VENUS

SWITCHED/SYNCHRONOUS RELUCTANCE MAGNET-FREE MOTORS FOR ELECTRIC VEHICLES

Collaborative Project
Theme: GC.SST.2013-2. (Next Generation Electric Motors)
Grant agreement no.: 605429
Start date: 1st Nov. 2013
Duration: 3 years

3rd Strategic Innovation Network Workshop for substitution of Critical Raw Materials
Wednesday, February 11, 2015, Brussels (Belgium)

CRM_InnoNet
Substitution of Critical Raw Materials

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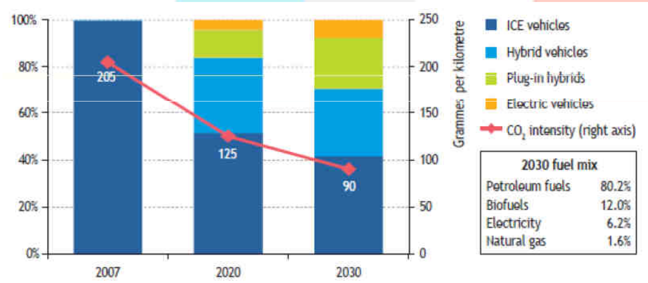
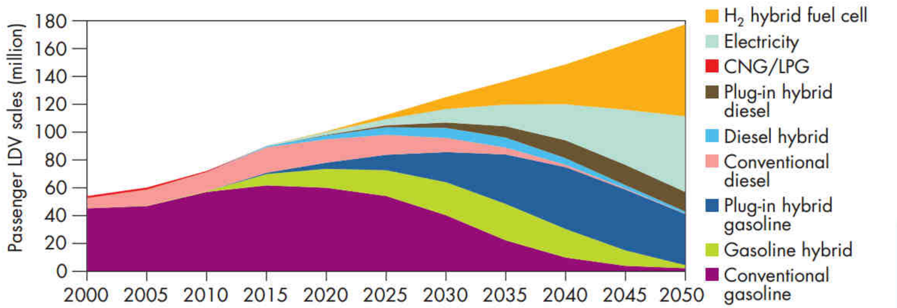
Context

- EV and Plug-In Hybrid Electric Vehicle markets to grow in upcoming years:
  - Energy efficiency, emission reduction
  - Figures vary: market growth is agreed, how much and when not that clear
  - e.g. between 2-7 million units sold per year by 2020



Source: International Energy Agency, Transport, Energy and CO2, EU, 2009.



Forecast of car sales evolution by technology type for the upcoming decades
Source: International Energy Agency, Transport, Energy and CO2, EU, 2009.

	EVs and Power Plants	Engines and Fuel Refining
Processing	39% (electricity generation)	90% (fuel refinement)
Transmission lines	94%	-
Charging (charger + battery)	86%	-
Inverter	95%	
Motor and drivetrain	90%	20% (gasoline) 30% (diesel)
Overall Efficiency	27%	18% - 27%

Problem

- PM motors for EV-s
  - PM motors: most traction applications (power density, efficiency)
  - Others: Induction motors (Tesla), Variable reluctance motors (SR: Land Rover Defender)

- Issues with PM-s
  - PM-s use neodymium and dysprosium: China accounts for 95% of global rare-earth oxide (REO) supply
  - Future global shortages? July 2010: China's REO export quotas slashed by 72%
  - Material cost in PM motor: 75% of total (gross margin exc.); magnets 45% of material cost (34% of total cost)

