UNIVERSITY OF L'AQUILA

DEPARTMENT OF INDUSTRIAL AND INFORMATION ENGINEERING AND ECONOMICS

ReFreeDrive

Synchronous Reluctance Motor for Traction Applications

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The hybrid electric vehicle and pure electric vehicle represent the most viable solutions to solve the problems associated with the traditional internal combustion engine motors.

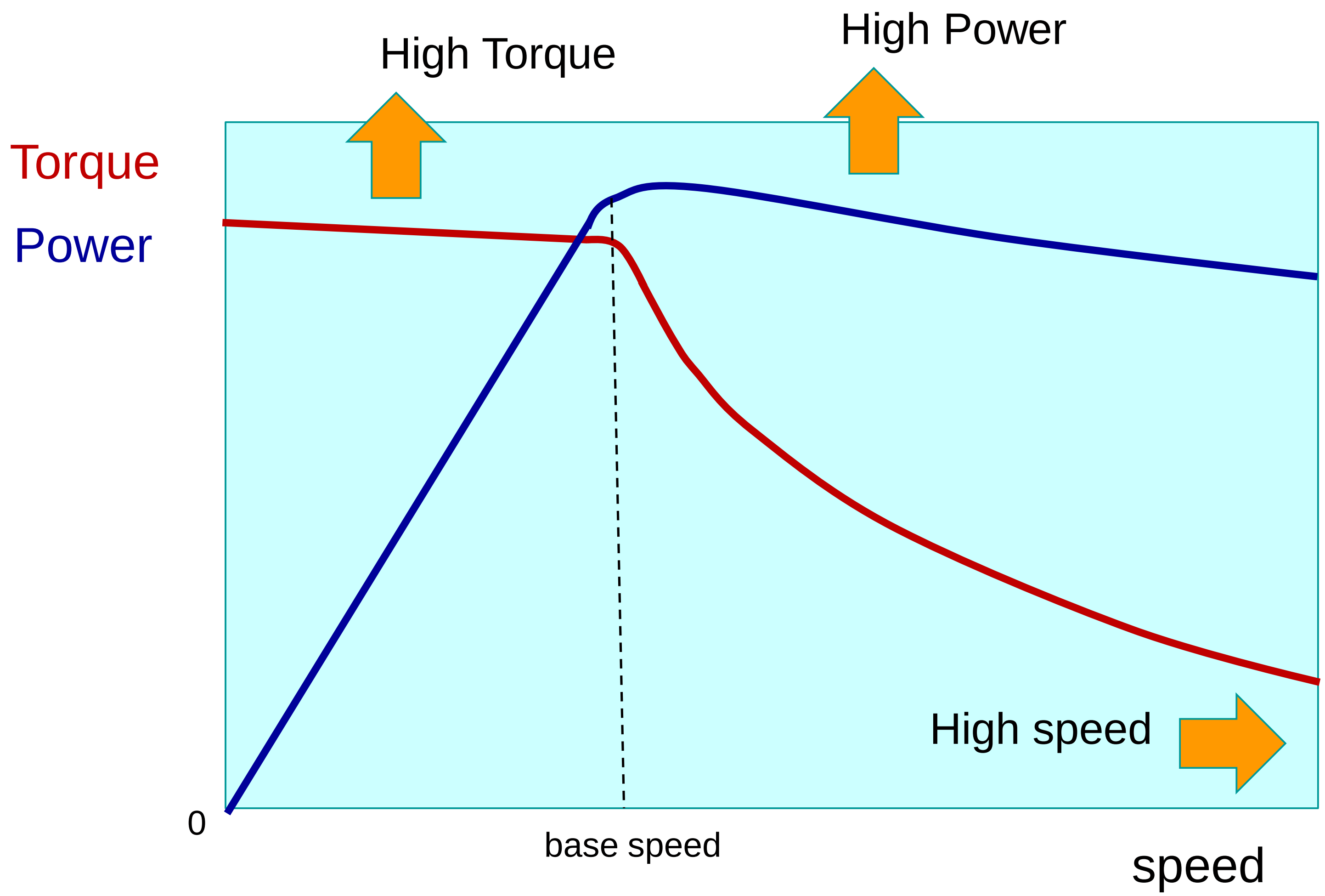
There are many demands for developing propulsion systems with high power density and high efficiency and the research in this field has been intense in the past few years.

Main requirements

The main requirements of electrical machine for traction applications are:

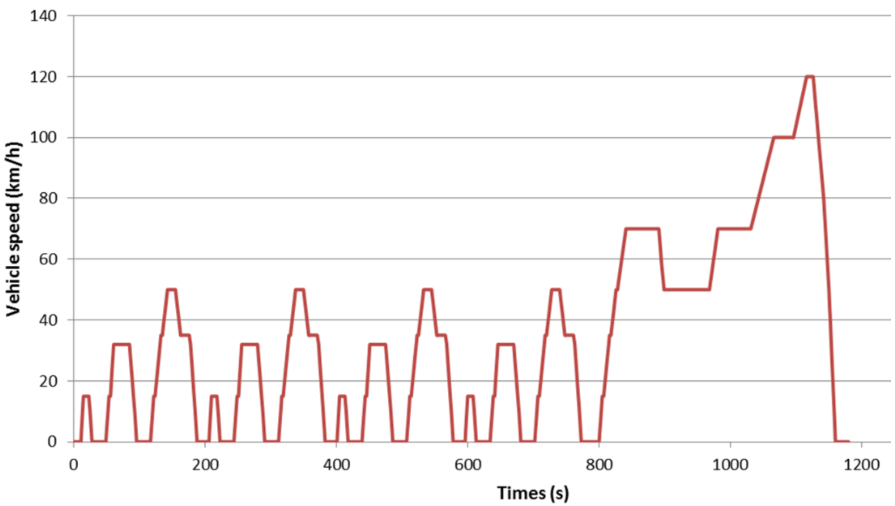
- high torque and power density;
- wide speed range;
- high efficiency over wide torque and speed range;
- wide “constant power” operating capability;
- robustness and reliability;
- reasonable cost.

