FT'19
Sub-system and system analysis
9/10 11:30-12:00

Aerospace electric generator specification and selection – **opportunities and challenges**

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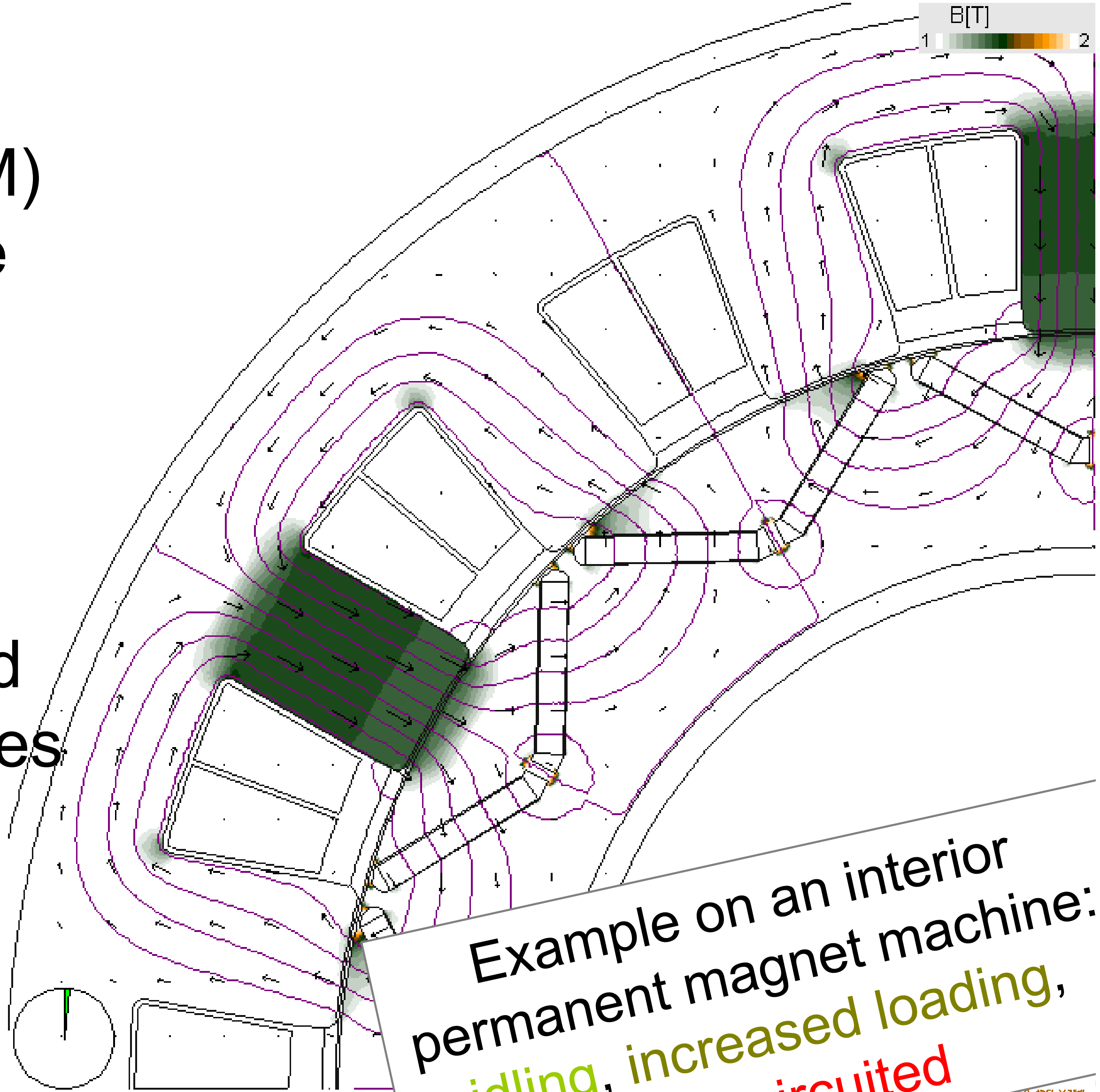
Electromechanical energy converter

- Focus on **embedded** electrical machines (EM) for more electric engine (MEE)
  - low pressure spool
- **Find suitable** electric drive system = power electronic converter and EM topology that enables desired performance, efficiency and reliability

