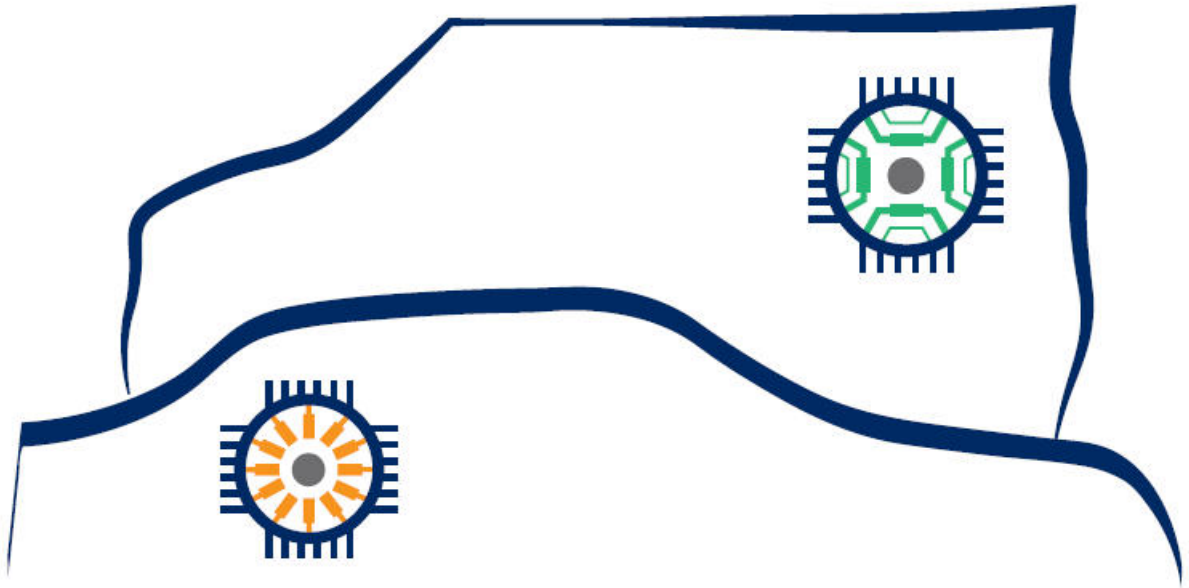


ReFreeDrive

Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

IFPEN

ReFreeDrive

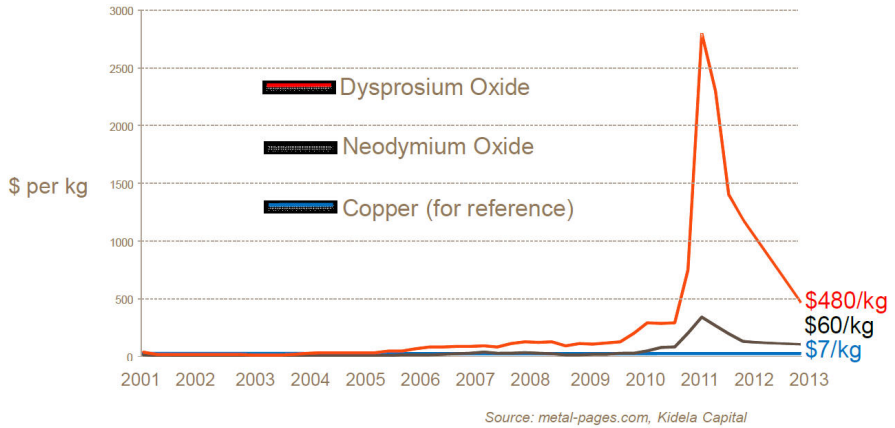
Content

- Introduction
- Preliminary design of a 200kW PM SynRel Motor without rare-earth magnets
  - Main specifications
  - Design procedure
  - Electromagnetic design
  - Thermal design
  - Mechanical design
- Parametric study according to:
  - number of pole pairs
  - magnet type
- Scalability
- Conclusion and outlook

Introduction

Context

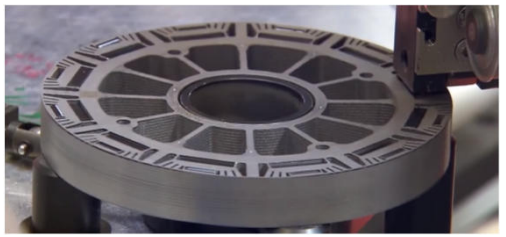
- Electrical machines with rare-earth permanent magnets exhibit excellent performances, such as:
  - power density,
  - torque density,
  - efficiency,
  - power factor,
  - a wide speed-regulation region
- However, there are some limits :
  - high costs
  - volatile costs
  - supply chain uncertainty for rare-earth PMs because of neodymium and dysprosium
- Therefore, less or no rare earth PMs can be considered to decrease the total cost of electrical machines



Introduction

Context

- Although some electrical machines without rare-earth PMs can achieve some excellent performance such as:
  - Induction, wound rotor
  - Switched reluctance machines
  - Synchronous reluctance machines

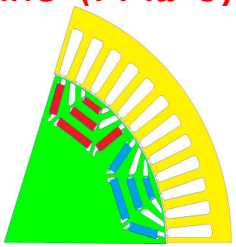


- Nonetheless, there are some problems, such as :
  - Copper rotor losses in IM and wound rotor
  - Vibration acoustic noise in SRMs
  - Low power factor in SynRels

Otherwise, rare-earth PMs can be replaced by low-cost ferrite magnets

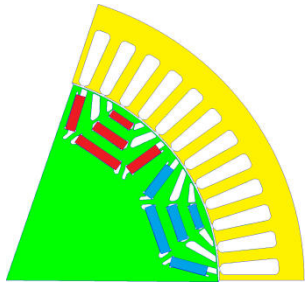
- In order to achieve high performances and for reducing total cost of electrical machines,

→ a novel permanent magnet-assisted synchronous reluctance machine (PMa SynRel) with ferrite magnets is proposed



Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Main specifications



Performances	Reference
DC Voltage [V]	350
Base speed [RPM]	5000
Rated torque [Nm]	210
Rated power [kW]	100
Maximum torque [N.m] (30 s)	400
Maximum power [kW]	200
Maximum current [A]	1000
Cooling	Water Jacket

Geometry	Reference
Stator external diameter [mm]	<300
Active length [mm]	200
Airgap [mm]	0,6
Number of pole pairs	5
Number of slots	60

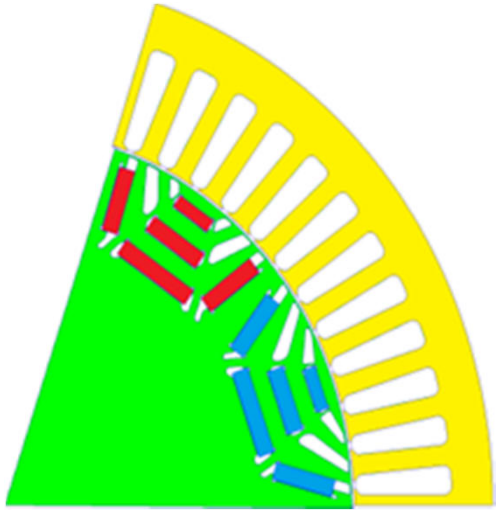
Materials	Type
Magnets	NMF_15G
Electrical Steel	M235-35A
Working Temperature [°C]	[20°-100°]

Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Design procedure

- The electromagnetic design is performed by 2-D FEA
  - Iterative design to ensure the electromagnetic performances
  - Torque ripple minimization is achieved by the position barriers' optimization
- The thermal and mechanical analysis are performed by using Ansys Workbench

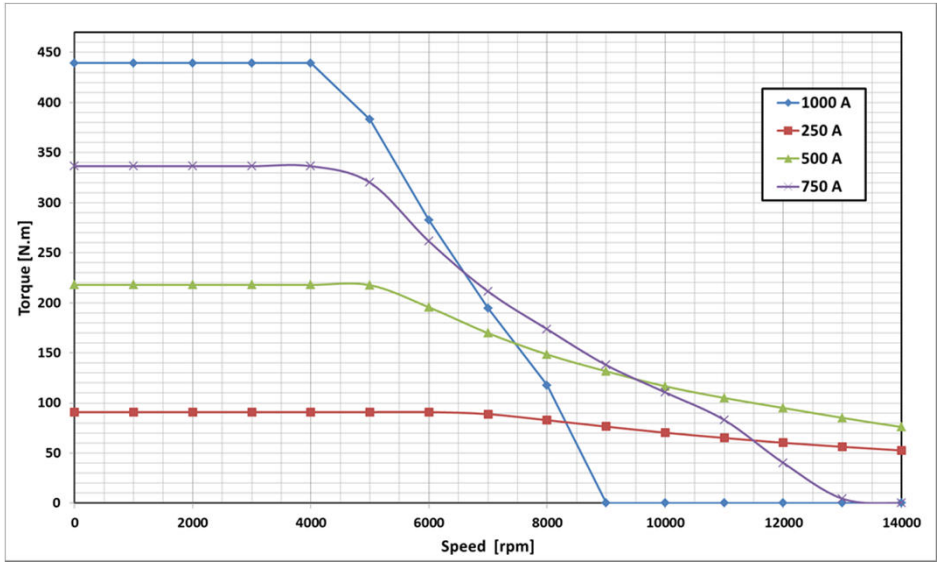
The designed PM SynRel Motor with asymmetric rotor

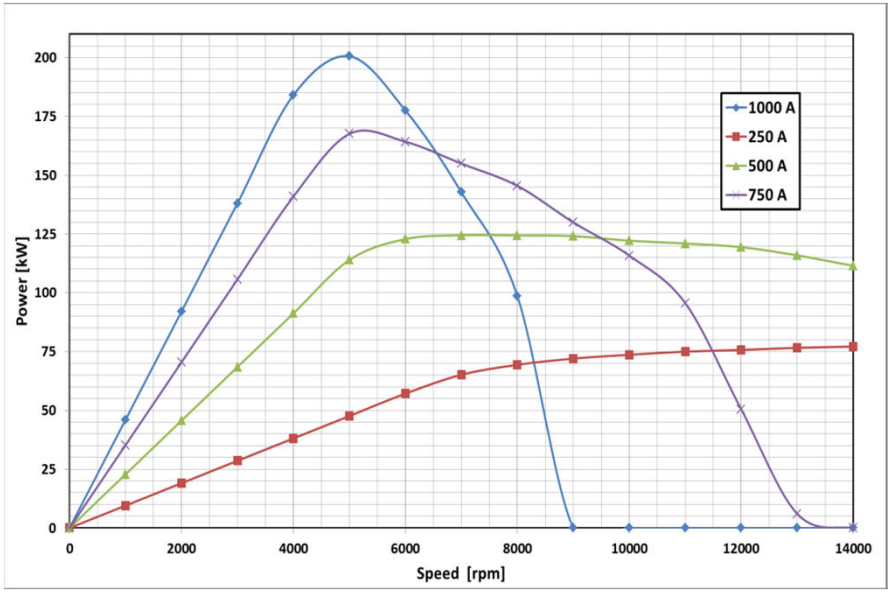


Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Electromagnetic design

- Torque and Output Power vs. Speed





- The designed PM SynRel Motor develops 200kW at 5000rpm
- The maximum torque is about 445 Nm.