Element	Demand REO (tons)	Supply REO (tons)	Balance	Balance as % of Demand
Lanthanum	51 050	54 750	3 700	7.25
Cerium	65 750	81 750	16 000	24.33
Praseodymium	7 900	10 000	2 100	26.58
Neodymium	**34 900**	**33 000**	**-1 900**	**-5.44**
Samarium	1 390	4 000	2 610	187.77
Europium	**840**	**850**	**10**	**1.19**
Gadolinium	2 300	3 000	700	30.43
Terbium	**590**	**350**	**-240**	**-40.68**
Dysprosium	**2 040**	**1 750**	**-290**	**-14.22**
Erbium	940	1 000	60	6.38
Yttrium	**12 100**	**11 750**	**-350**	**-2.89**
Ho-Tm-Yb-Lu	200	1 300	1 100	550.00
Total	180 000	203 500	23 500	13.06

Forecast of demand-supply of rare earths in 2014
Source: J. Seaman, Rare Earths and Clean Energy: Analyzing China's Upper hand, Ifri, FR, September 2010

Cost Contributor	Cost ($)	Avg. Cost ($)	Avg. Share (%)
Material cost	390	390	62.2
Assembly and testing (20-30% of mfg. cost)	97-167	132	21.1
Total mfg. cost	487-557	522	83.3
Gross margin @ 20% of mfg. cost	97-111	104	16.7
OEM price	584-668	626	100.0

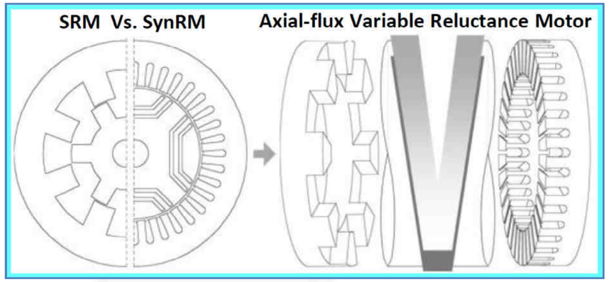
PM motor manufacturing cost

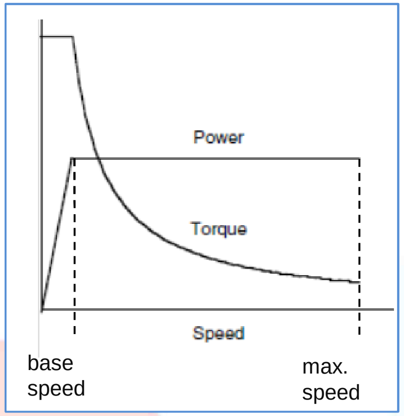
	Mass		Cost		
Component	(lb)	(%)	($)	(%)	($/lb)
Stator core	24.0	27.4	68[a]	17.4	2.83
Stator winding	11.0	12.6	22	5.6	2.00
Housing	21.0	24.0	50	12.8	2.38
Rotor	16.0	18.3	26	6.7	1.63
Magnets	3.5	4.0	175	44.9	50.00
Attachment band	0.5	0.6	6	1.5	12.00
Shaft	5.5	6.3	3	0.8	0.55
Miscellaneous	6.0	6.8	40	10.3	6.67
Total	87.5	100.0	390	100.0	4.46

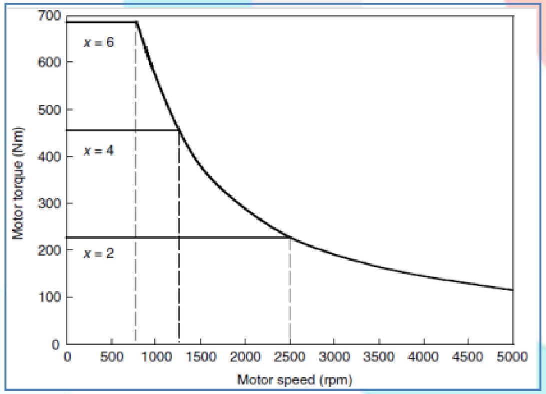
PM motor material content and component cost

Source: R.M. Cuenca et al., Evaluation of Electric Vehicle Production and Operating Costs, Center for Transportation Research, Energy Systems Division, US, November 1999.