Main requirements

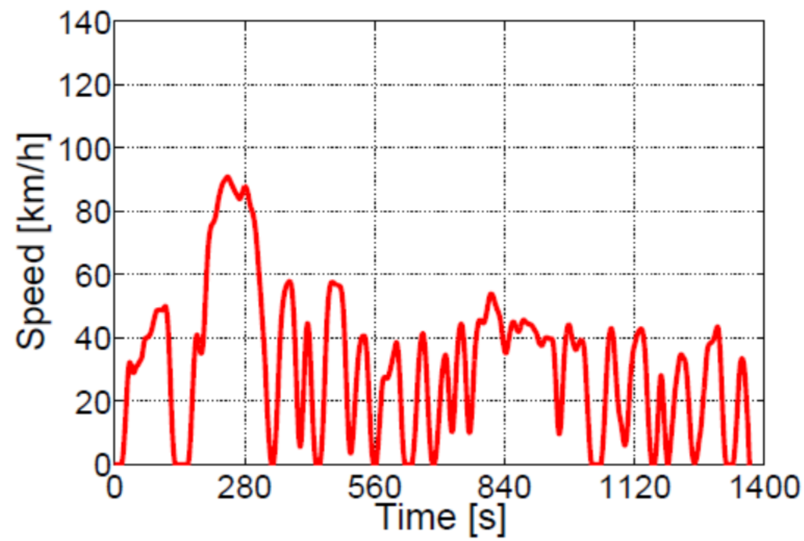


Since the EV operates over a wide torque-speed range in various driving conditions, the motor design should also be aimed to achieve overall energy saving over a driving cycle of the vehicle.

New European Drive Cycle – NEDC



Urban Driving Schedule (UDDS)

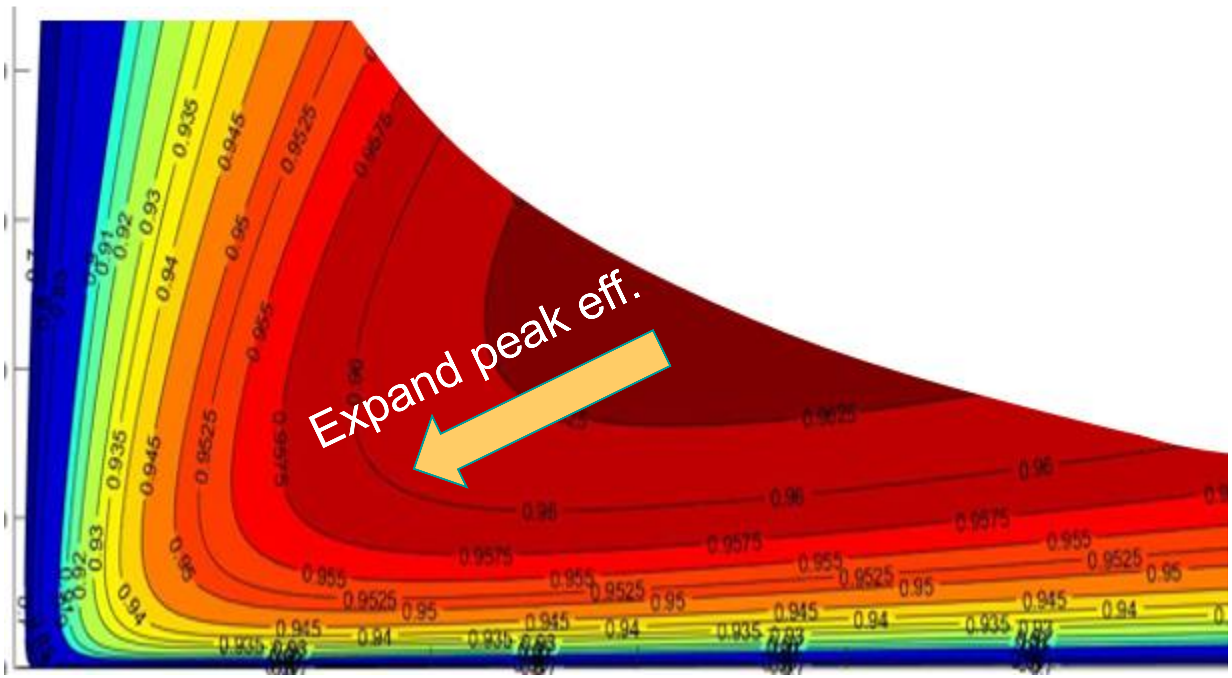


On-road traction motor Efficiency map

expand regions of high efficiency operation

(peak efficiency regions do not match the most frequent operating points)

Torque



Speed

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The vast majority of motor solutions rely on PM technology using rare-earth magnets. They offer a good compromise of high specific torque and low losses, which justifies its choice in most applications.

Electric vehicles in the European & US markets

Vehicle	Motor type	Specifics
BMW i3	Interior PM	Rare-earth
Chevrolet Volt	Interior PM	Ferrite/ Rare-earth
Hyunday Sonata	Surface PM	Rare-earth
Mitsubishi PHEV	Interior PM	Rare-earth
Nissan Leaf	Interior PM	Rare-earth
Porsche Panamera	Surface PM	Rare-earth
Tesla S	Induction motor	Copper cage
Toyota Prius	Interior PM	Rare-earth

IPM rotors for EV motors

J.R. Hendershot – Electric traction machines choices for hybrid and electric vehicles

The high and volatile cost of raw materials for magnets makes uncertain their long term availability, especially since the electric traction technology is called to be deployed at large scale in the future transportation system.

It has become mandatory to find alternative solutions, that include **rare-earth free machines** or reduced rare-earth PM machines.

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Types of EVs Motors

Three types of rare-earth free motors have been designed for propulsion:

- Induction motors

- Synchronous Reluctance motors

- PM-assisted SynRel motors

Aim:

To design high performance motors with a strong focus on industrial feasibility for mass production, targeting lower costs with higher specific torque and power density.