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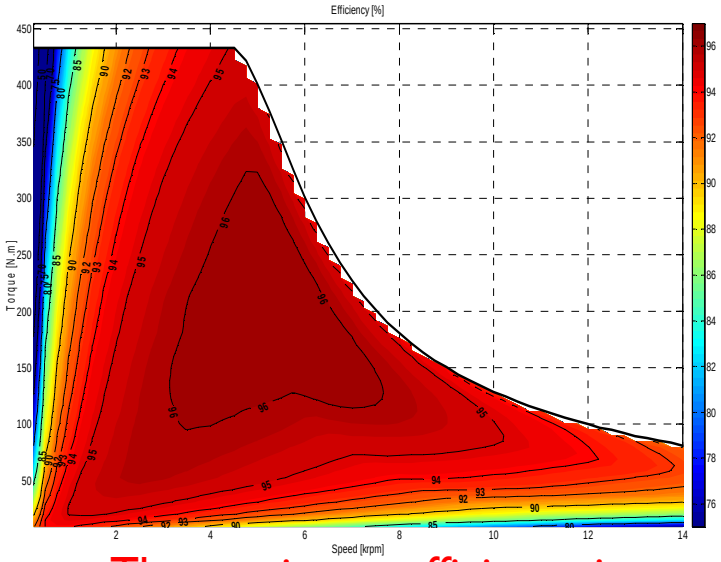
Electromagnetic design

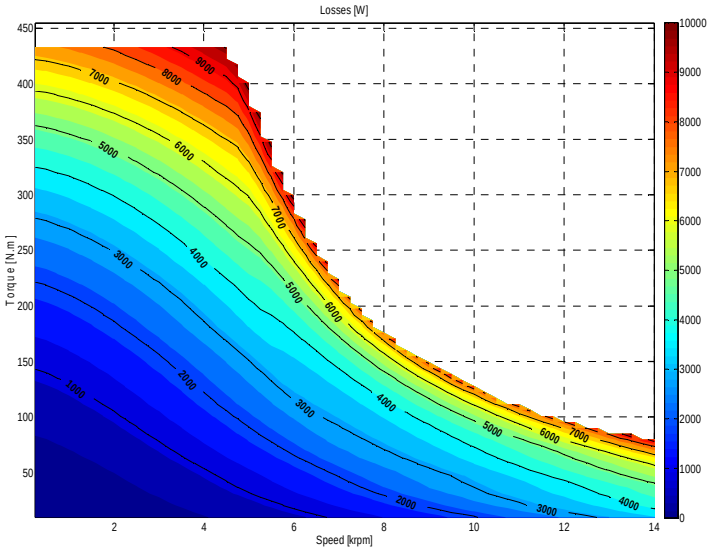
- Ripple torque v. currents

Current [A]	Mean Torque [Nm]	Ripple [%]
250	87,1	19
500	214	11
750	337	9,1
1000	445	7,8

=> At maximum torque operation, the torque ripple is less than 8 %.

- Efficiency and loss maps





The maximum efficiency is around 96.4% and for 50% of the map area, the efficiency is higher than 95%.

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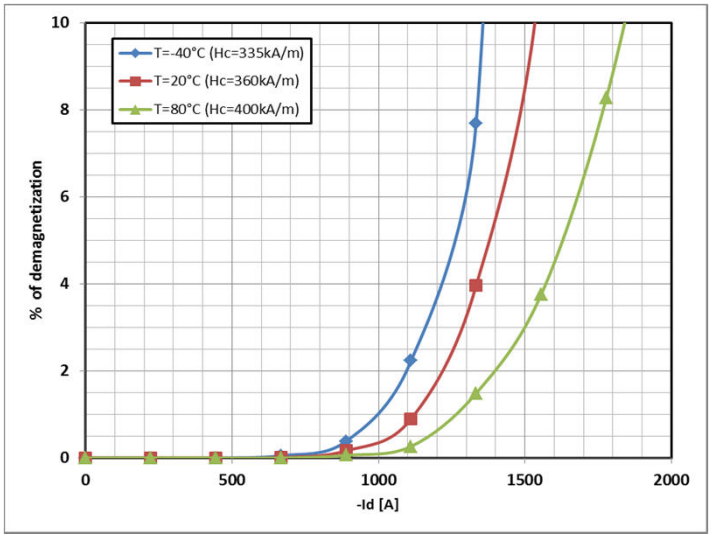
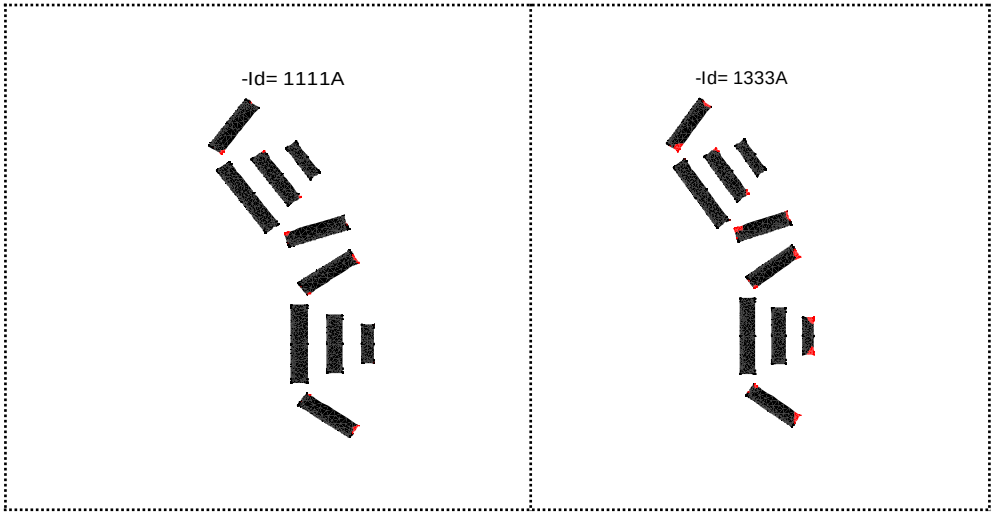
Electromagnetic design

- Evaluation of the Irreversible Demagnetization Rate



Demagnetization rate of magnets



Partially demagnetized magnets

- For a short-circuit current (Id=1333Apeak)

=> the demagnetization rate is around 7.5% for a magnet temperature at -40°C.

- The rate falls to 4% considering a magnet temperature of 20°C.