- Alternatives/solutions for PM use in EV motors:
  - New motor designs without magnets: challenges on power density, efficiency and manufacturability
  - New materials for magnets (no rare-earths): challenges on high coercitivity and remanent induction
- VENUS approach:
  - Variable reluctance motor: no use of magnets (no demagnetization risk, no-load induced voltage), speed ratio increase (transmission simplification, cost),
  - Axial-flux configuration: pancake shape for power density, challenge on manufacturability







Source: M. Ehsani et al., *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, CRC Press.

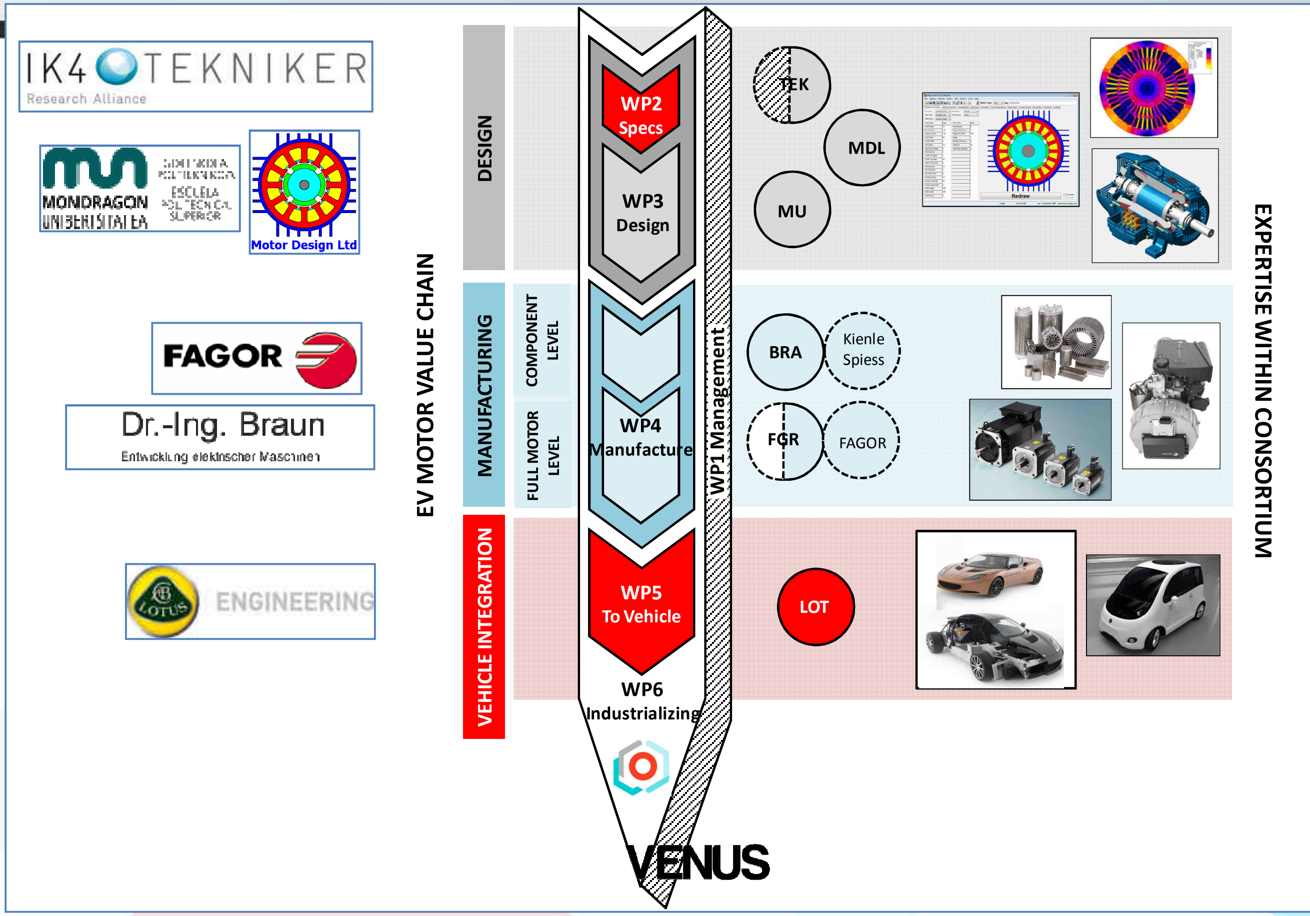
Objectives

- High level objectives
  - EU policies for upcoming decades: cut 60% of CO_2 emissions from transport (fossil fuel dependence 96%)
  - EV-s seem to be most plausible alternative to fossil fuel-based road transport: enhance EV take up (could be limited by PM supply shortages at a competitive cost)

- Specific objectives
  - Develop high efficiency motors without PM-s
  - Solution to be equivalent in specs (power density, efficiency), manufacturable and cost-effective

STRATEGIC OBJECTIVES	CURRENT STATUS	PERFORMANCE INDICATOR