Synchronous Reluctance motors

These motors with multi-barriers rotor structures have been obtained a great interest in brushless AC drives.

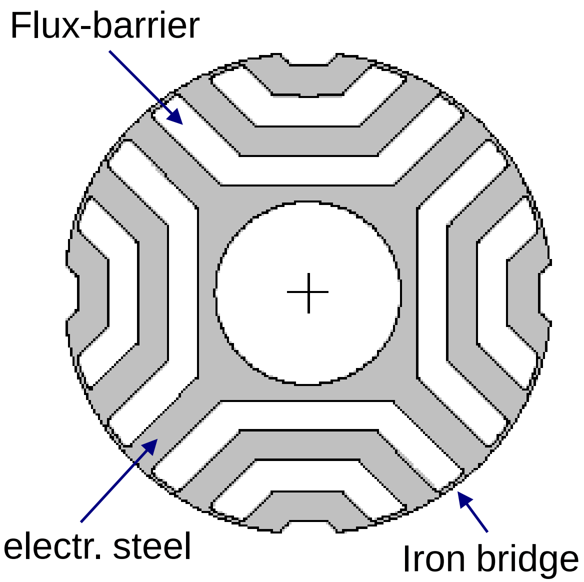
Advantages:

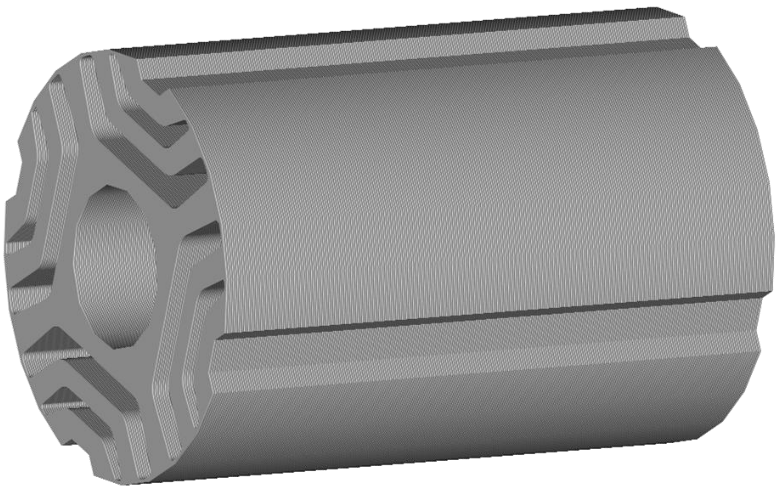
- no winding and PM in the rotor (“cold” rotor),
- low inertia,
- good acceleration performance,
- good flux weakening operation,
- low manufacturing cost.

Drawbacks:

- low power factor;
- torque ripple.

Flux barriers Rotor





Saliency ratio $k_s = L_d/L_q$

The torque produced by the SynRM is due to the **anisotropy** of the rotor.

The number of rotor flux barriers affects the anisotropy, so as this number increases → the reluctance torque component increases.

Electromagnetic Torque

The electromagnetic torque of the SynR motor in the rotor reference frame is:

$$T = \frac{3}{2} p \left[\left(L_d - L_q \right) I_d I_q \right]$$

Reluctance Torque

The Torque can be varied by an accurate control of the d-q axis currents (→ "**Vector control**").

Laminated rotors with flux barriers can be manufactured with normal punching tools at very low cost.

(UnivAQ)

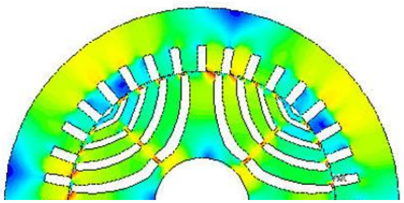
Other important features of the SynRMs are:

1) the rotor is potentially less expensive than both PM and IM motors due to cancelling cage, winding, and magnets from its structures:

2) the Torque per Ampere is acceptable and unlike the PM and IM motors it does not depend on the rotor temperature;

3) the control system is simpler than that of the field oriented IM drives. However, rotor position information is necessary.

Design steps



Requirements

↓

Prelim. designs — Sizing procedure by UnivAQ

↓

FEA
- Electromagnetic
- Mechanical
- Thermal

↓

Design OPT — Optimization tool by UnivRM and UnivAQ

↓

Choice of final design

↓

Prototypes and Test

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Requirements

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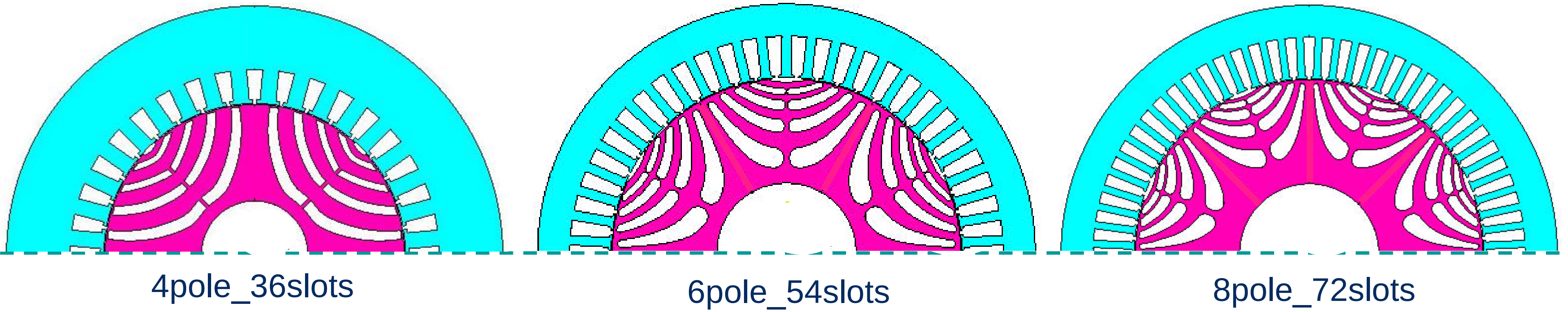
Requirements		Value
DC Voltage	V	**700**
Base speed	rpm	6000
Peak Power @ base speed	kW	200 (60 sec.)
Rated Power @ base speed	kW	125
Max speed	rpm	14000
Rated Power @ max speed	Nm	125
Efficiency	%	> 94
Outer stator diameter	mm	≤ 280
Stack length	mm	≤ 200
Cooling		liquid

Three different solutions have been analyzed



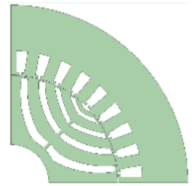
Rotor → 4 layers of flux barriers and radial ribs to improve the mechanical robustness.