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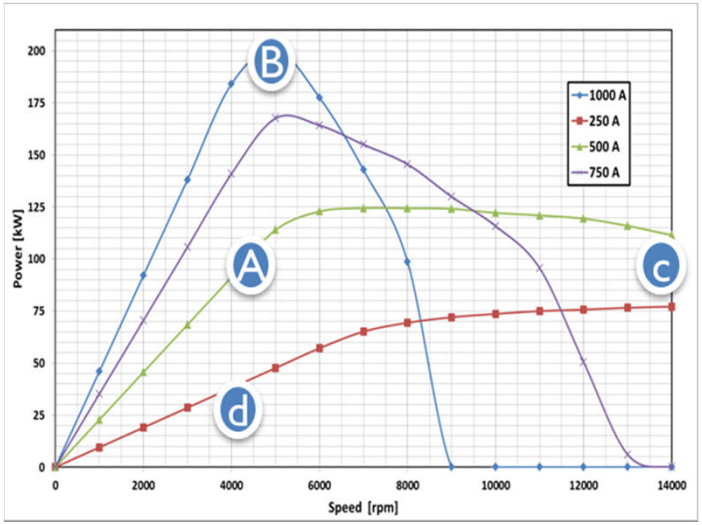
Thermal design

- Assumptions :
  - Housing water jacket type – EGW 50/50
  - Housing outer cooling: natural convection
  - Coolant Flow Rate: 10 l/min
  - Inlet Temperature; 65 °C
  - Ambient operating temperature: 40 °C



- Duty cycles : to evaluate the health status of the magnets and windings
  - High torque A: (40 min) to B(30s)
  - High speed C (10 min) to d (10 min) to c (60 min)

A :rated torque operation

B : peak torque operation

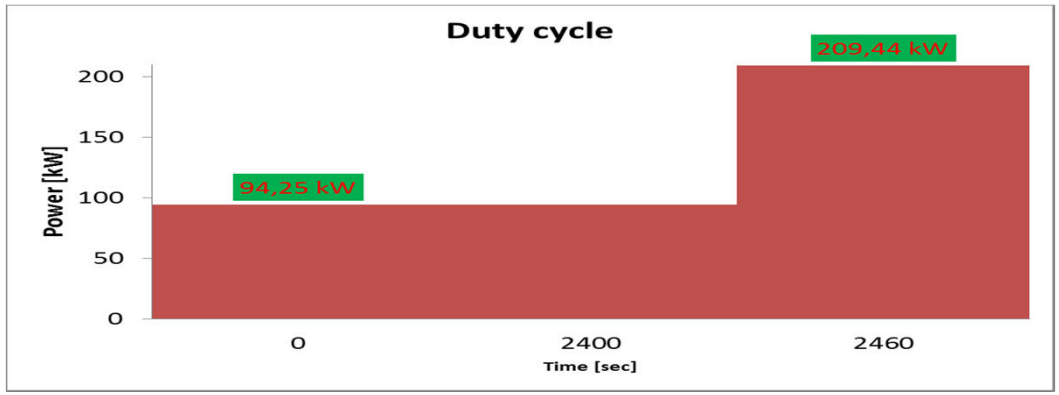
c : high speed operation

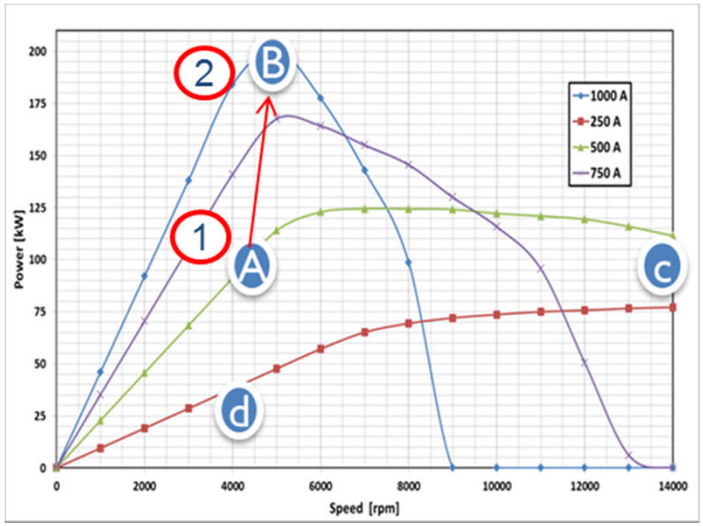
d : low speed operation

Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Thermal design

- Duty cycle : Winding temperature
  - From the rated torque to peak torque (or power)
  - 40 minutes at continuous power then 60 sec at the maximum power