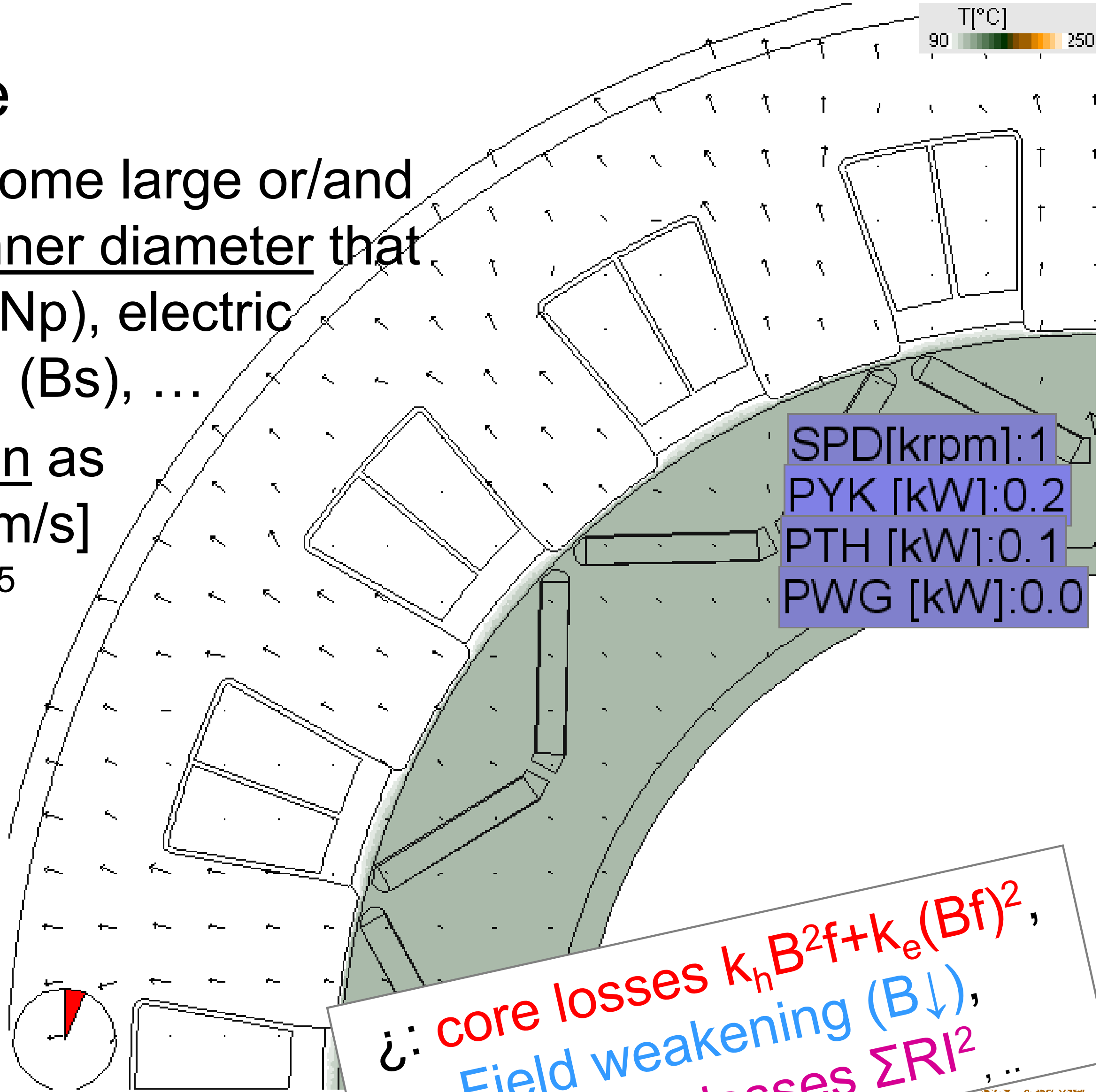


Example on an interior permanent magnet machine: idling, increased loading, short-circuited

Integration challenges

Back to square 1:
find suitable EM for
given space and speed

- Space and speed range
  - EM has tendency to become large or/and inefficient due to large inner diameter that drives number of poles (Np), electric frequency (f), saturation (Bs), …
  - Mechanical safety margin as peripheral speed >200 [m/s] & figure of merit >1.5·10^5 [rpm·√kW]
- Cooling integration
  - Improve coil2coolant thermal impedance
  - (cooling) System perspective



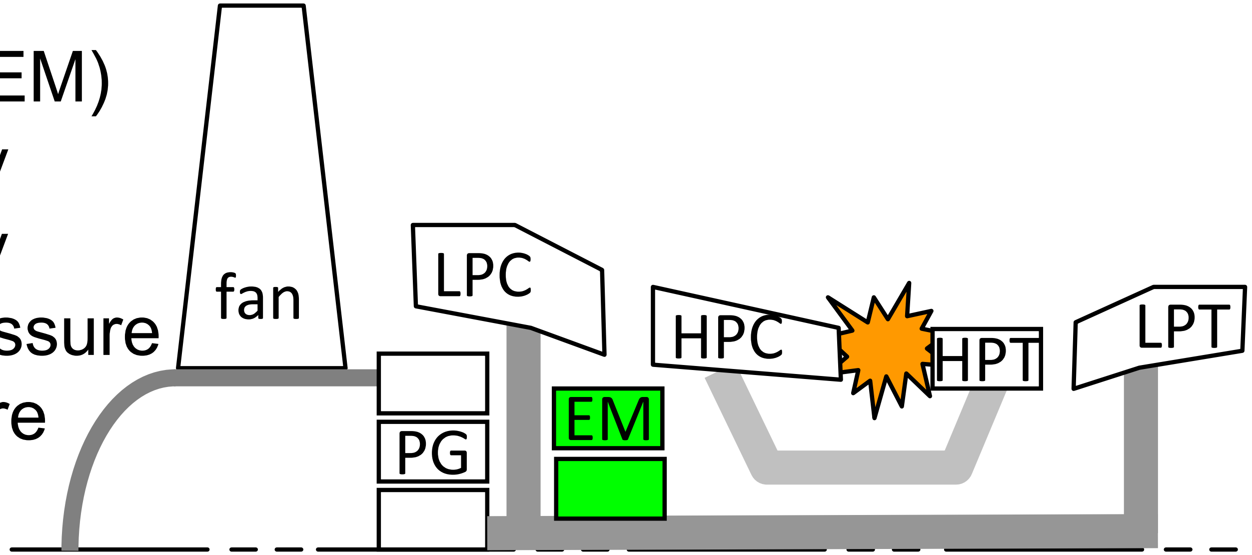
¿: core losses $k_h B^2 f + k_e (Bf)^2$,
Field weakening (B↓),
conductor losses ΣRI^2, ..

