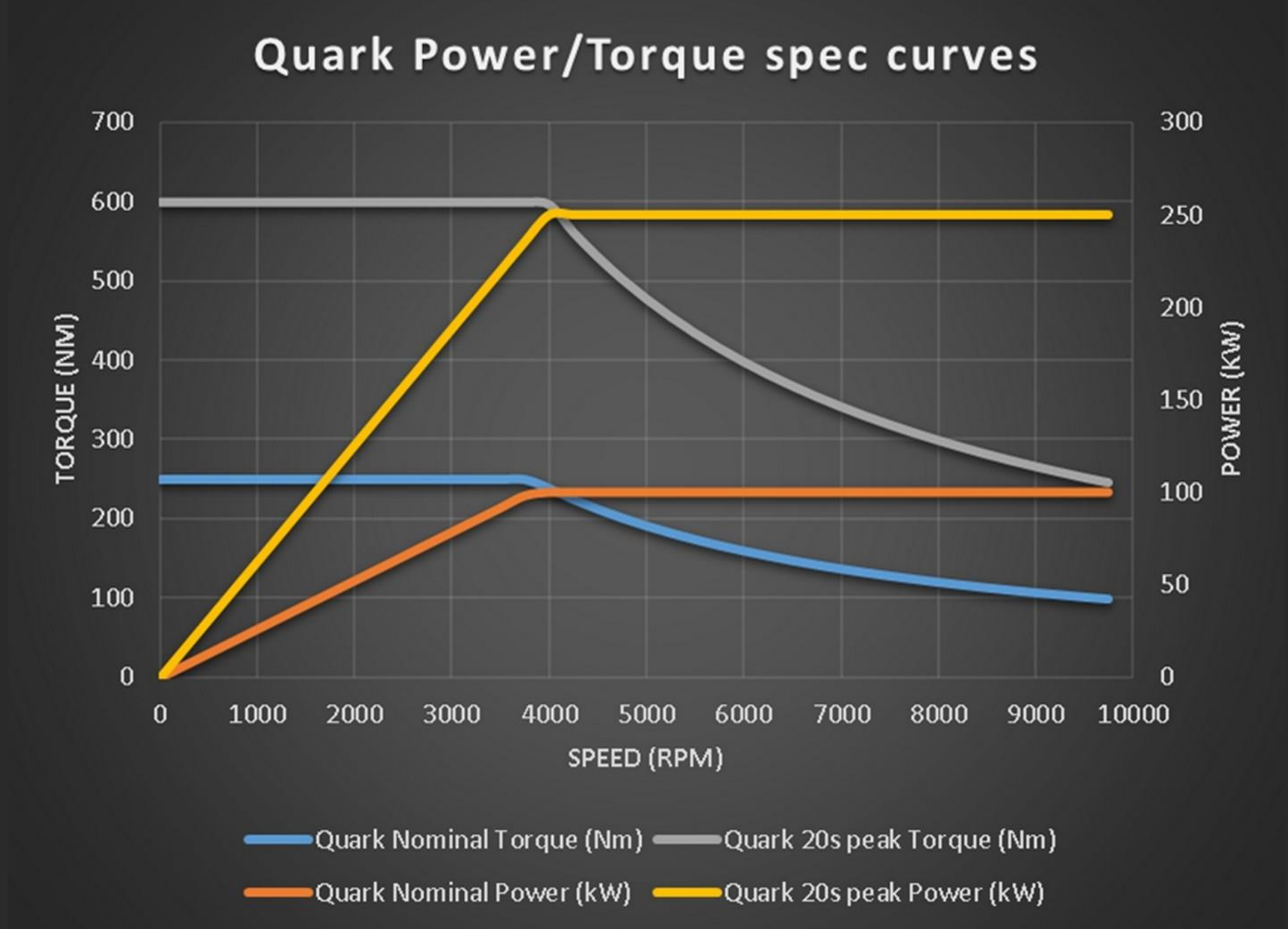
Axial-flux PMSM with two rotors + outer-rotor PMSM to use torque-producing surfaces as efficiently as possible. 3D flux path





Raxial-flux machine by Koenigsegg

Raxial-flux machine by Koenigsegg



250 kW,
8.3 kW/kg peak and
4.15 kW/kg continuous

Motor manufacturing

Increasing rotational speed is a crucial means of increasing material efficiency and reducing cost .

- Cooling solutions
- Hairpin windings
- Simplified comparison of different motor types for mobile machinery traction drive systems

How to achieve high specific power – and low cost?