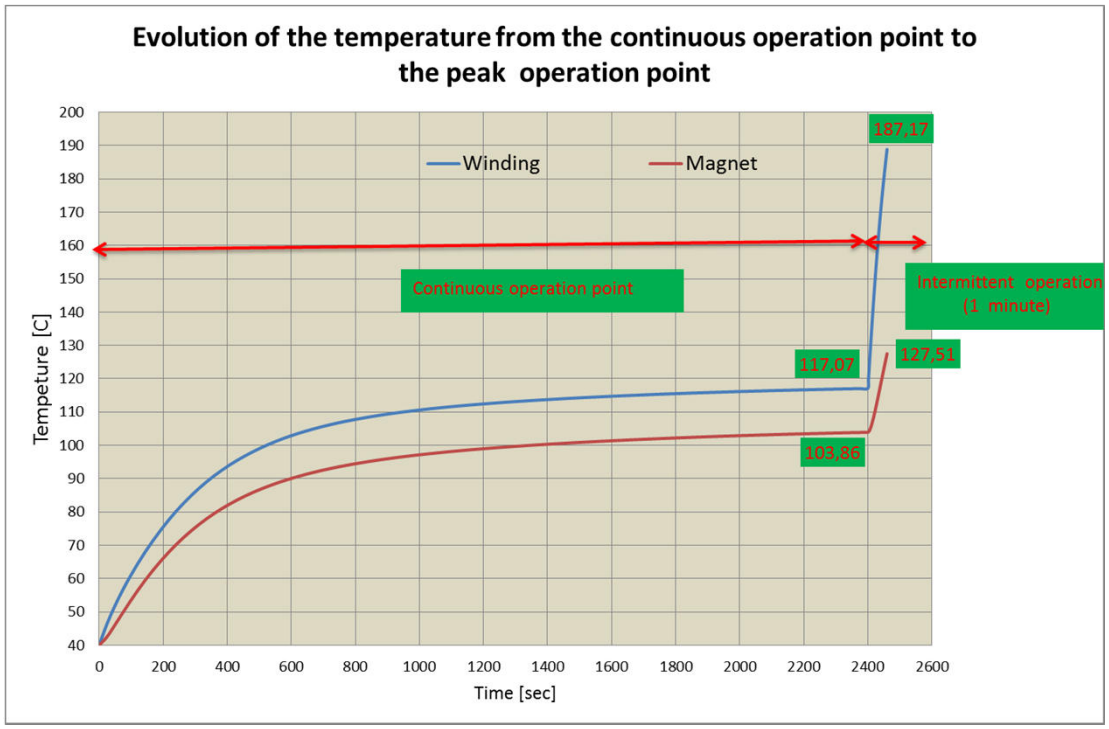




Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Thermal design

- Temperatures : Flow 10 l/min and Tin = 65 °C

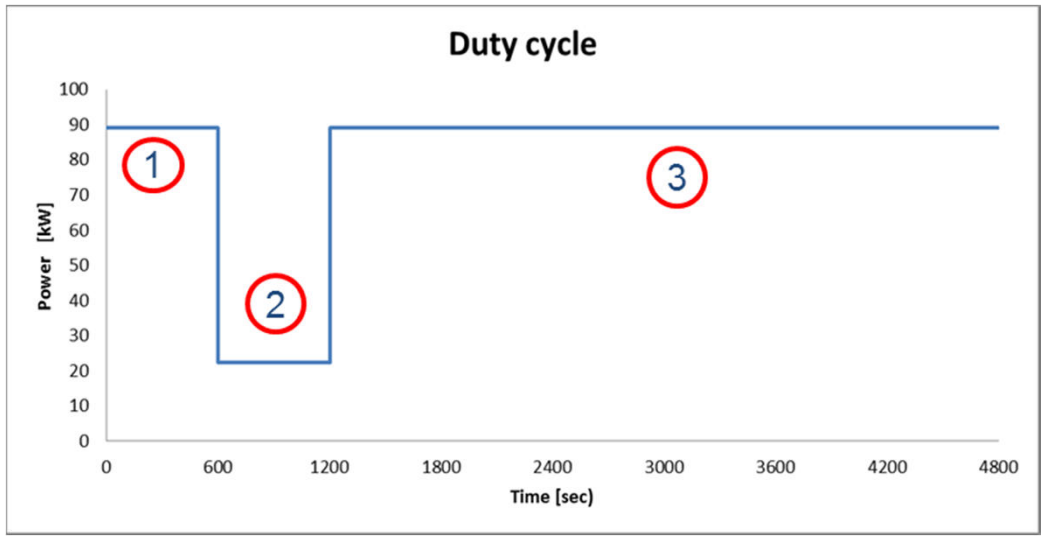


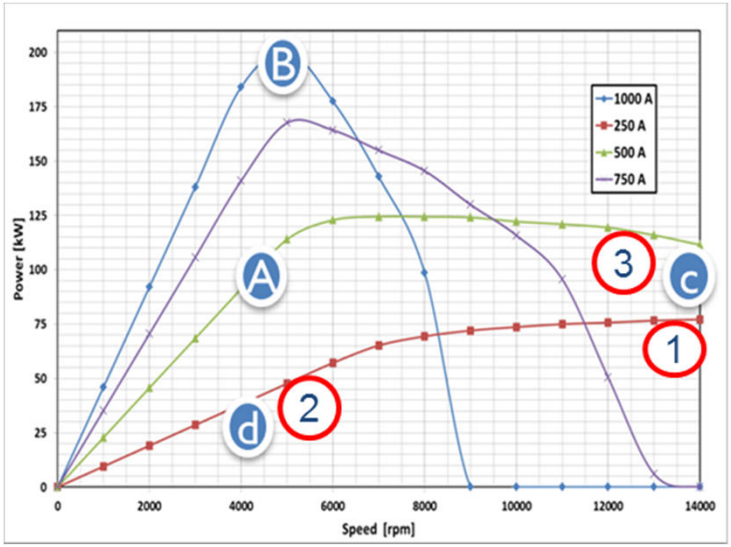
Continuous temperature : <120°C
Intermittent temperature: <180°C (30 seconds)

Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Thermal design

- Duty cycle : for maximum power at high speed
  - 10 minutes at high speed then 10 minutes at low speed, and at the end 60 minutes at high speed.