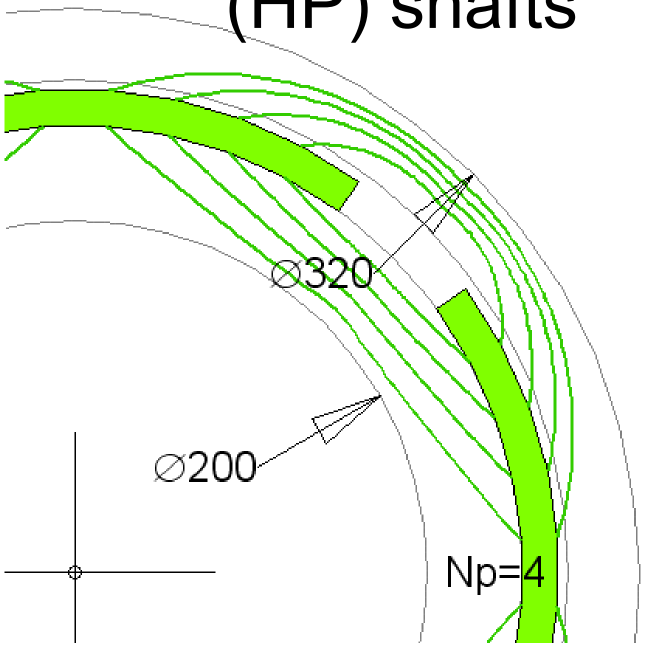
Content

- More Electric Engine
  - Accommodate electric machine on low-pressure spool
- Power systems and generators
  - Identify suitable drive and machine topology
- Integration challenges
  - Large diameter, space envelope and speed range
- Technological opportunities
  - Impact of magnetic core and enhanced cooling
- Comparison of PM machines
  - Design specification, spacing and performance

More Electric Engine

- Electric Machines (EM) connected indirectly (external) or directly (internal) to low pressure (LP) or high pressure (HP) shafts



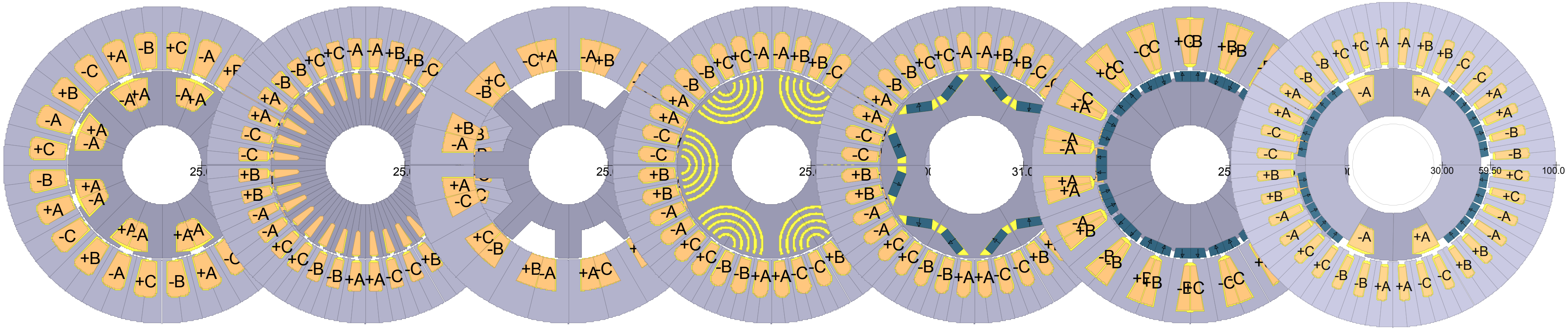


- Electrification ≡ improve system energy conversion **efficiency** + reduce **weight** by introducing low weight components
- Space and speed constrains may force EM to be **large** and inefficient

More Electric Expectations

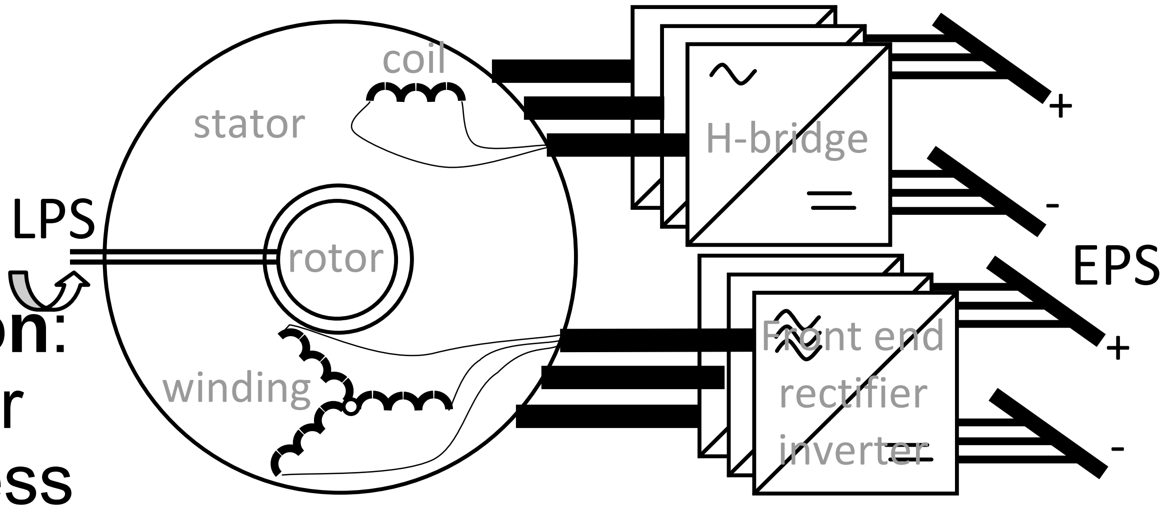
- High power light weight = more electric, due to electrification – increase of electric loads so do sources
- Power, energy and fault management anticipated by the presence of power electronics
  - Wide speed range and risk for induced over voltage
- Self maintenance = Ability to operate at faulty conditions and carry out health monitoring