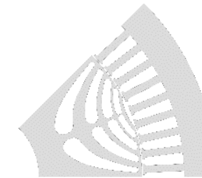
Stator winding → Round wire winding

Electrical steel → Commercial SiFe M235-35A 0.35 mm

Control strategy → max Torque per Amp (MTPA)

Comparison (rated Power)

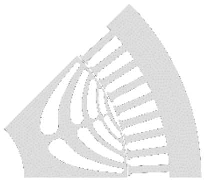




		4 pole – 36 slots	6 pole – 54 slots	8 pole – 72 slots
Stack length	mm	200	200	190
Outer/Inner stator diameters	mm	280 / 170	260 / 180	260/190
Volume (active parts)	lit	12.3	10.6	10.1
Power @ 6000 rpm	kW	125	125	125
Phase current	Amax	425	486	483
Phase voltage	Vmax	300	250	300
Current density	A/mm^2	12.6	12.1	15.0
Efficiency	%	96.27	96.32	96.54
Power @ 14000	kW	120	125	70
Phase current	Amax	350	355	280
Phase voltage	Vmax	360	360	360
Current density	A/mm^2	10.4	8.9	8.6
Efficiency	%	95.79	95.82	94.92

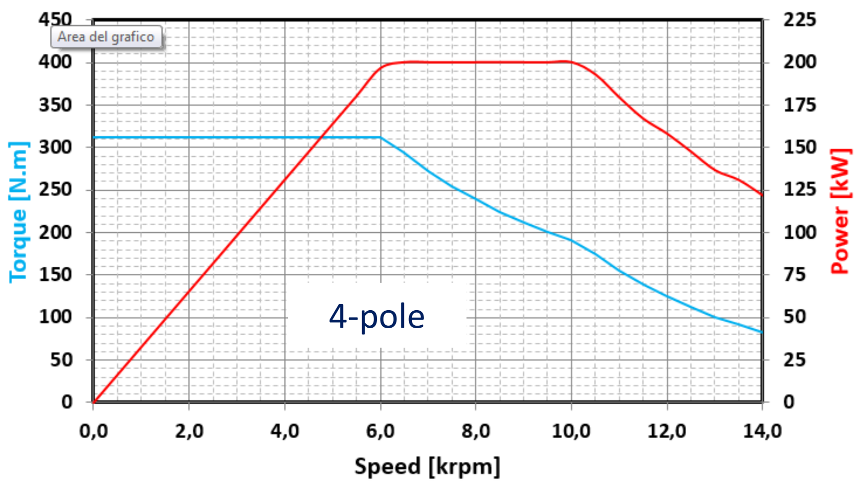
Comparison (peak Power)

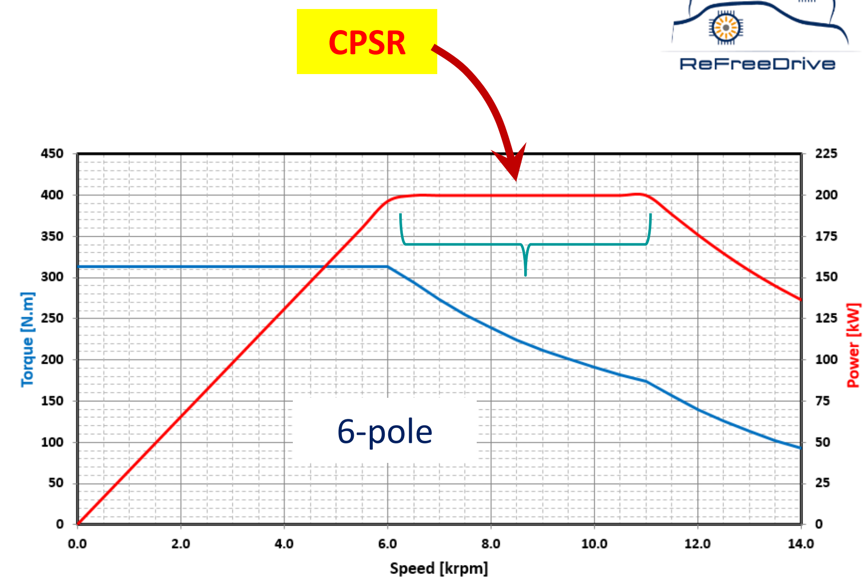


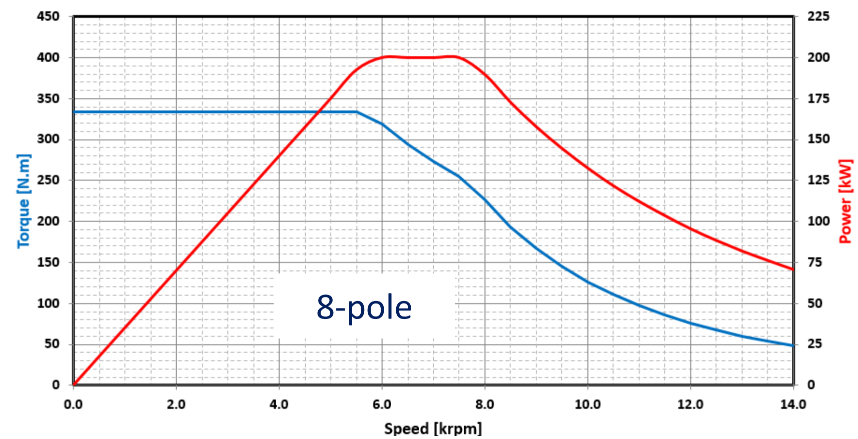


		4 pole – 36 slots	6 pole – 54 slots	8 pole – 72 slots
Stack length	mm	200	200	190
Outer/Inner stator diameters	mm	280 / 170	260 / 180	260/190
Volume (active parts)	lit	12.3	10.6	10.1
Power @ 6000 rpm	kW	200	200	200
Phase current	Amax	600	820	775
Phase voltage	Vmax	320	280	330
Current density	A/mm^2	17.9	20.5	24.0
Efficiency	%	95.05	94.79	93.13
Power @ 14000	kW	120	136	70
Phase current	Amax	350	445	280
Phase voltage	Vmax	360	360	360
Current density	A/mm^2	10.4	11.1	8.6
Efficiency	%	95.79	95.50	94.92