Weight reduction and power density increase	Power density of current SR machines: 1 KW/kg Power density of current axial-flux PM machines: 2 KW/kg	Target power density: 1.5 KW/kg
Replace or greatly reduce REO content	Current PM content in EV motors: 1.6 kg (5-10% of total motor weight)	Magnet-free
Optimised design and processes for manufacturing	Manufacturing Current PM motor cost: manufacturing 25%, material 75% Magnets are 45% of material cost (34% of total cost)	Target manufacturing cost: 40% of total cost (when scale economies are applied) 10-15% cost margin respect to current PM motors

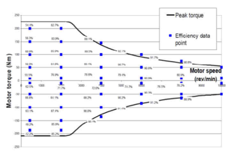
Project Partners

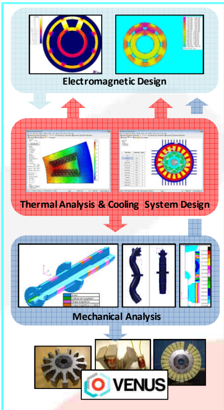


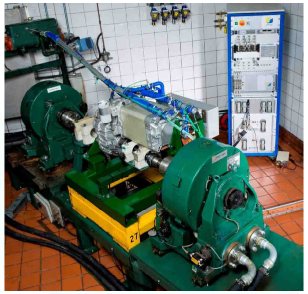
Work Plan

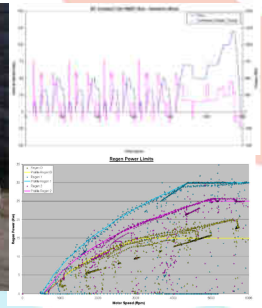
- Set motor specifications at vehicle and component level
- SRM or (PM)SynRM?
- Eletromagnetic design, cooling system, mechanical design, power electronics & control
- Fabrication and test-bench evaluation
- Integration on Azure Ford Transit Connect

Specifications → Design → Fabrication and Test-bench → Integration and Driving Tests

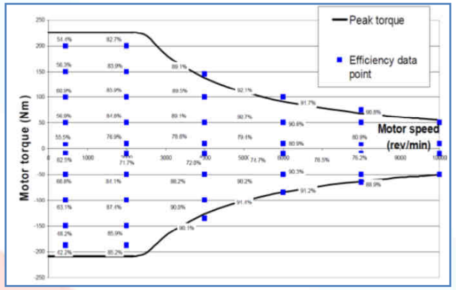


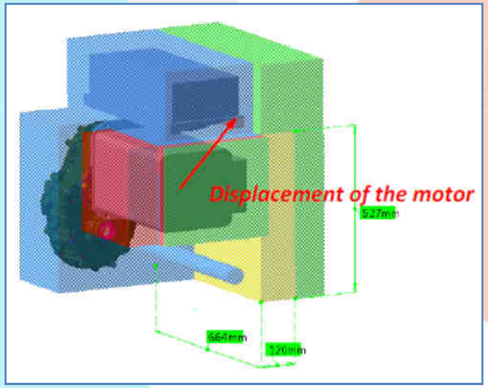






- Specifications:
  - Vehicle: reference torque-speed curves (current motor and best-in-class PM motor)
  - Motor: available space, gearbox, battery pack, etc.