Electrical Machine Topologies



Electrically magnetized	Induction machine	Switched reluctance	Synchronous reluctance	Interior PM	Surface PM	Hybrid magnetized
FW & Field enhancing	Simple, robust, widely used	Robust rotor, high speed capability	No magnets, simpler control	High torque density, FW capability	High torque density,	Combine advantage of EM and PM
Limited high speed capability	Relatively low efficiency	Large torque ripple and noise	Low power factor	Limited high speed capability	Large gap, Low inductance, PM retention	Escitation arrangement

Converter to EM integration



- Voltage and frequency on EM terminals: from constant to **wild**
- Regulation of **excitation**: tradeoff between power density and faultlessness
- Topology arrangement: tolerate + increase likelihood of **no fault**
- PEC rising time vs PD activity & electric stress **relaxation** across EIS

- Modular single-phase multi-coil connected to a bridge
- Multi-channel multi-phase winding connected to a 2 or 3 level inverter

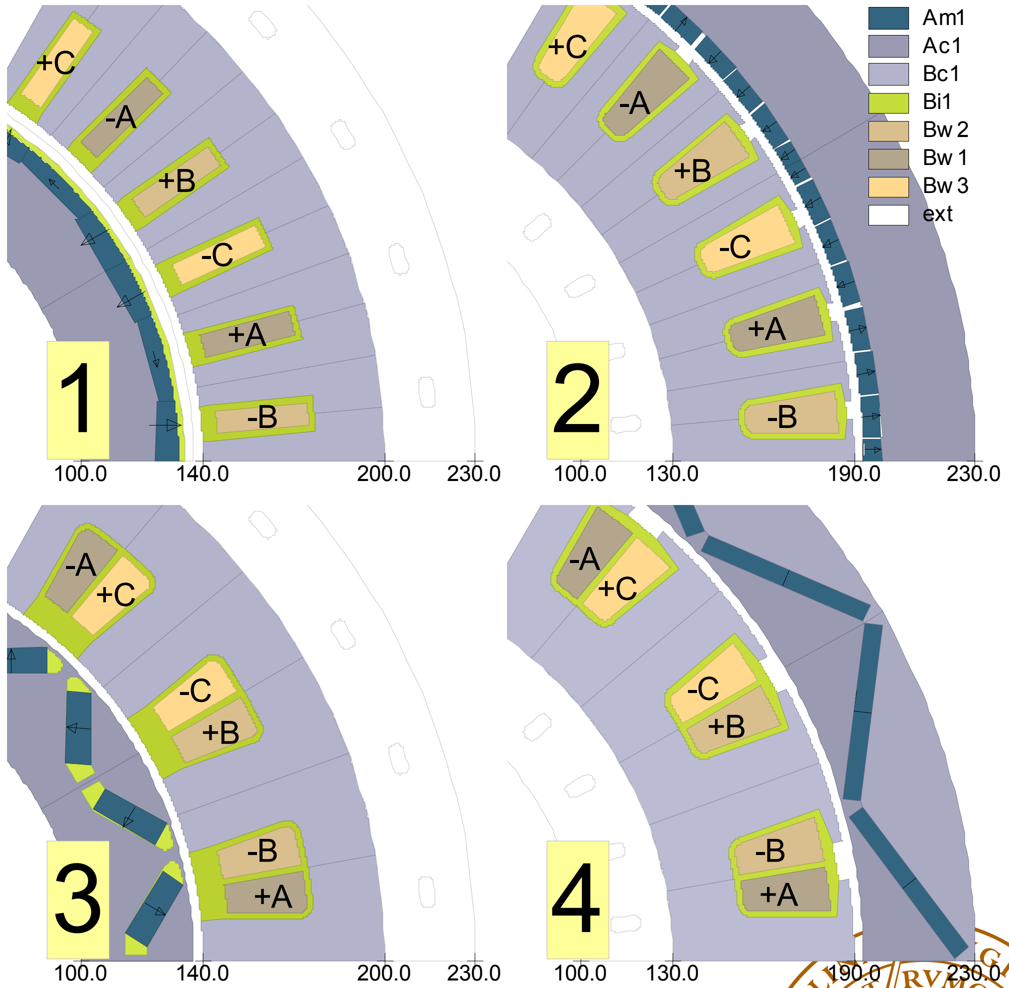
Challenges and Opportunities

- Intention: high power density (=increase loading) and efficiency (=reduce power losses)
- Materials engineering
  - High **temperature** materials for EIS and PM
  - High **durability** materials for high-speed rotors
  - High **efficiency** high flux density magnetic cores
- Manufacturing, assembling, integration
  - Interfaces and related stressors – mech., therm., ..(design factors, building coefficients, ..)
  - Cooling integration=reduce thermal impedance