Torque and Power vs. Speed @ peak Power







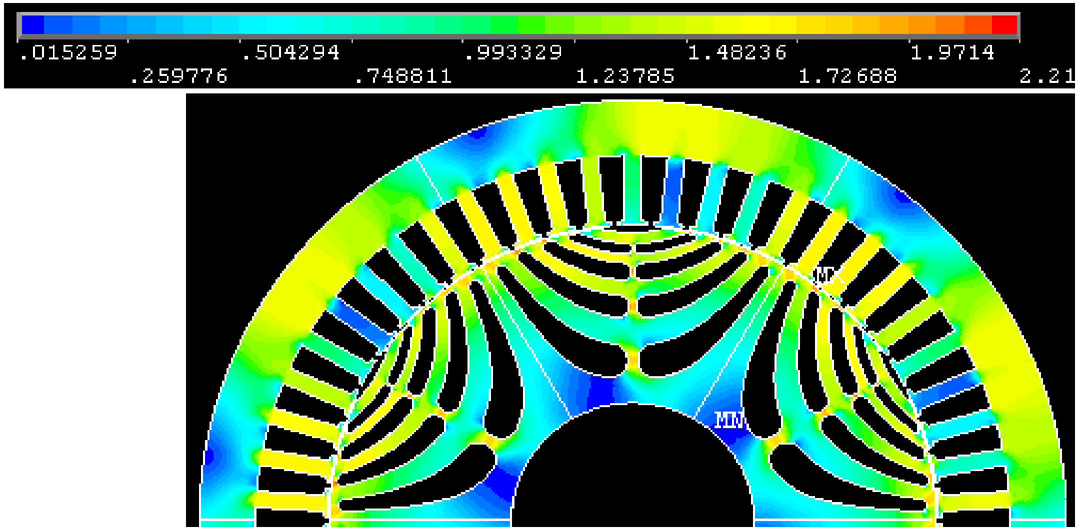
Comments

- the current density values of the proposed designs are reasonable for the liquid cooled machines;
- the 4-pole design presents the highest outer Diameter and this is due to the flux density in the stator yoke: this allows to reduce the phase current but reflects on the volume of the active parts;
- all the proposed designs have an efficiency at rated power higher than 94%; at peak power the 8-pole only does not satisfy this constraint;
- at base speed (6000 rpm), the 6-pole design fully satisfy the requirements with a lower phase voltage than the 4-pole and 8-pole;
- at peak power, the 6-pole design presents a wide “Constant Power Speed Range” compared to the other solutions.

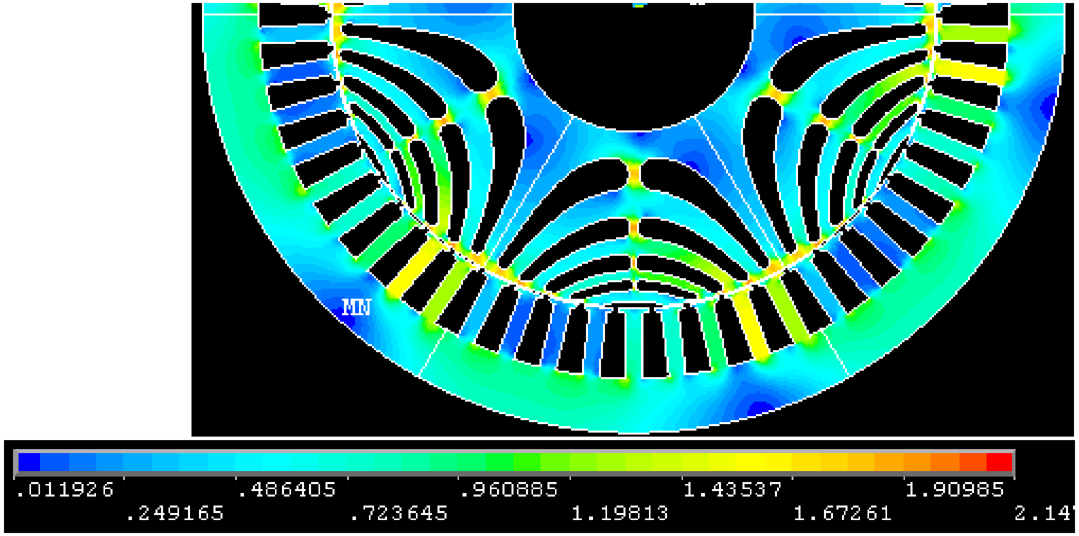
These results clearly indicate that the 6-pole, 54-slots design is the better topology for SynRel motor, with a limited volume and satisfactory performances at Rated and Peak power.