- SRM or (PM)SynRM:
  - Further pre-designs including FEA

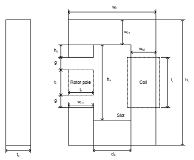
SRM

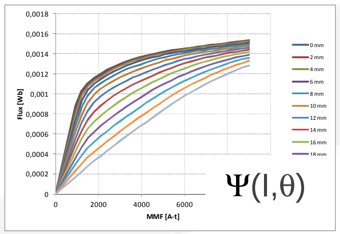
(PM)SynRM

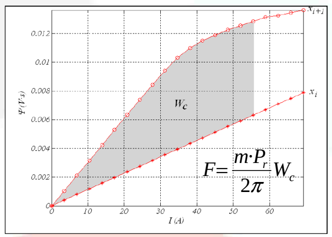
	Disadvantages	Advantages
SRM	- 90% of top specs - Non-standard power electronics	- **Manufacturability and cost** - Power density - Magnet-free
(PM)SynRM	- **Manufacturability and cost: high risk** - Power density - Some use of magnets	- Top specs - Standard power electronics

- SRM Motor Design:
  - Optimum design: FEA (not flexible); development of analytical design tools

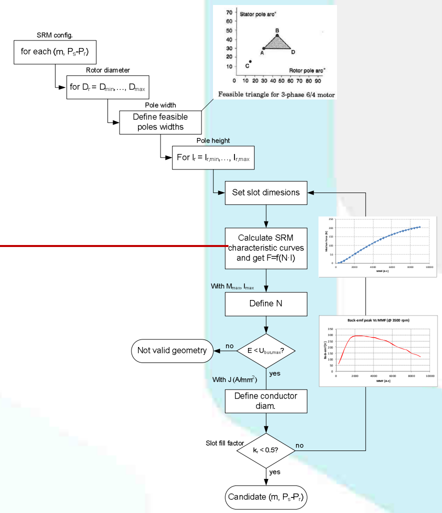
i. Analytical Calculation (parameterization, induced force and voltage)



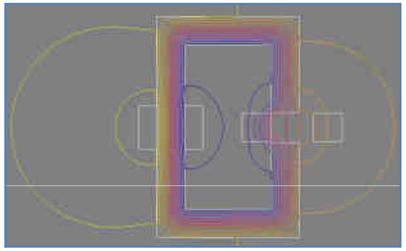


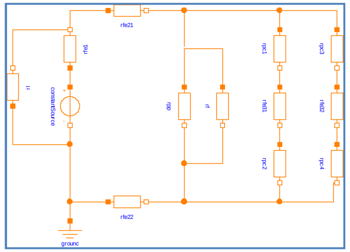


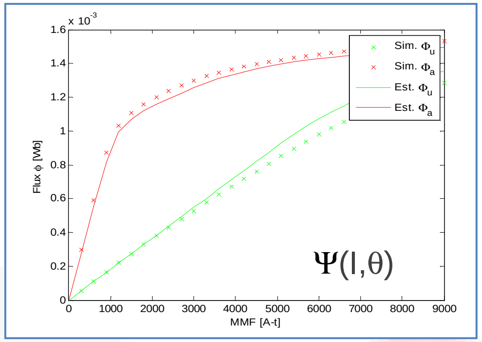
II. Design Algorithm based on Multivariate Analysis

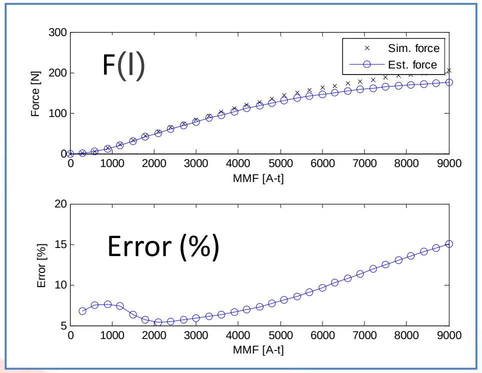


- SRM Motor Design:
  - Challenge on magnetic circuit: non-linear, flux through air, etc.