PMSM topology specification

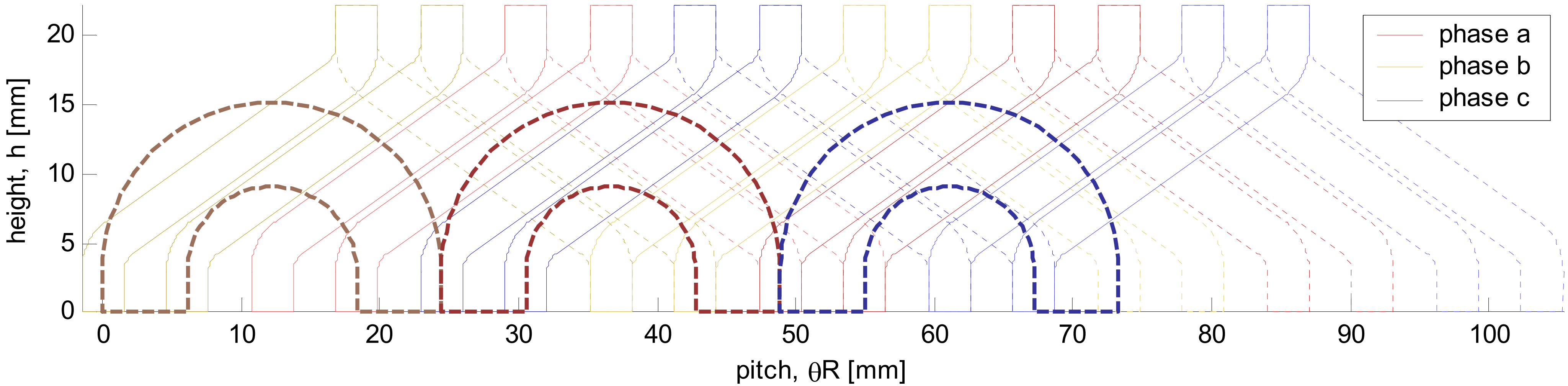
Focus on inner rotor EMs

- Interior permanent magnet (IPM)
- Halbach array surface magnet (HAPM)
- Distributed winding (DW)
- Concentrated winding (CW)



topology	P/Vol	Po/Pi	I_{SC}	ripple
DW+IPM	high	high	low	low
CW+IPM	low	higher	lower	high
DW+HAPM	higher	high	higher	low
CW+HAPM	low	higher	high	high

EM design specification

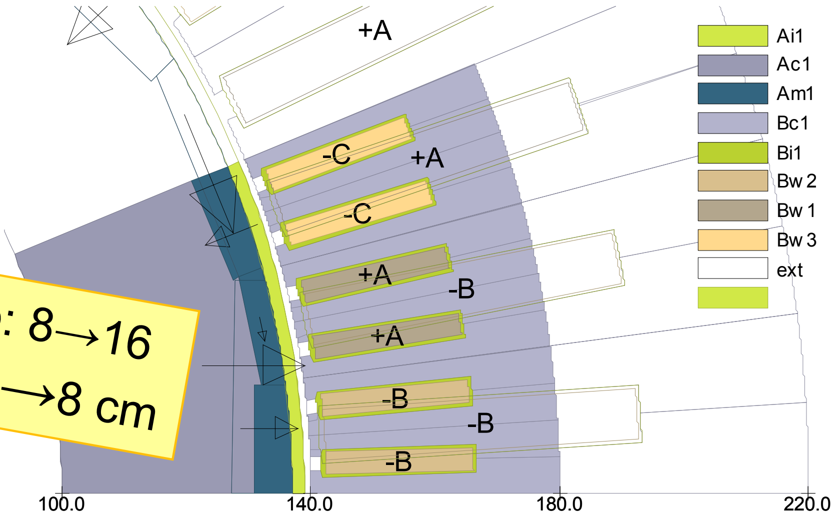


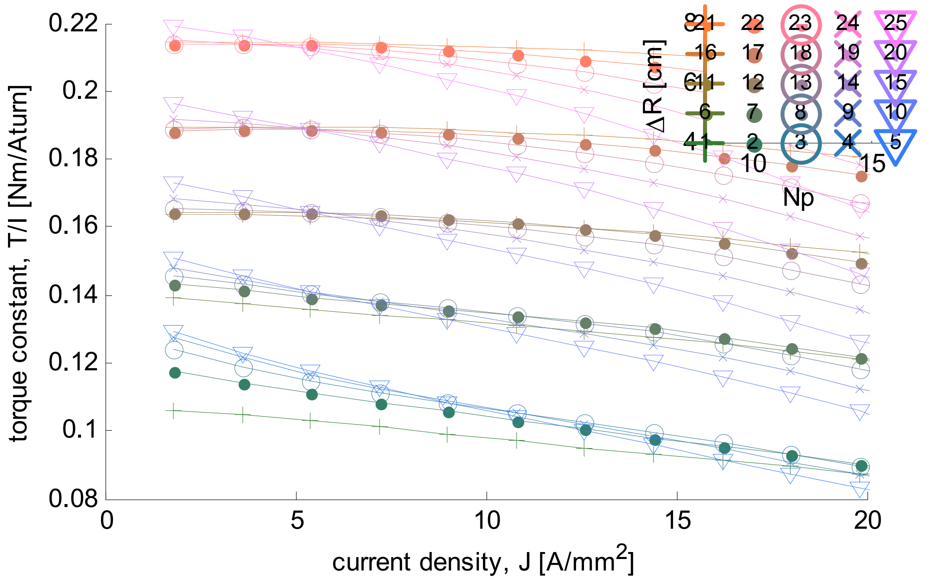
- Peripheral view of winding overhangs where a multi-layer distributed overlapped winding is compared to non-overlapped concentrated winding
  - 3-phase 12-pole 72 or 18-slot stator seen at Ø280 mm
  - Packing, EIS, manufacturabilty, heat dissipation, …