Flux density @ rated Power (6p-54s)

(T)



6000 rpm



14000 rpm

(T)

Flux density @ peak Power (6p-54s)

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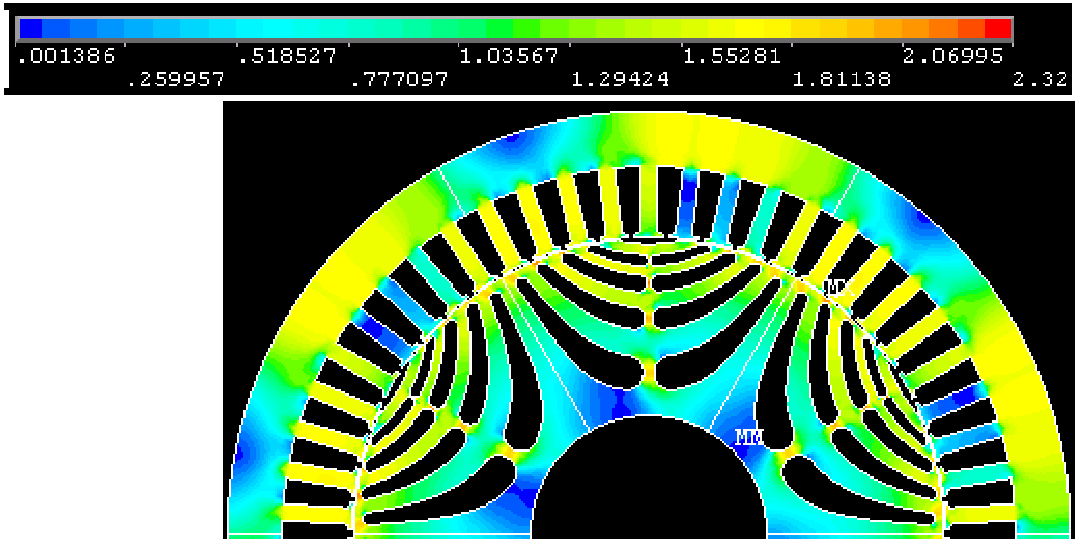
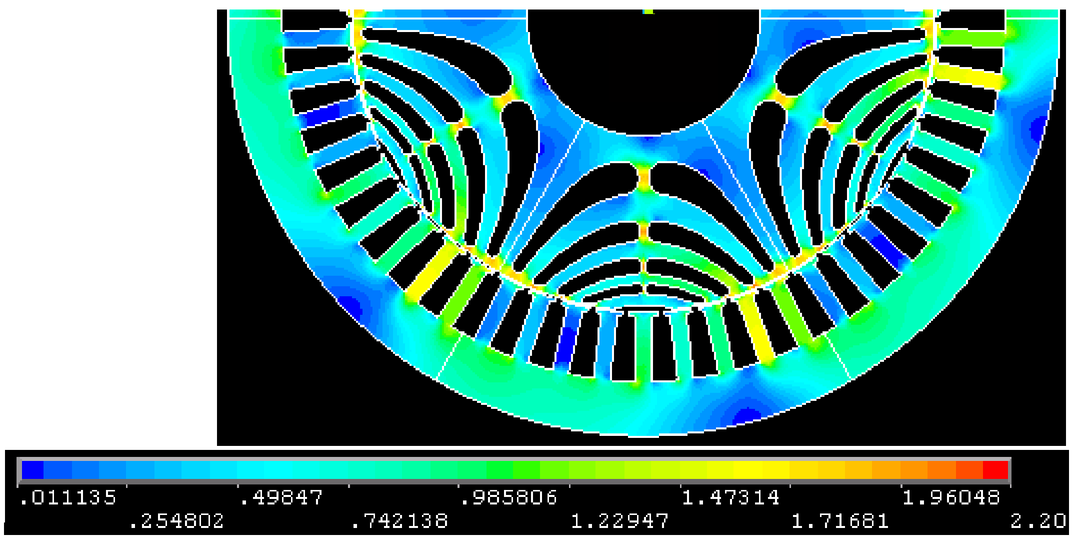
(T)



6000 rpm

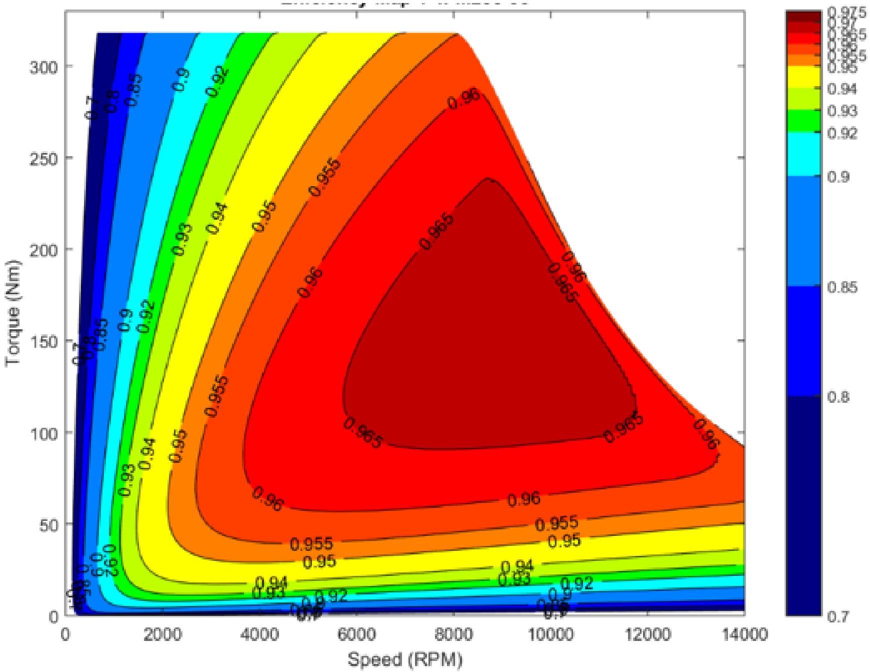


14000 rpm

(T)

Efficiency maps (6p-54s)