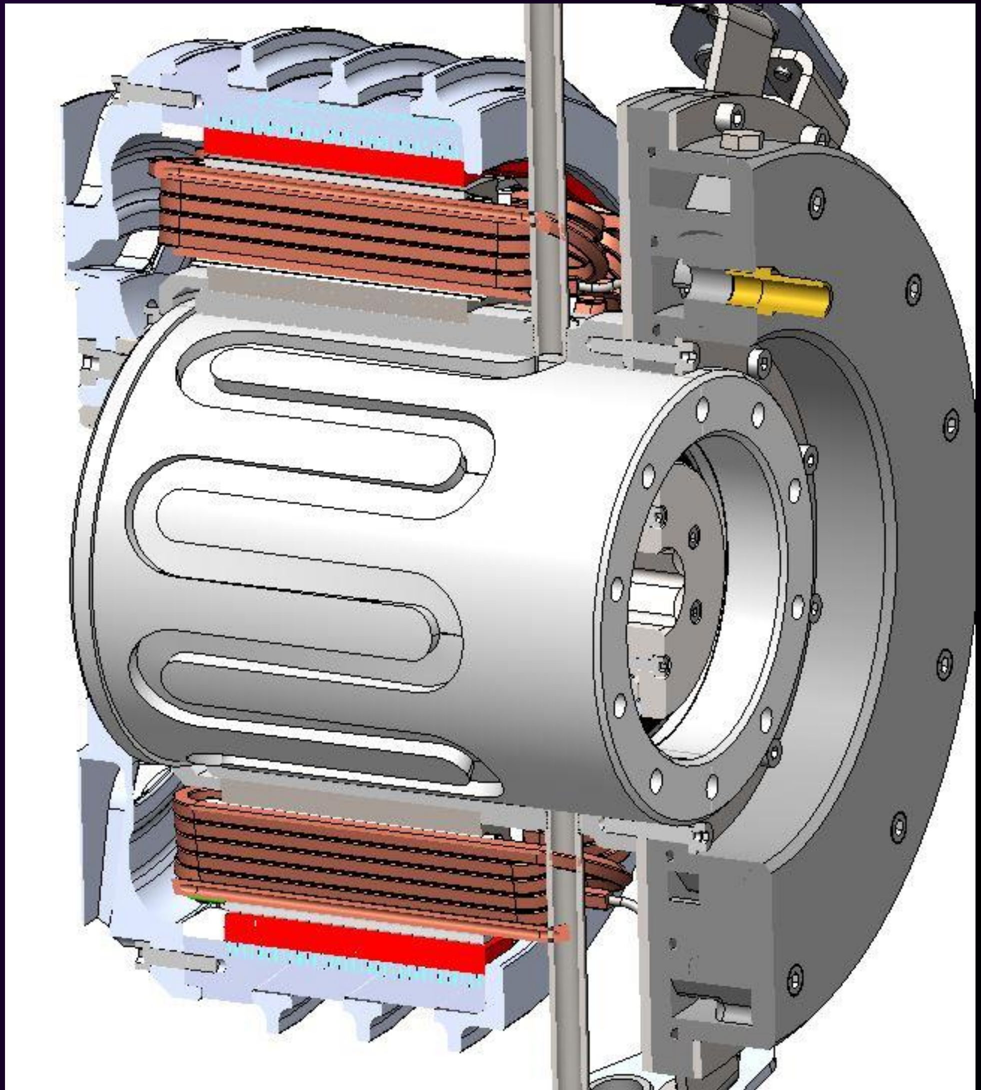
1. Increase speed – make the machine smaller, use less materials
2. Use low-loss materials in windings and magnetic circuit
3. Improve cooling
   a) Liquid jacket cooling
      i. Bring loss sources as close to the heatsink as possible
         I. Use a high number of poles to make the yoke thin. This increases the operating frequency and may result in problems with converter availability. 1000 Hz and beyond is the new normal
      ii. Do not transfer heat across lamination stack insulation
      iii. Use rectangular conductors to minimize high thermal resistance perpendicular to the winding
      iv. Use VPI to make sure there are no air pockets in the winding
      v. Use potting materials to connect end windings to the heat sink
   b) Go to direct cooling of the windings
      i. LUT has proven 50 A/mm^2 in Cu with DLC!
   c) Combine best practices

Magnax's heat-transfer solution

1. Copper conducts heat well in the motor radial direction 385 [W/(m·K)]
2. SMC core has isotropic heat transfer 20 [W/(m·K)]
3. The bottleneck of heat transfer is at the external end winding area
   I. Potting material with e.g. 4 [W/(m·K)]? (Epoxy 0.2 [W/(m·K)]!!)
4. Aluminium frame with 205 [W/(m·K)]
5. Heat transfer to the liquid in jacket