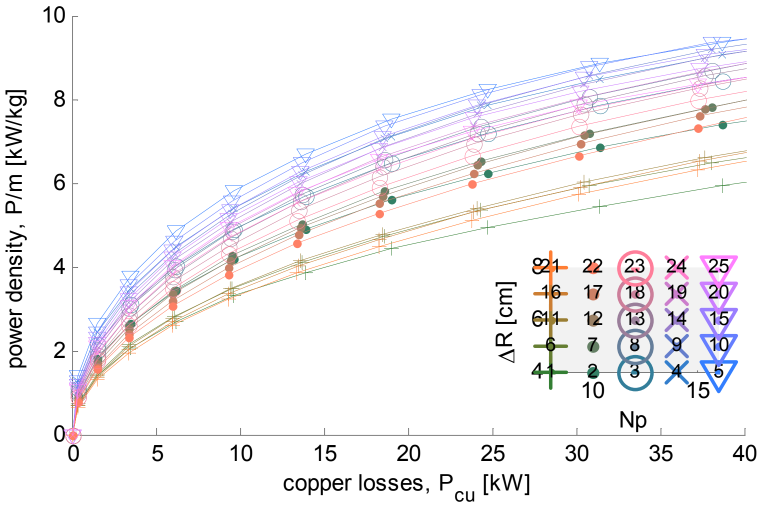
Design space (A)

