Comparison between Permanent Magnet and Wound Field Synchronous Machines for Traction Application: Efficiency and Energy Consumption

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PSA / Nidec PSA emotors

1) Introduction

2) Electric machine design methodology

2.1) General approach

2.2) Specification main parameters

2.3) Electromagnetic design parameters

3) Electric machines optimized designs

3.1) Parametric study: examples

3.2) Permanent Magnet Synchronous Machine design

3.3) Wound Field Synchronous Machine design

4) Performances comparison

4.1) Efficiency maps

4.2) Continuous powers

4.3) Energy consumption

5) Conclusion

1) Introduction

- Various electric machines technologies are used in the traction domain.

- The main used technology is Permanent Magnet Synchronous Machine (PMSM) appreciated for compactness and high efficiency.

➔ Main drawbacks : cost and use of rare earth permanent magnets.

- Wound Field Synchronous Machine (WFSM) offers interesting magnet free solution with controllable rotor.

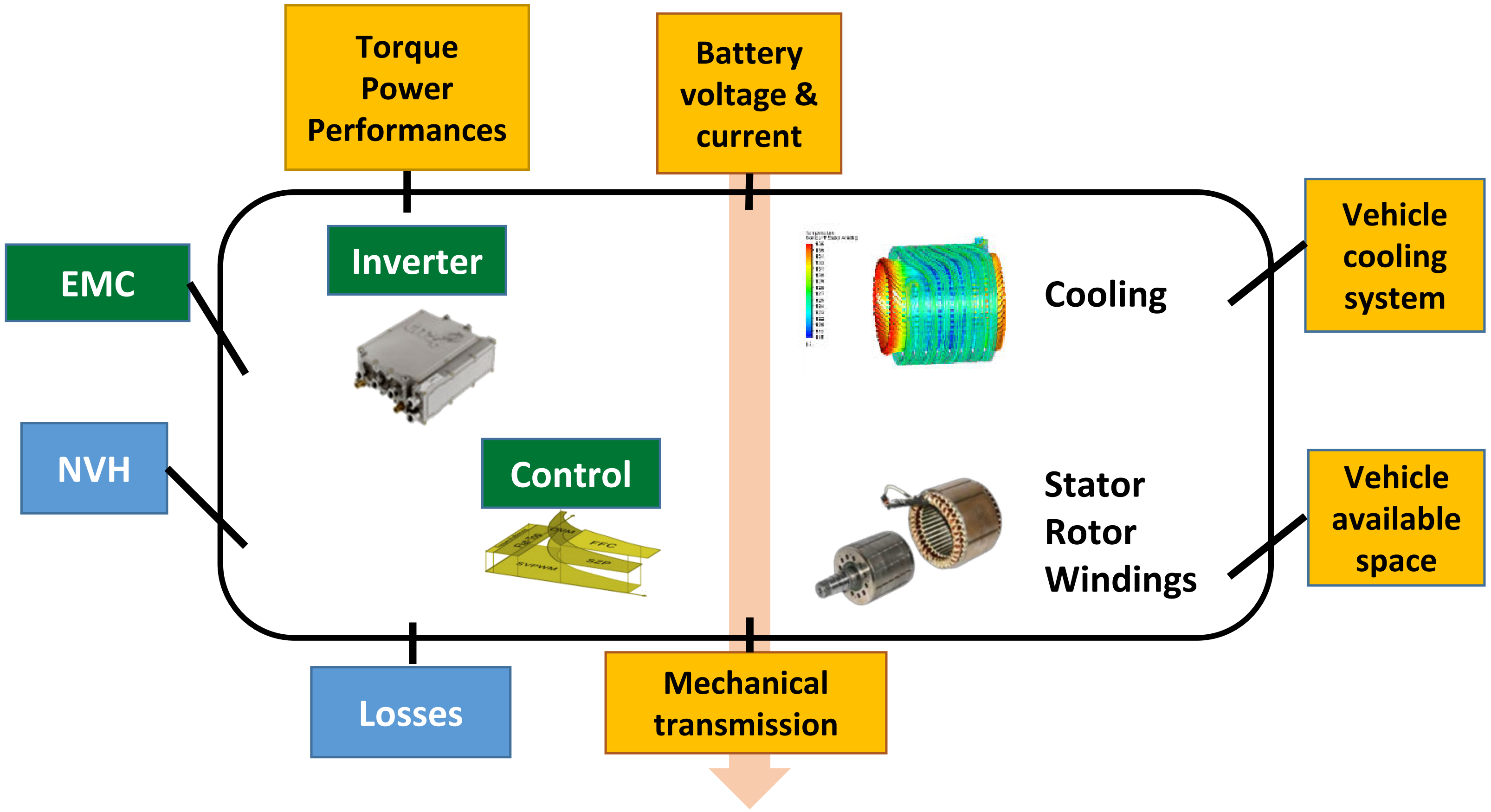
➔ Main drawbacks rotor losses and supply.

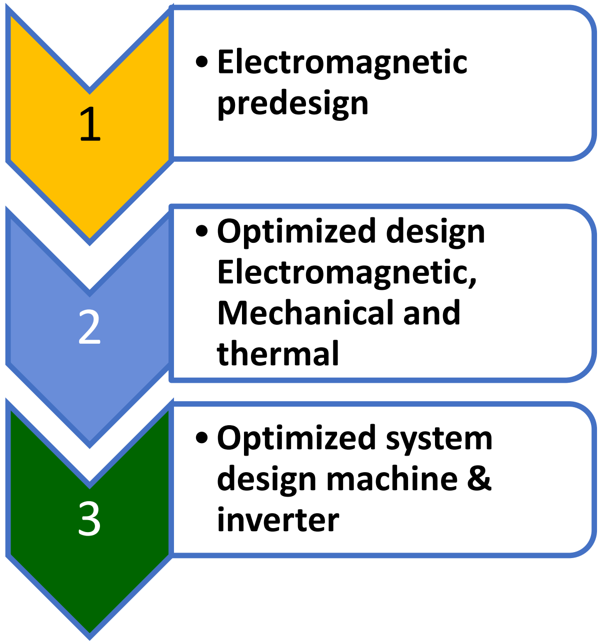
Let’s design WFSM and PMSM for the same specification

What are the main differences?