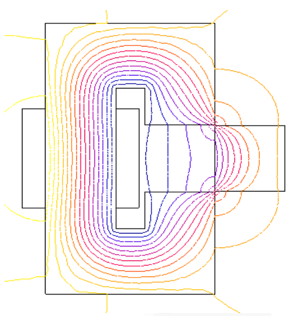


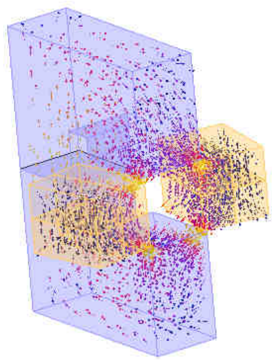


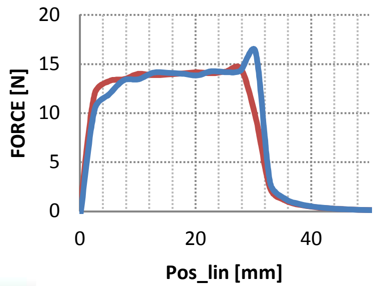
FEM: **27 min** simulación
(2 machines/hour)
vs.
Analytical tool: **5.5 s** calculation
(654 machines/hour)

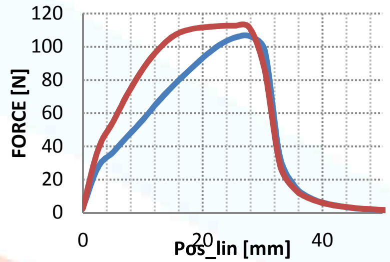
3D finite element model (FEM)

- To calibrate analytical tool (initially 2D)
- For more accurate calculations: 3D leakage flux, influence between adjacent poles,…
- Take in account the influence between phases (mutual inductance).



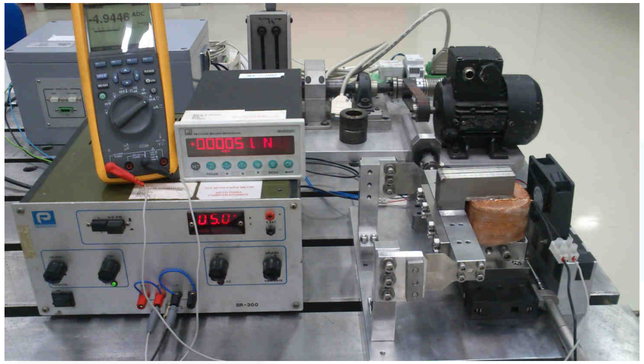




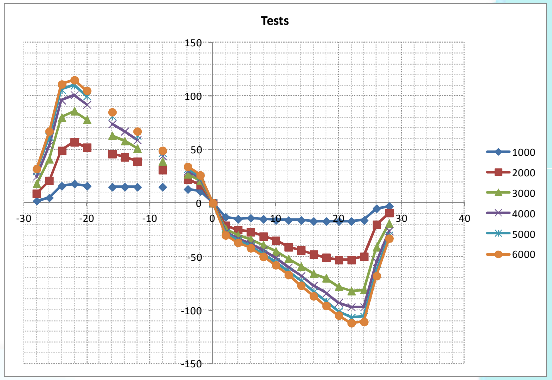


3D leakage flux effects are important in saturated motor

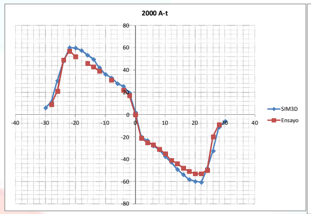
Test-bench to validate the tools and see the influence of manufacturing process (laser-cutting Vs wire-cutting)