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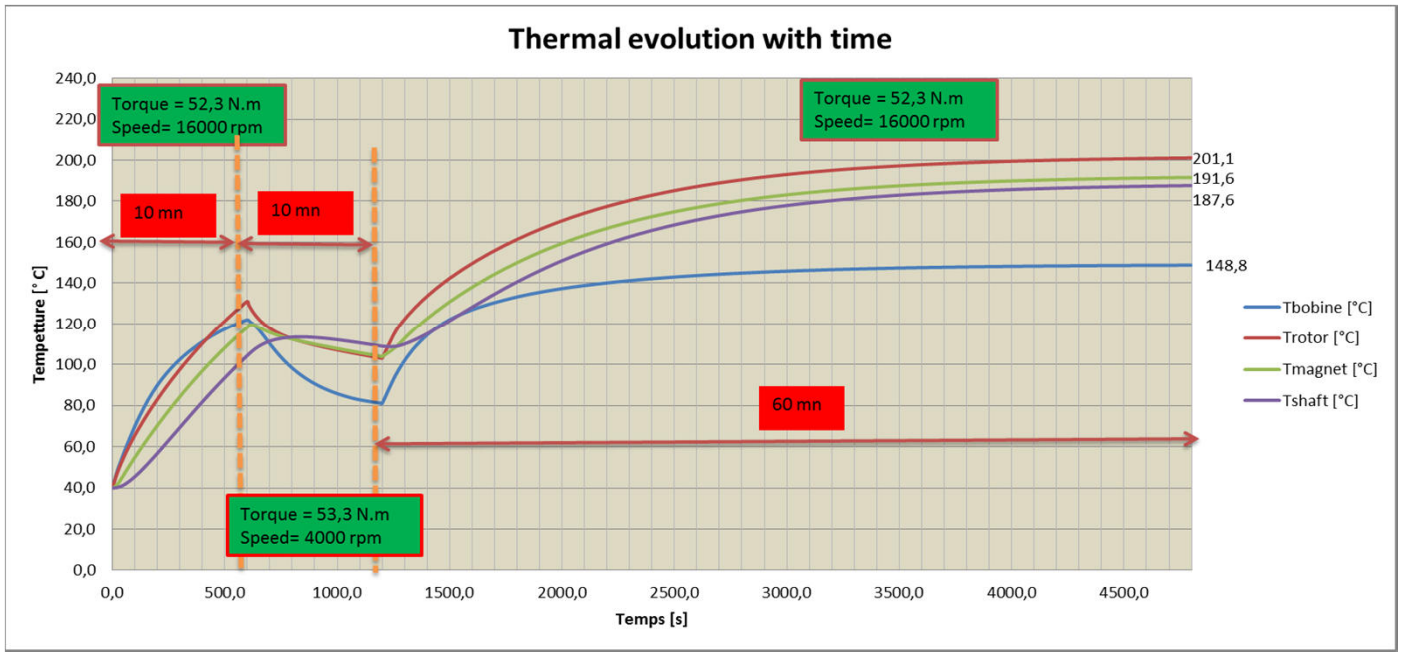
Thermal design

- Thermal Analysis at high speed (53.4N.m, 4000 to 16000 rpm).



The thermal evaluation shows that to rotor temperature is too high=> cooling system must to be improved or the rotor losses must to be reduced

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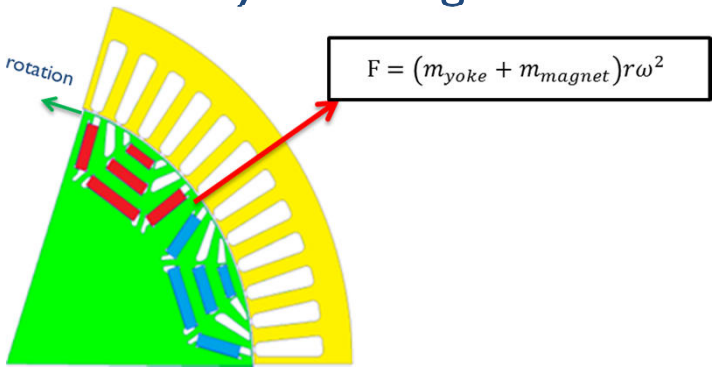
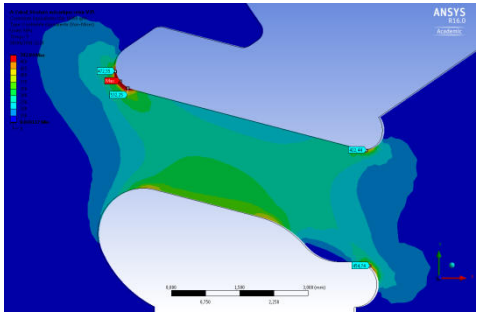
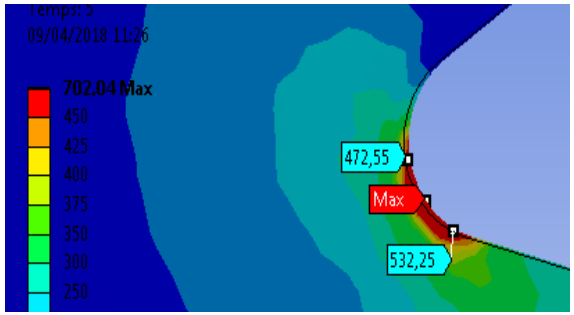
Mechanical design

- Mechanical stress analysis during the rotation : Centrifugal force





The von Mises stress at 16 000 rpm



Zoom: the von Mises stress at 16 000 rpm

The thickness of bridge has to be accurately designed in order to contains rotor at high speed

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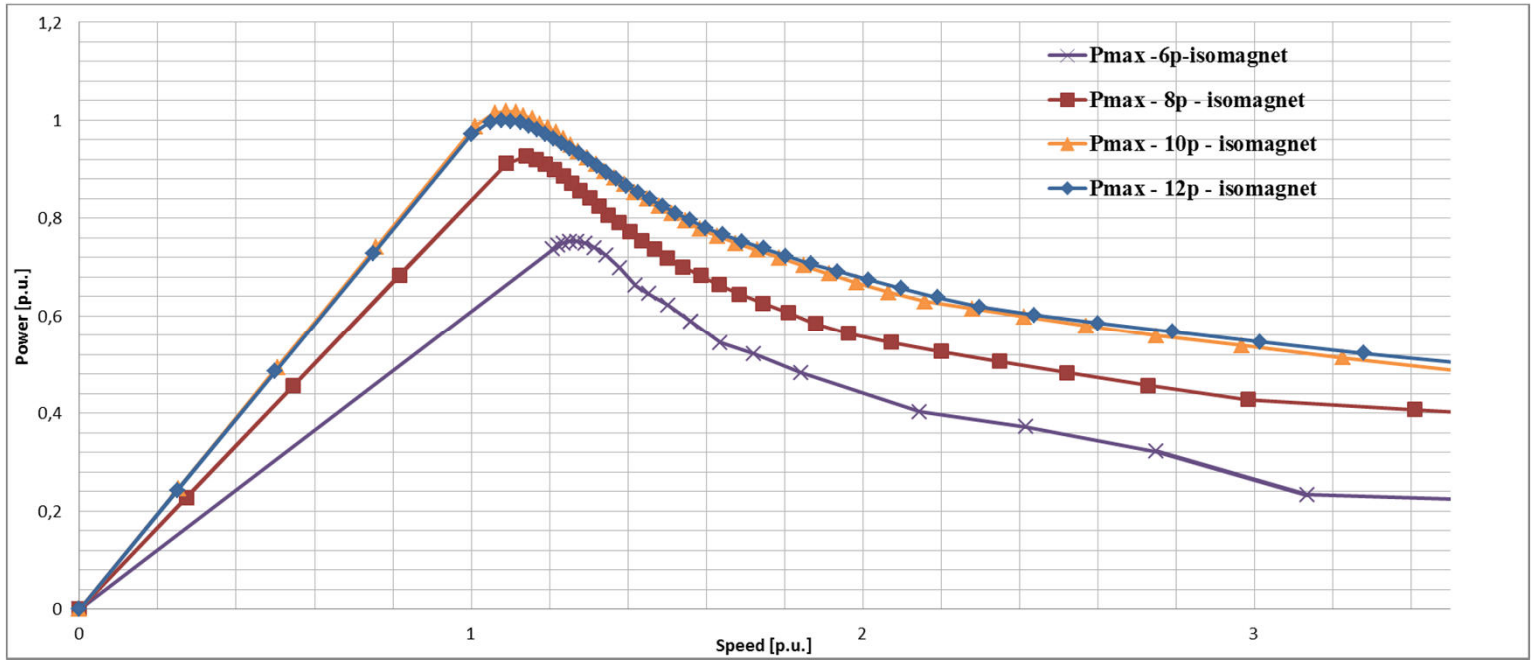
Parametric study: Pole pair number