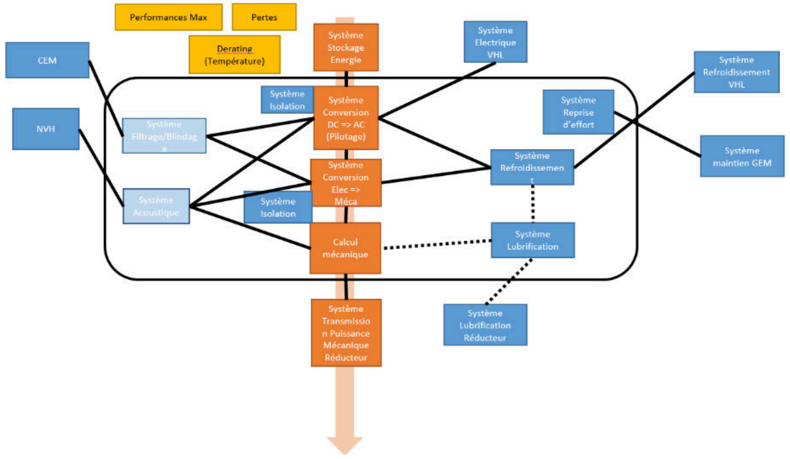
2) Electric machine design methodology

2.1) General approach: Specification

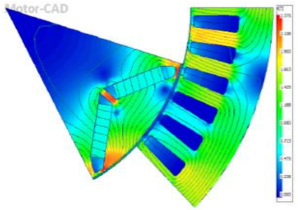




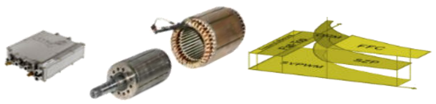
2.1) General approach: design loops



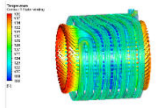
Optimisation & loops
Electromagnetic/mechanical



Optimisation & loops
Electromagnetic/Inverter/control



Optimisation & loops
Electromagnetic/thermal

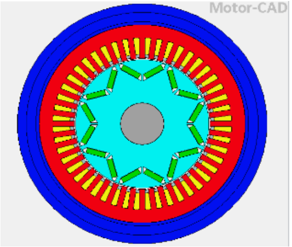


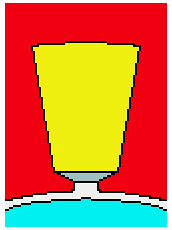
2.2) Specification main parameters

Main Inputs	Comment
Voltage (V)	Depends on Battery, minimum voltage for which performances are ensured
Max Current (A)	Corresponds to peak torque, depends on Battery and power electronics
Peak Torque (Nm)	Curves depending on speed and voltage Parameters: peak torque values, occurrence, peak duration, base speed
Cogging torque & torque ripple (Nm)	Depends on the allowed variation on the electric traction
Continuous Power (kW)	Curves depending on speed and voltage Parameters: power values, duration
Diameter & Length (mm)	Depends on available space
Maximum speed (rpm)	Depends on the wheels maximum speed and the gear ratio
Maximum short circuit current (A)	Depends on power electronics

2.3) Electromagnetic design parameters

- Technology.
- Number of poles and phases.
- Stator & rotor geometries: diameter, length, number of slots, slots shapes.





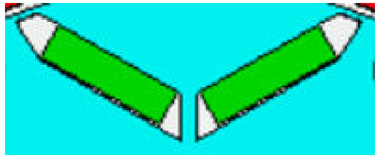
- Stator and rotor materials: steel, magnets, copper.
- Windings definition: number of turns, winding type, copper filling, hairpin / stranded.

3) Electric machines designs

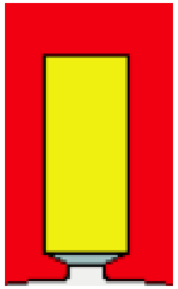
Focus on Electromagnetic design

3.1) Parametric study: Example Stator and rotor geometries

- 8 poles machine for peak torque and maximum speed.
- V shape magnet for maximum torque.



- Maximum torque increases with magnet weight → cost!!
- Maximum torque increases with slot surface → slot width versus tooth saturation!!