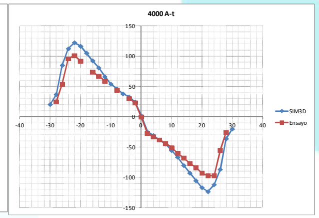
Force Vs position and current



Test Vs Simulations



Low saturation



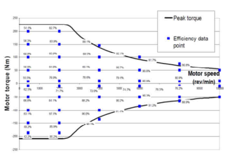
High saturation

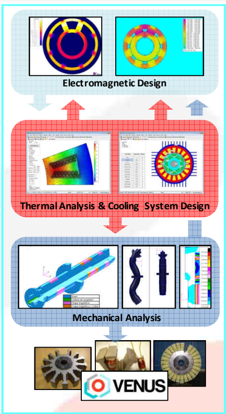
- No difference between laser-cut and wire-cut samples.
- Differences between tests and simulations on high saturated conditions identified: model refinement

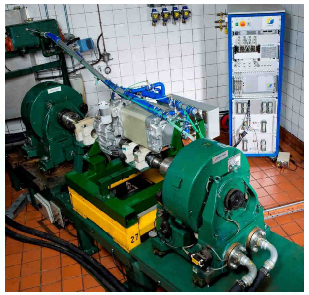
Upcoming Tasks

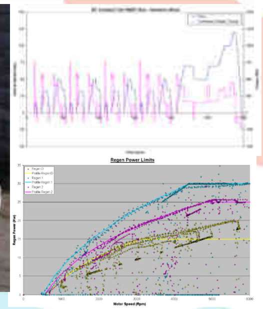
- Finalize design (end of March)
- Fabrication and test-bench evaluation
- Integration on Azure Ford Transit Connect

Especificaciones → Diseño → Fabricación y ensayos en banco → Integración y ensayos de campo









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Notes/Comments

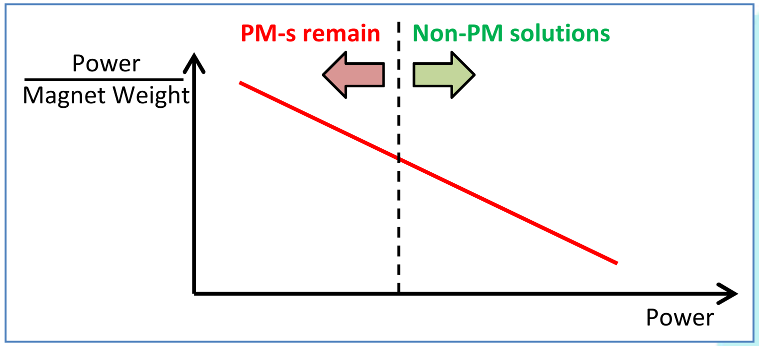
- More use of copper per motor (up to 50%)
  - Copper could be considered a sustainable material (100% recyclable), however consumption growth requires new mines
- Easy manufacturing
  - No difficulty to include them in production chains
- Non-standard controllers
  - Few controller suppliers and with few references/products

Impact in other sectors

- Extension of new axial reluctance topology to other applications:
  - Railways
  - Elevators
  - Machine tools

- Railway applications (similarities with EV traction):
  - Current new trends oriented to PM motors
  - High induced voltage problem in PM motors: in case of short-circuit other traction units move the train inducing high currents (burning risk)
  - Reluctance motors could improve efficiency and also avoid over-voltages in case of short-circuits

- Exchange of ideas/views



Reflection by James Widmer (Newcastle Univ.)

- Synergies: same problem explored from different approaches
  - New motor designs + New materials for magnets
- Sensible recommendations for EU industrial / R&D initiatives

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