- Influence of pole pair number



Performances decrease with the reduction of the pole numbers => 10 poles is an optimum

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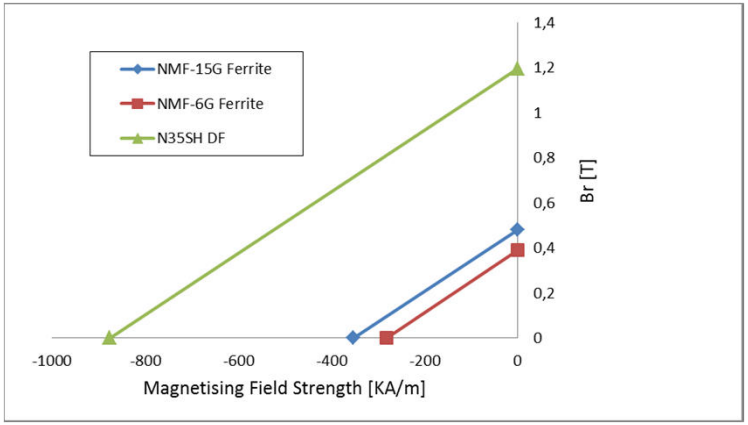
Parametric study: Magnet type

- Influence of the magnets type on the performances

	Br [T]	Hcb [kA/m]	Hcj [kA/m]	(BH)max [kJ/m^3]	μ_r [-]	Tmax [°C]
NMF-15G (Ferrite)	0,48	353	382	43	1,08	250
NMF-6G (Ferrite)	0,39	282	382	28,6	1,10	250
N35SHDF (Dy Free)	1,195	876	1600	275	1,08	150



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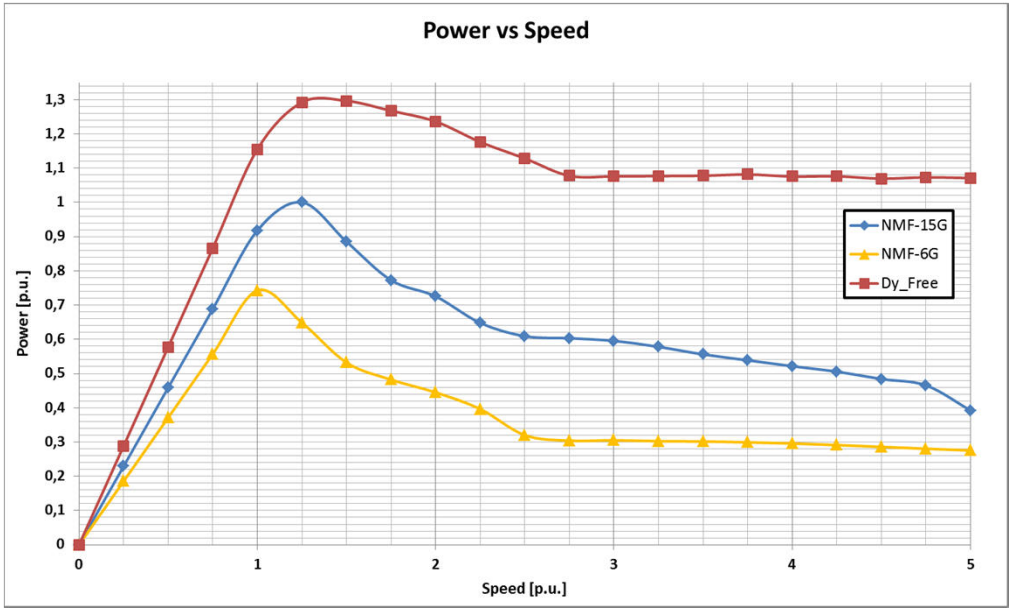
Parametric study: Magnet type

- The type of the magnet has an important impact on the performances:

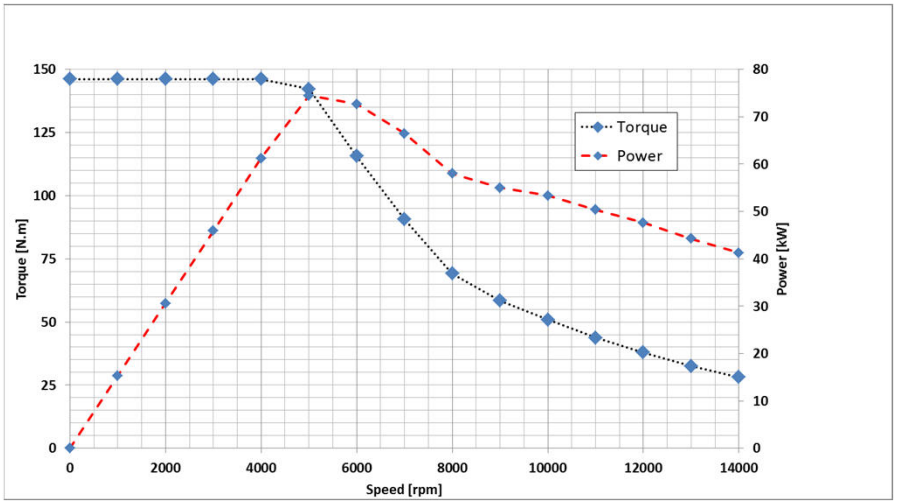


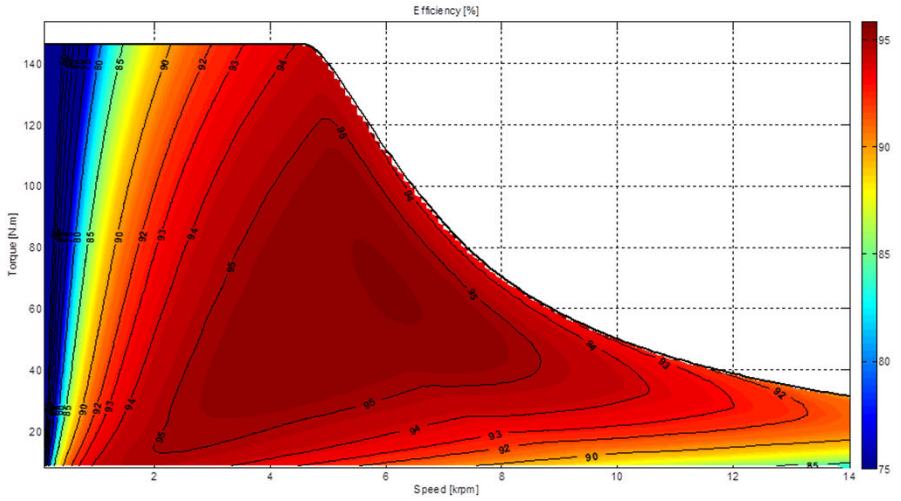
	Max Power (vs NMF- 15G)	Cont Power (vs NMF-15G)
NMF-6G (Ferrite)	-25%	-50%
N35SHDF (Dy Free)	+30%	+300%

Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Scalability

- The same stator and rotor design is used to size a 75kW PM SynRel Motor
  - Active length of the motor :75 mm
  - Number of spires per slot : 14
  - Maximum current per phase : 350 Apeak
- Torque and Output Power vs. Speed/ Efficiency map

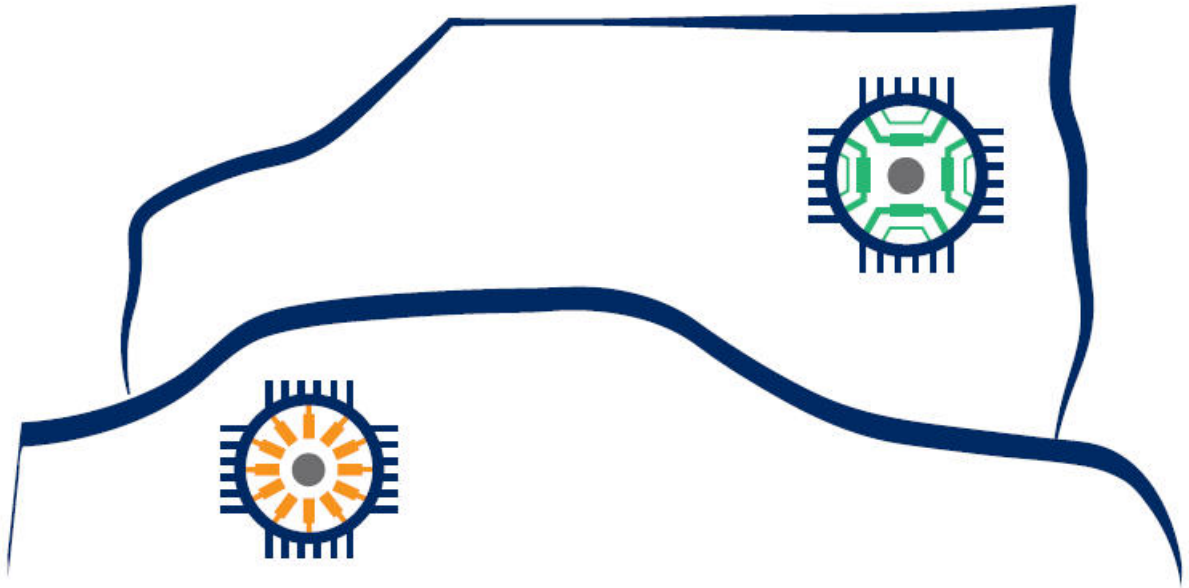




Rare Earth Free PM Assisted Synchronous Reluctance Motor for Electric Vehicles

Conclusion and outlook

- ✓ A preliminary design of a 200kW PM SynRel Motor without rare-earth magnets is proposed
  - The electromagnetic design meets the requirements
  - The mechanical and thermal analysis show that:
    - Rotor temperature must to be reduced by using an adapted cooling system or by reducing the rotor losses
    - Rotor bridges must de be designed to withstand the centrifugal force at the maximum speed
  - Parametric Study
    - 10 poles is an optimum to meet the electromagnetic requirements
    - the type of magnets has an important impact an the performance => the maximal power is reduced by 30% compared to the low cost NeDFB
- ✓ Scalability has been investigated by designing a 75 kW motor using the same geometry as for the 200 kW motor design
- ✓ An optimisation of the preliminary design will be carried out in order to:
  - Improve the performances
  - Satisfy the thermal and mechanical constraints
- ✓ 200 and 75 kW PMa SynRel motors will be prototyped and tested at IFPEN facilities



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Thanks for your attention!