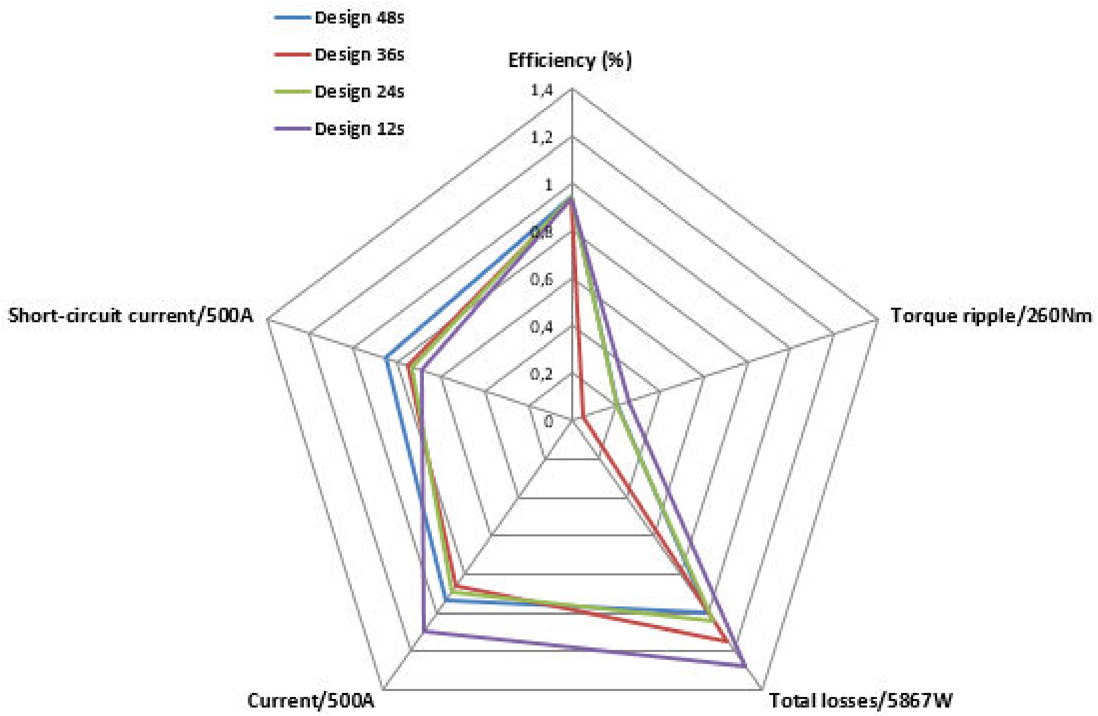


- Cogging torque increases with slot opening → industrial feasability!!

3.1) Parametric study: Example Stator and rotor geometries

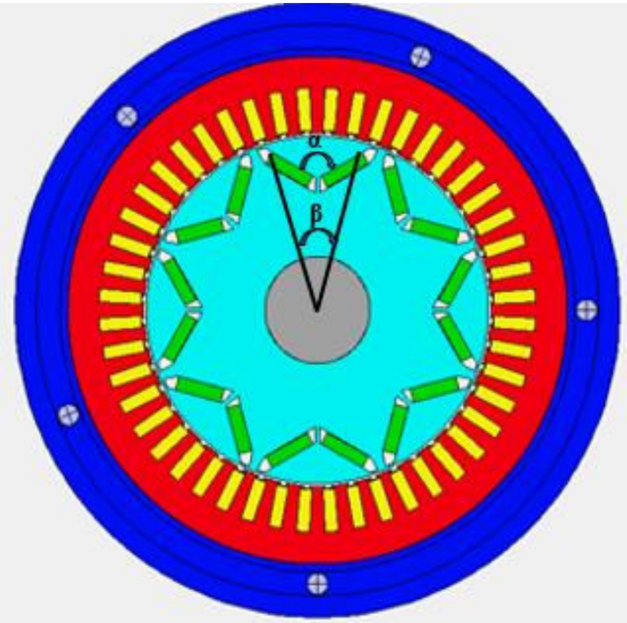
- 48 slots in the stator

8 poles, V shape magnet PMSM performance comparison for 12, 24, 36 and 48 slots in the stator



Compromise losses VERSUS torque ripple

3.2 Permanent Magnet Synchronous Machine design



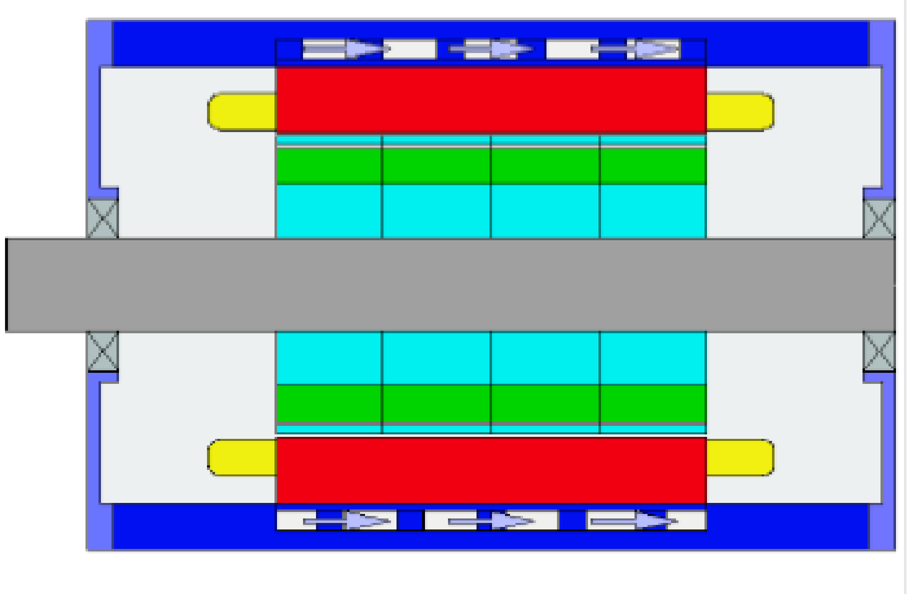
M250_35 steel
M40 UH magnet
L = 150mm

- 260 V, 260 Nm, 13000 rpm, D = 190 mm, Idcmax = 450 A
- Minimum magnet weight
- Maximum efficiency
- Peak torque
- Minimum cogging torque and torque ripple

Stator parameter name	Value	PMSM rotor Parameter name	Value
Stator outer diameter	190 mm	Magnet thickness	5 mm
Stator inner diameter	132 mm	Magnet lenght	18 mm
Slot width	4,8 mm	Bridge thickness	1 mm
Slot depth	17 mm	Pole V angle (α)	120 °
Slot opening	2,5 mm	Pole arc (β)	145 °
Airgap	1 mm	Magnet separation	3 mm