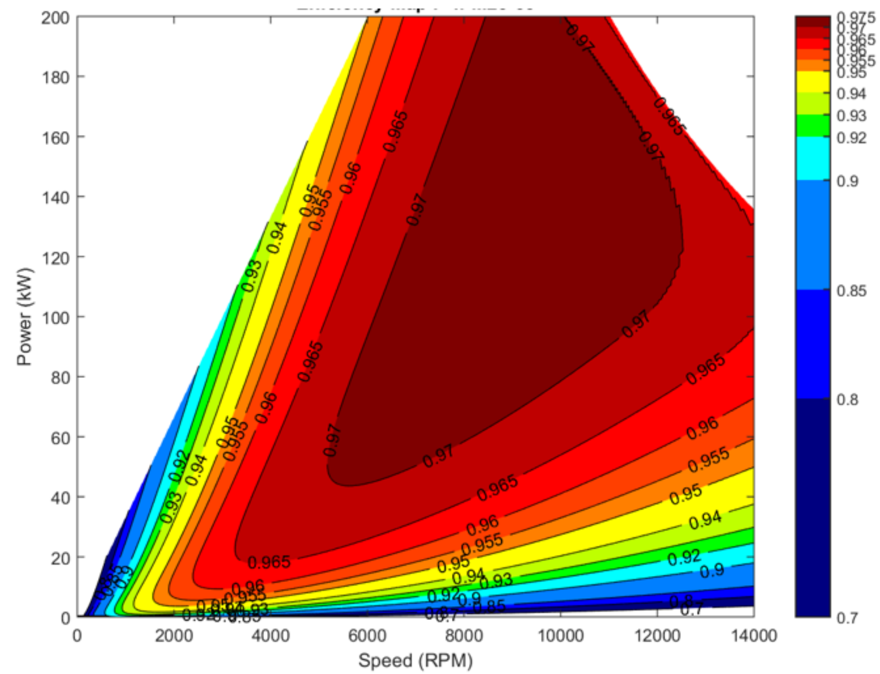
Torque vs. Speed



η %

Power vs. Speed

η %



Losses (6p-54s)

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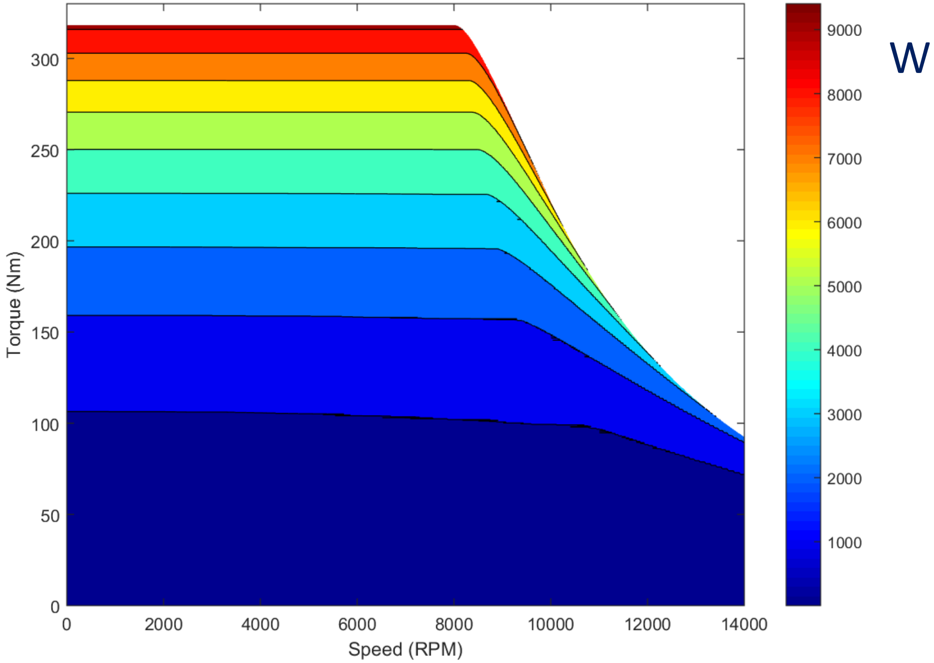
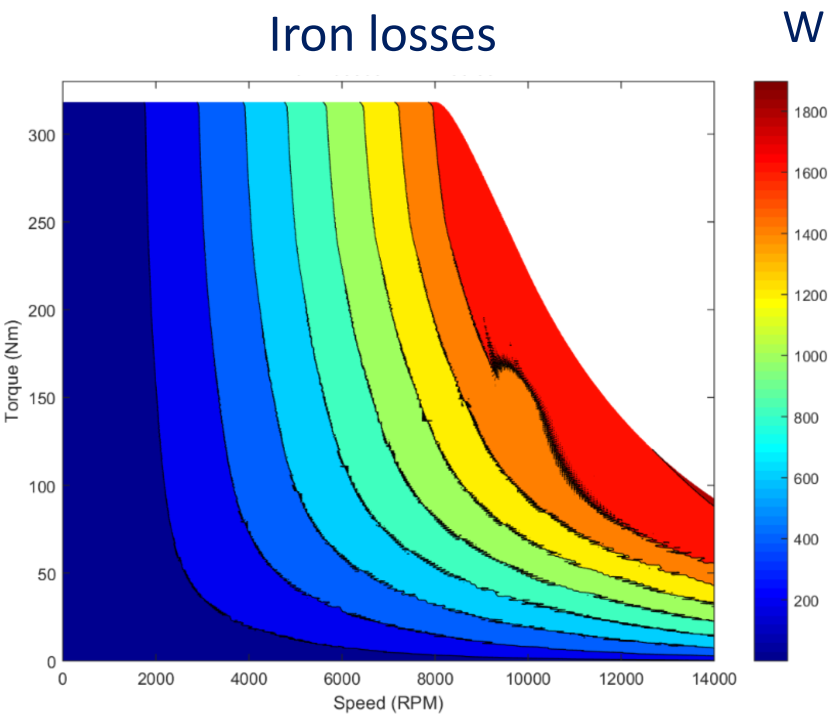
Joule losses