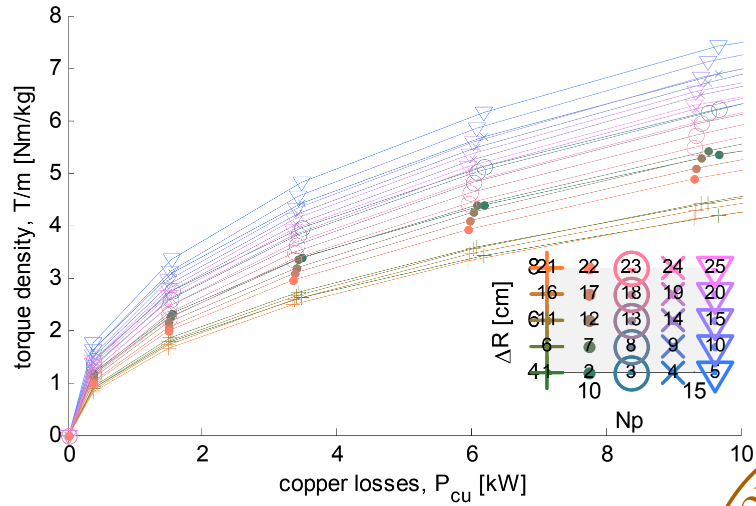
Torque capability

Np: 8→16
Δr:4→8 cm





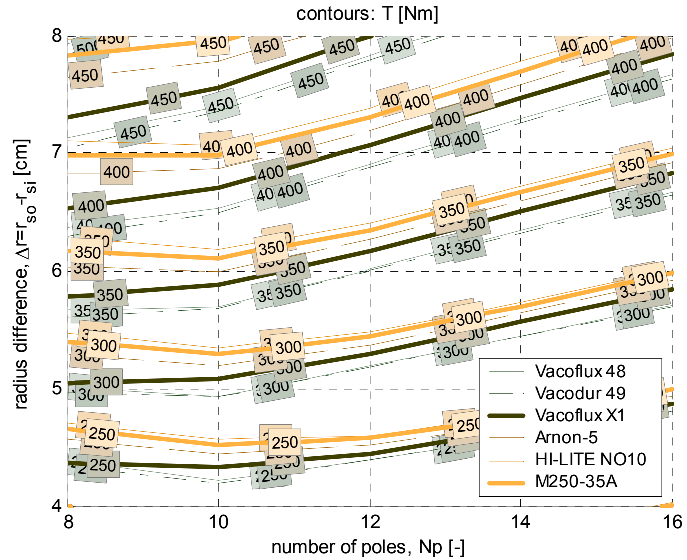


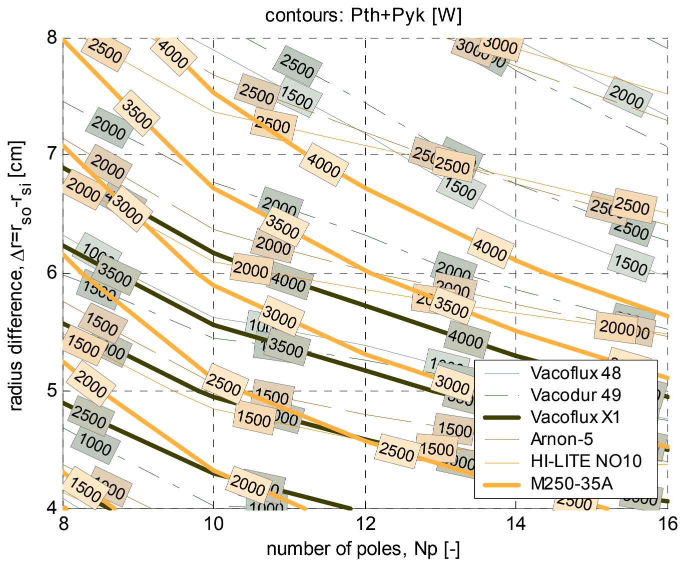


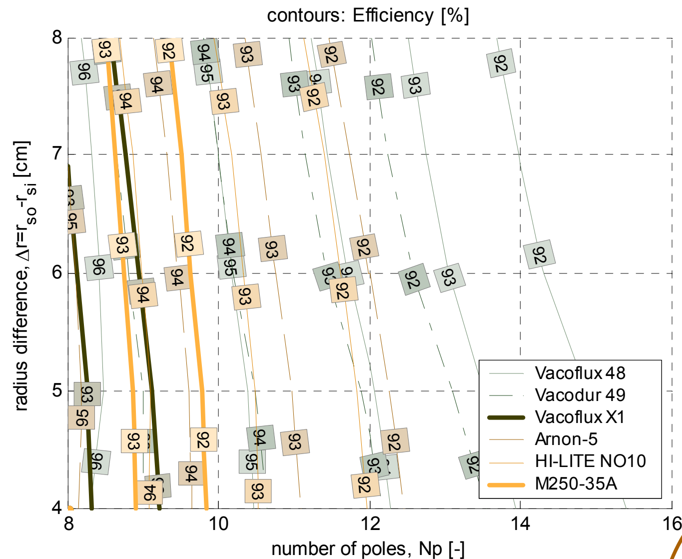
Design space (B)

Efficiency capability

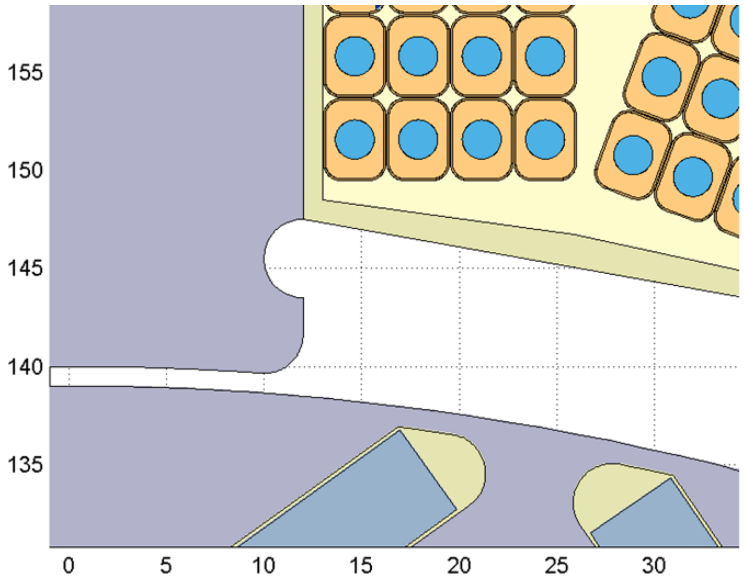
grade	mm	g/cc	μ/B	W/kg
Vacoflux 48	0.1	8.12	20k/1.4	38
Vacodur 49	0.15	8.12	18k/1.24	100
Vacodur X1	0.2	7.9	13k/0.76	146
Arnon-5	0.13	7.65	9.8k/0.75	78
HiLite NO10	0.1	7.65	8.4k/0.74	84
M250-35A	0.35	7	8.2k/0.80	191







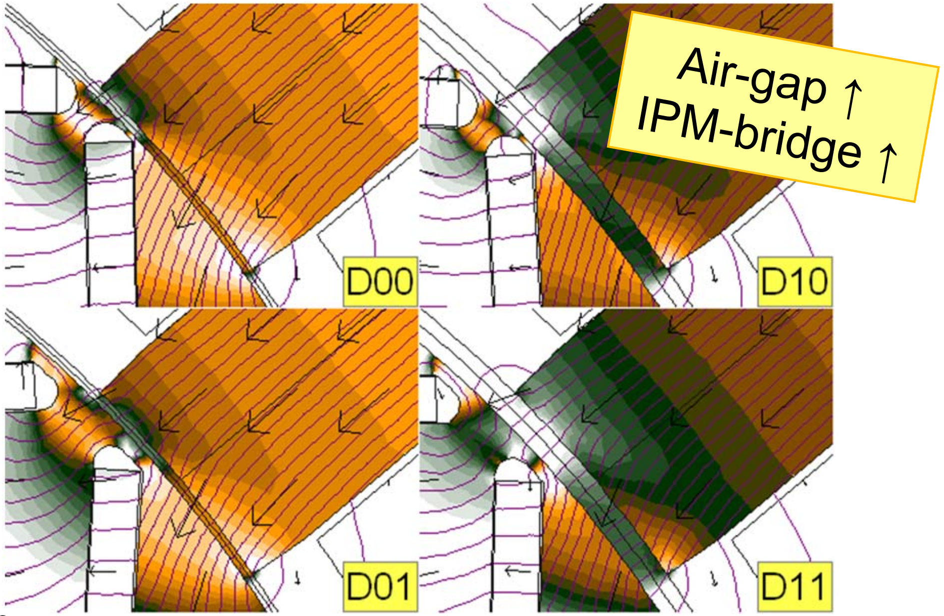
Design investigations (A)