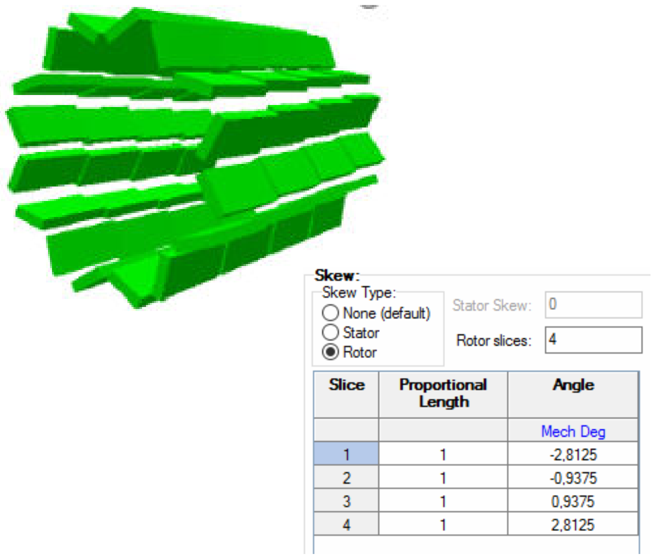
3.2 Permanent Magnet Synchronous Machine design

Cooling = Water Jacket



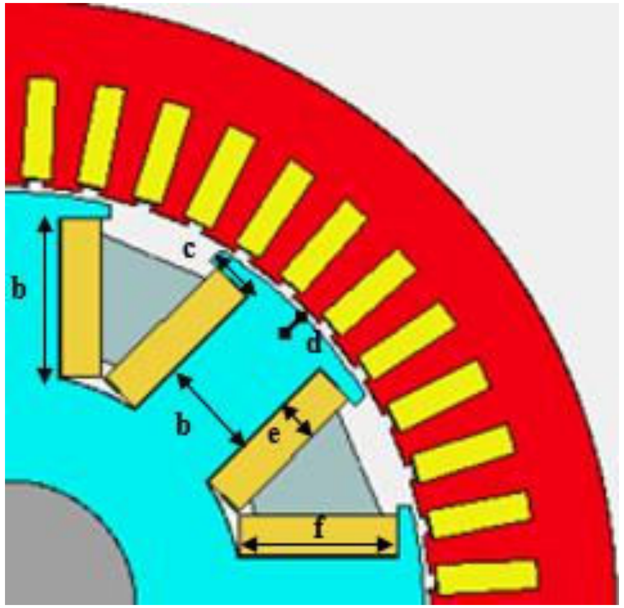
- 50% water, 50% glycol

Skewed rotor



- 4 segments

3.3 Wound Field Synchronous Machine design



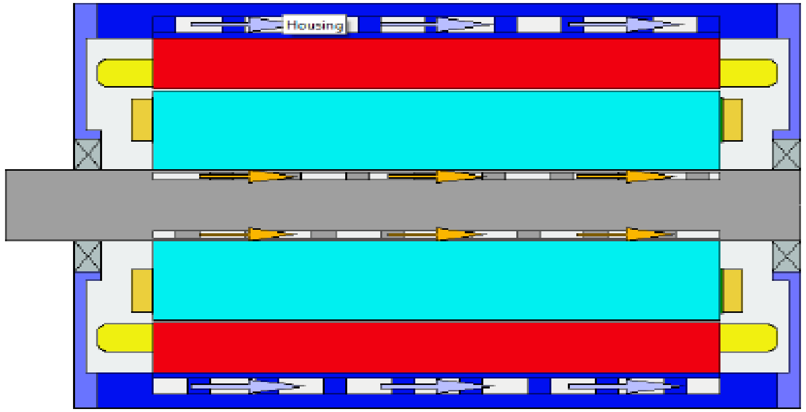
M250_35 steel
Length 250mm → +56%

- 260 V, 260 Nm, 13000 rpm, D = 190 mm, Idcmax = 450A
- The same stator as PMSM
- Maximum efficiency
- Peak torque
- Minimum torque ripple

WFSM rotor Parameter name	Value
Pole width (a)	16 mm
Pole depth (b)	25 mm
Pole tip width (c)	8 mm
Pole tip depth (d)	4 mm
Rotor coil width (e)	6,5 mm
Rotor coil depth (f)	24,5 mm

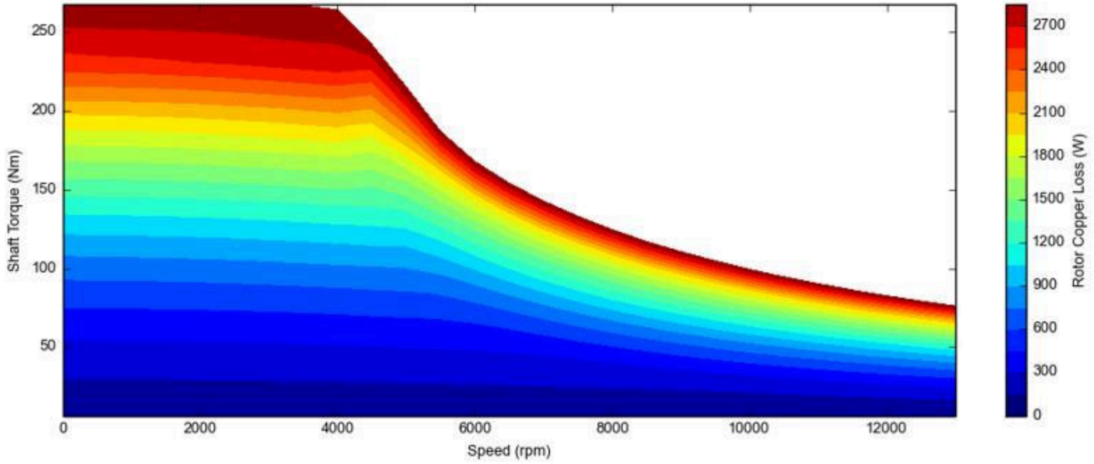
3.3 Wound Field Synchronous Machine design