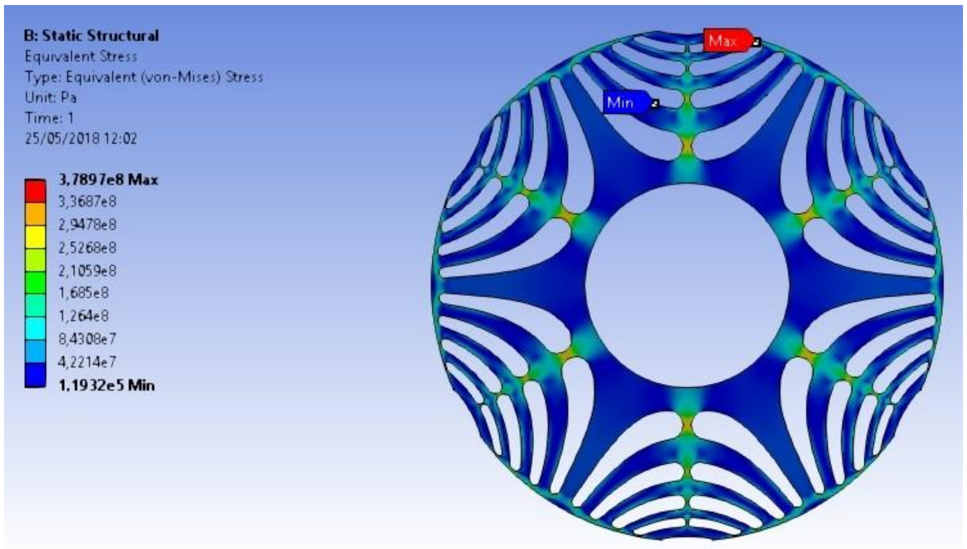


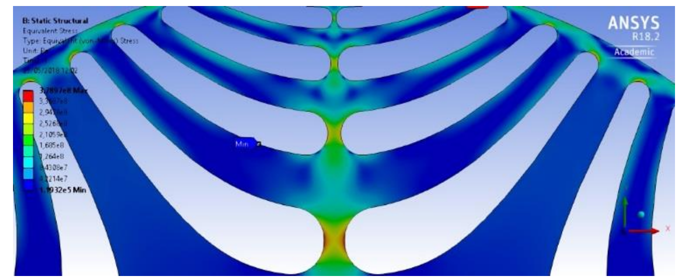
Iron losses

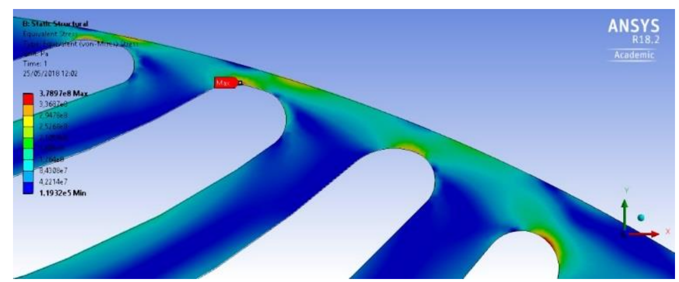


Mechanical stress analysis

Centrifugal force on the steel @ 14000 rpm

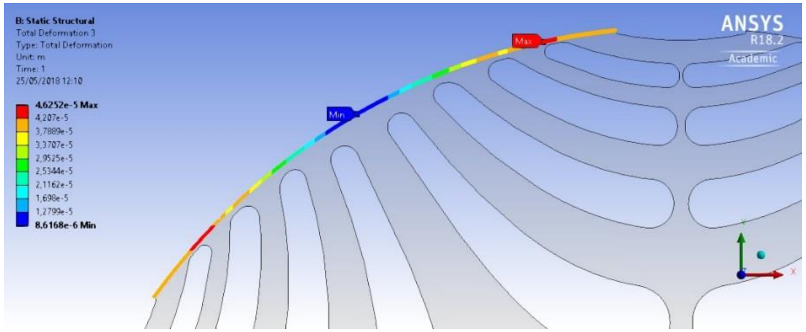


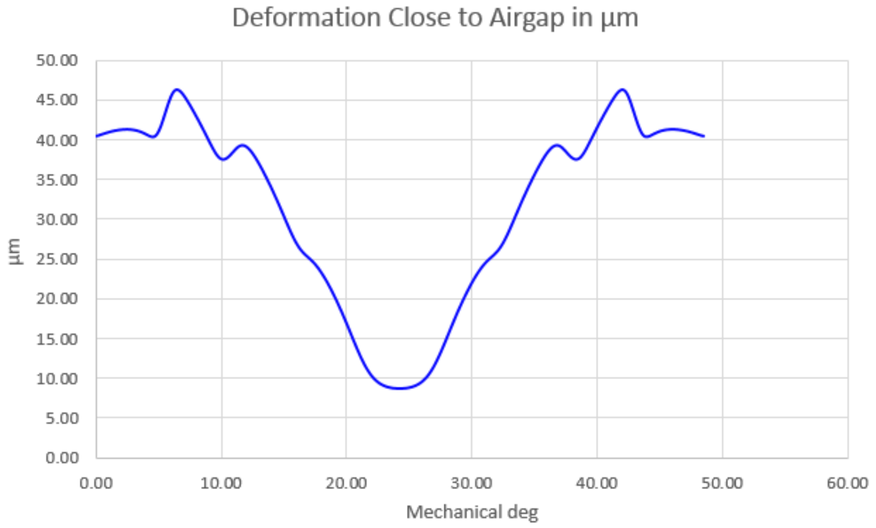




Mechanical stress analysis

Deformation analysis @ 14000 rpm





No critical values have been reached and there is safety margin at maximum speed, with a maximal deformation close to airgap of about 46 µm (8.0% of the airgap).

Conclusions

The vast majority of motor solutions rely on PM technology using rare-earth magnets. The key problem is the relatively high cost due to PM materials: this technology may not offer the best long-term solution for use in the electric vehicle.

It has become mandatory to find alternative solutions, that include rare-earth free machines or reduced rare-earth PM machines.

The Synchronous Reluctance motor represents valid alternative, though care must be taken during the motor sizing in order to satisfy the hard requirements and avoid an increasing on the system costs.

In the RefreeDrive project several solutions have been analyzed and compared and at the end of the sizing step several prototypes will be realized and tested.

The development of rare-earth free traction technologies allows to contribute to a greener transport, by offering new solutions non dependent on critical sources and making use of vast electric motor manufacturing capabilities.

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