Direct liquid cooling (DLC) by LUT

LUT Bus Mule motor with DLC

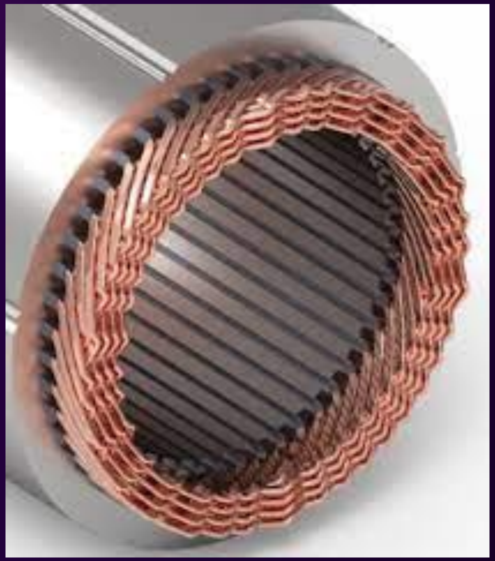


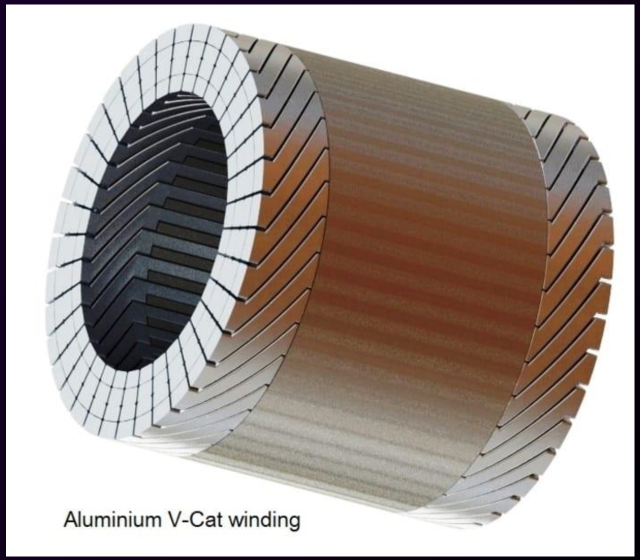
The eMAD outer-rotor PMSM with DLC + liquid jacket developed at LUT.

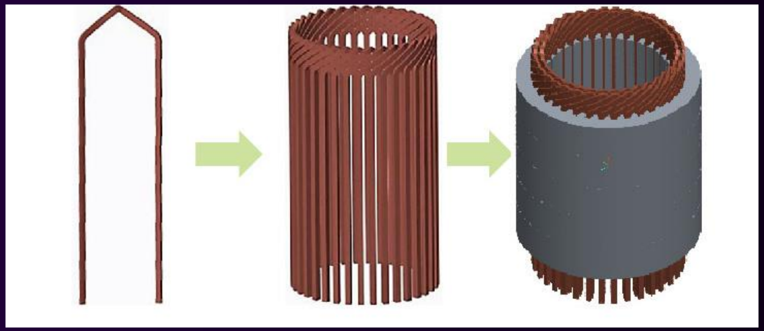
High specific power > 10 kW/kg

DLC litz tolerates 50 A/mm^2

Hairpin manufacturing







Hairpins seem to be the solution for high-scale production automation.

Aluminium as conductor suits in car traction motors! Why?

If using a 1–5 grading scale to evaluate the competitiveness of different motor types …

5 – Excellent, 4 – Good, 3 – Moderate, 2 – Satisfactory, 1 – Poor, n.a. - Not applicable

Parameters	Motor type							
	IM	SM	PMSM	SynRM	PMa SynRM	SRM	DC	BLDC
Efficiency	3	3.5	5*	3	4	3	3	5
Ease of control	3	2	3.5	3	3	1	5	5
Power factor or energy factor	3	5	4	2	4	3	n.a	3
Overload Capability on constant flux area	4	5	4**	2	3	4	2	3
Torque capability in field weakening	2	5	4***	1	2	2	4	1****
Specific Torque	3	3	5	3	4	3	3	5
High-Speed mech. capability	5	2	3	2	2	5	1	2
Manufacturability	5	2	2	4	3	5	2	3
Cost	5	3	1	4	3	4	3	1
Reliability	5	3.5	3.5	4	3	5	3	3.5
Noise	5	5	5	5	5	1	4	4

*In field weakening suffering from demagnetizing current caused extra losses
** Depending very much on the construction
***with characteristic current close to 1
**** Actually, not applicable with BLDC basic principle. Can operate in FW with similar control as PMSM but rotor surface magnets limit the FW operation strongly

Thank you

Juha Pyrhönen