Cooling = Water Jacket + Shaft cooling



- 50% water, 50% glycol

Rotor losses



Rotor copper losses represents until 25% of the total losses ⬄ 2,700 kW

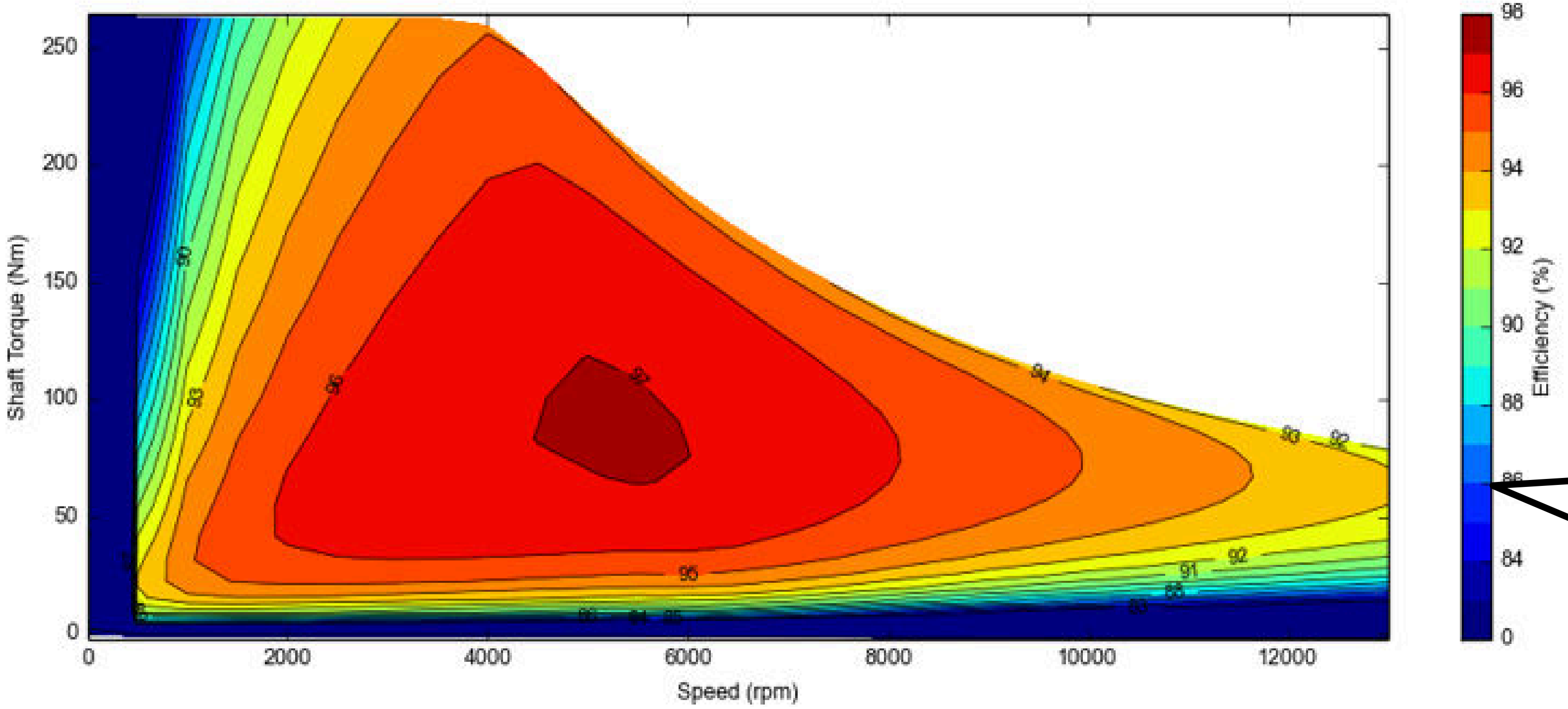
→ Rotor cooling

→ Lower efficiency compared to PMSM (magnet losses < 10W)