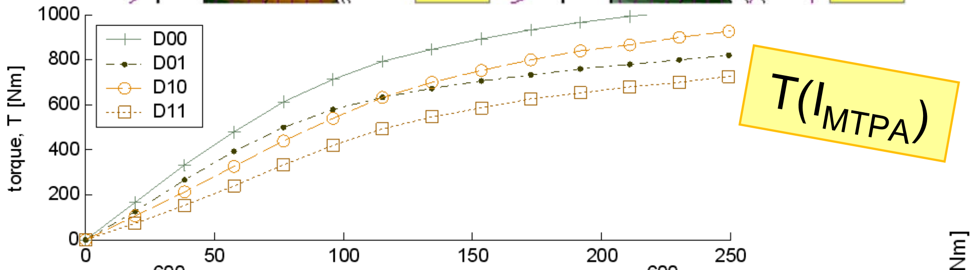


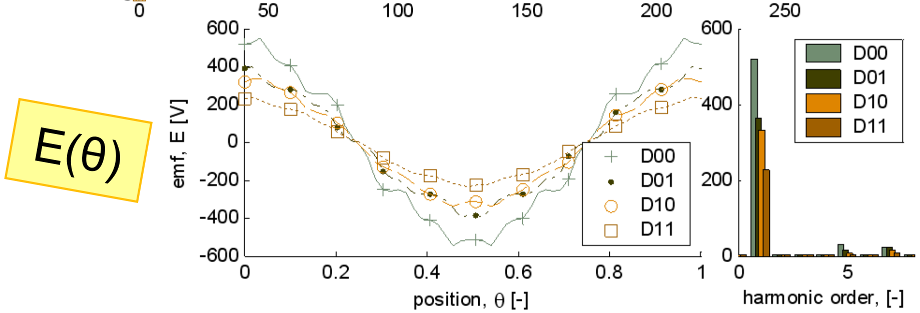
- Thermal impedance reduced by factor of 10 when comparing DW with cooling jacket and CW with direct cooled conductors

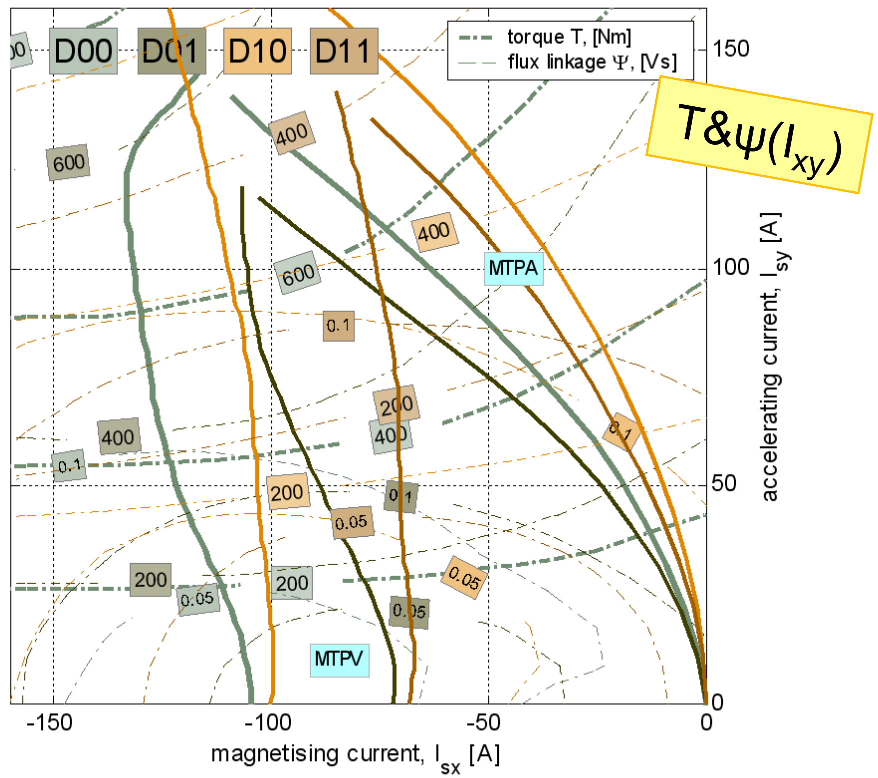
- Modular single-phase multi-coil concentrated winding made of hollow conductor
- IPM – rotor
- Speed range from 1500 to 7500, over speed at 15000 rpm
- Voltage limitation of 28 turn coil at 300V dc-link voltage restricts the power capability

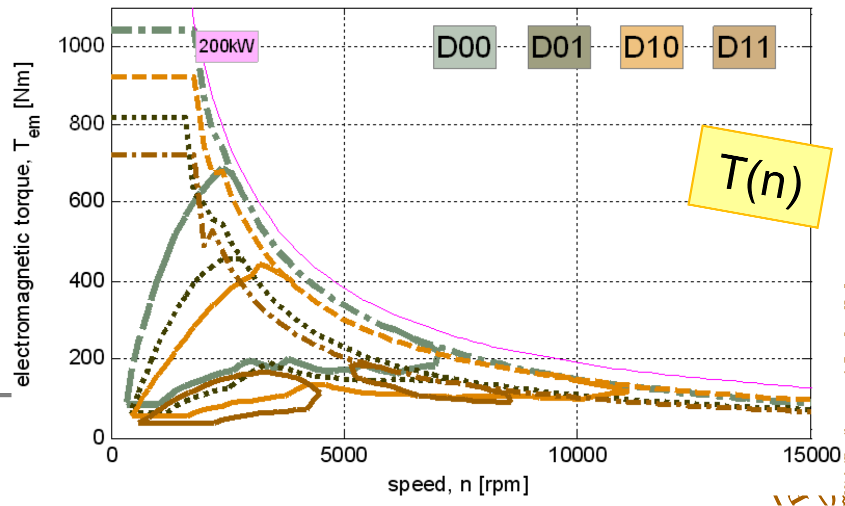
Design investigations (B)











Summary

- Replacing everything that needs maintenance or mechanically wears out, and expecting that electrification solves it all
- Concerning to EM for LPS
  - PMSM can attract with efficiency, torque and power density but not with over-voltage in case of failure
  - Apart from the wide speed range the large inner radius adds to high electric frequency/size and power losses
  - Various issues can be addressed and compromised in the design stage
    - plug and play with extra plugging play