4) Performances comparison

4.1 Efficiency maps: PMSM

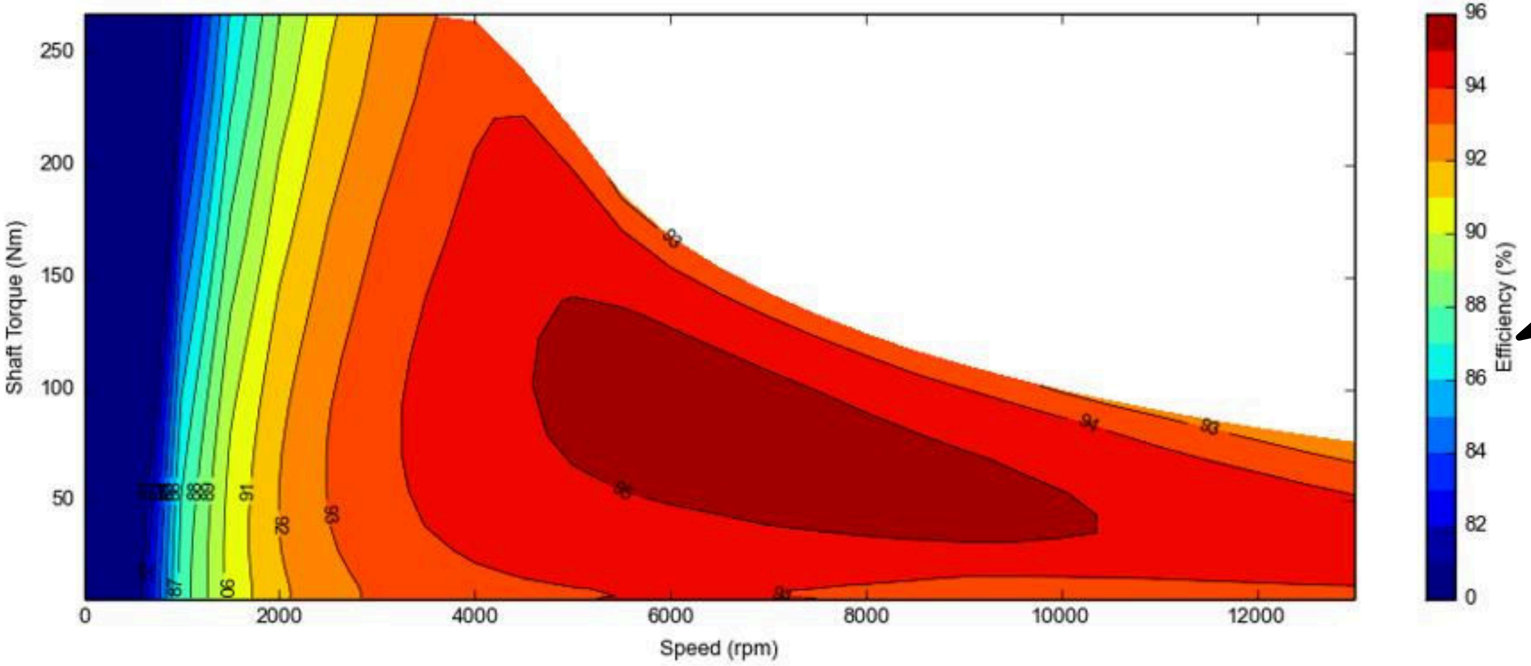
- 260 V, 450 A max, maximum torque control
- AC and DC losses
- Iron losses
- Magnet losses



η (5000rpm, 100Nm): 97,1%
η (4000rpm, 260Nm): 94,9%
η (13000rpm, 49.5Nm): 92,8%

4.1 Efficiency map: WFSM

- 260 V, 450 A max, Minimum total copper losses control
- AC and DC losses for stator
- Iron losses
- DC losses for rotor

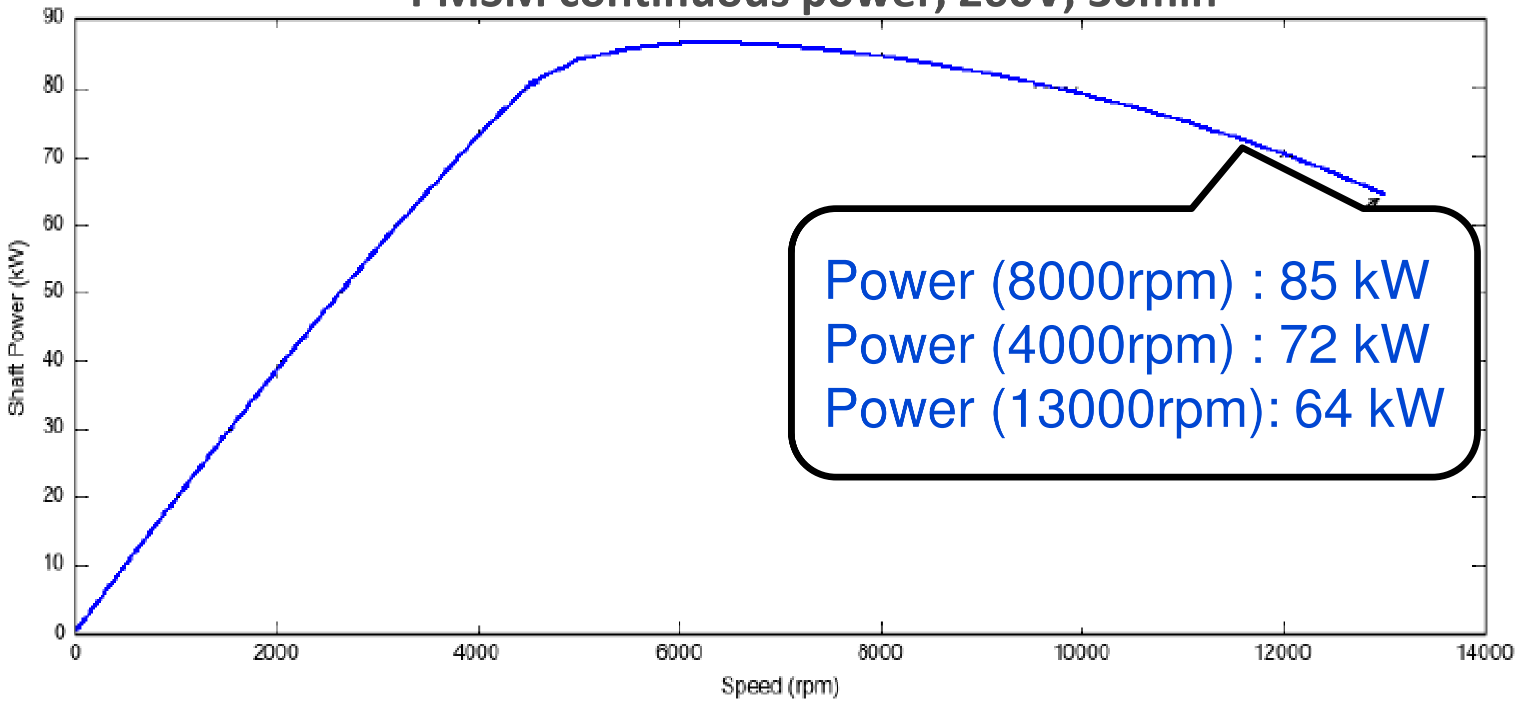


η (6500rpm, 67.5Nm): 95,5%
η (4000rpm, 260Nm): 93,5%
η (13000rpm, 50Nm): 94,2%

4.2 Continuous power: PMSM

- Stator winding maximum temperature = 180°C
- Magnet maximum temperature = 160°C

PMSM continuous power, 260V, 30min



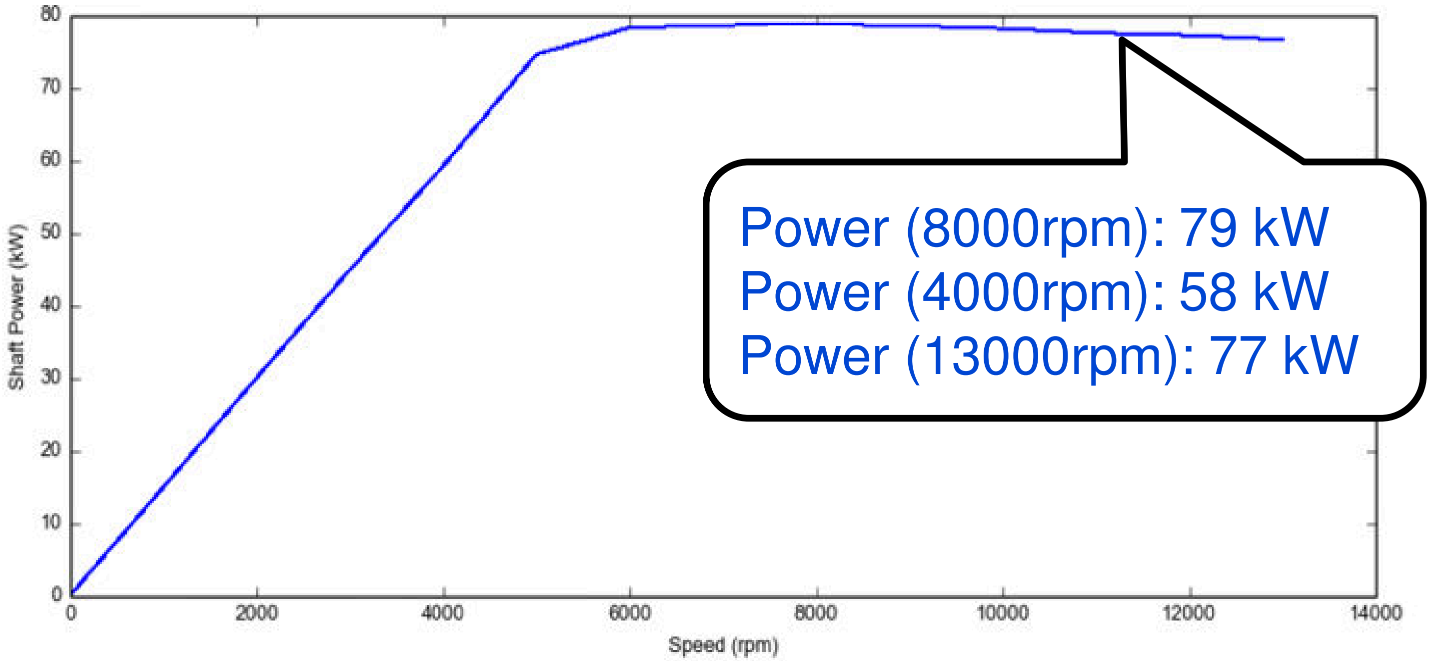
→ **Limited by stator winding maximum temperature**

→ **Power decreases at high speeds**

4.2 Continuous power: WFSM

- Stator winding maximum temperature = 180°C
- Rotor winding maximum temperature = 180°C

WFSM continuous power, 260V, 30min



→ **Continuous power limited by rotor winding max temperature**

→ **Flatter curve**

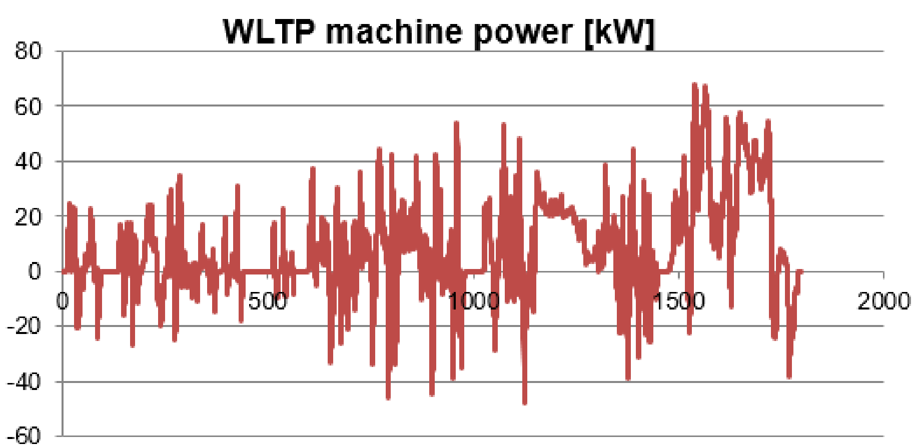
4) Performances comparison

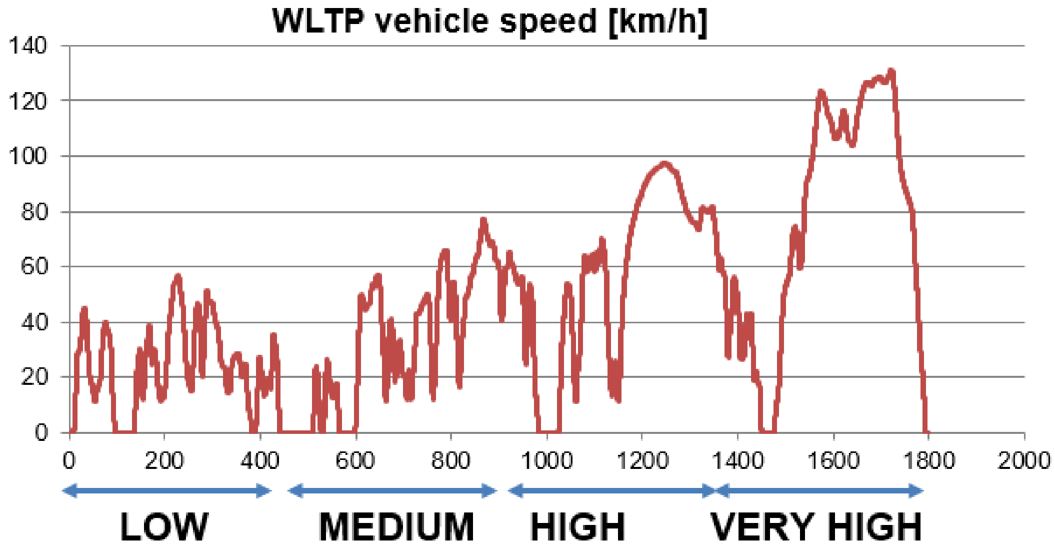
	PMSM	WFSM
Length (mm)	150	250
Continuous power at 13000rpm (kW)	64	**77**
Continuous power at 4000rpm (kW)	**72**	58
Max Efficiency (%)	**97,1**	95,5
Efficiency at base speed peak torque	**94,9**	93,5
Efficiency at high speed 13000rpm 50Nm	92,8	**94,9**

→ PMSM: Maximum efficiency and continuous power
→ WFSM: Higher efficiency and continuous power at high speeds

4.3 Energy consumption comparison

Cycle	Average speed (km/h)	Maximum speed (km/h)
WLTP	30	130
HIGHWAY	120	145
RURAL	70	120
URBAN	8	23

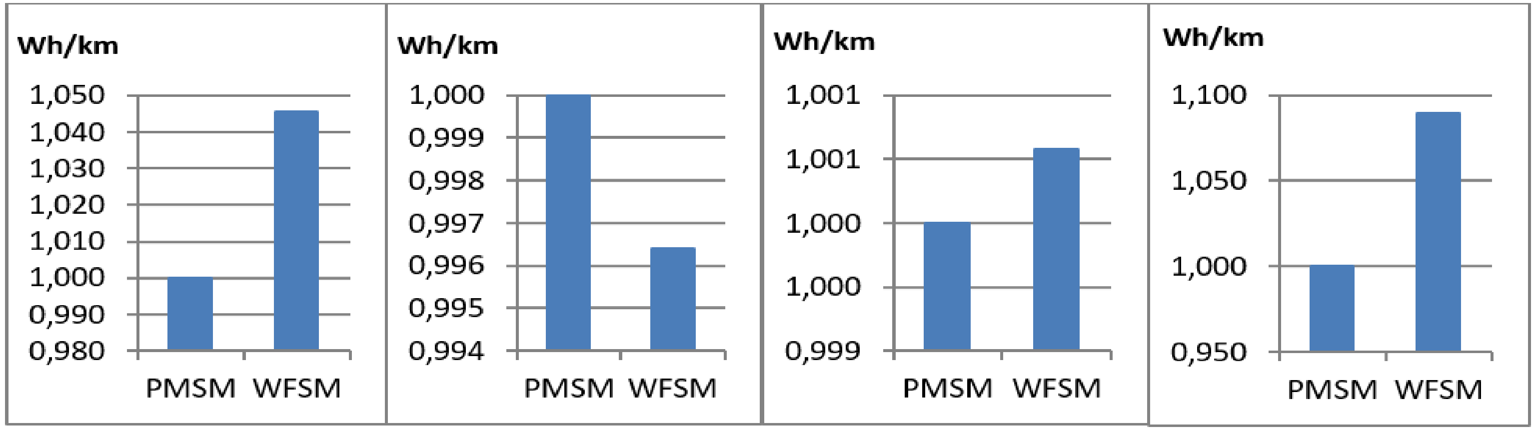




4.3 Energy consumption comparison

Consumption WFSM versus PMSM

+4,5% -0,36% +0,1% +8%



WLTP **HIGHWAY** **RURAL** **URBAN**

- → **WFSM better for high speed cycle : highway**
- → **WFSM equivalent for rural cycle**
- → **PMSM better for low speed cycles: urban**
- → **PMSM better for mixed cycle: WLTP**

5) Conclusion

- **WFSM**

- longer machine → +50%
- Additional rotor cooling and supply
- Lower efficiency for most of the operating points

+ Magnets free solution and rotor controllability
+ Consumption equivalent to PMSM for high and medium speed cycles

- **PMSM**

+ Reaches higher efficiencies
+ Low consumption for all the cycles

- Magnets: controllability, cost and prices volatility

Which machine for which cycle?

Cost, feasibility versus vehicle utilization