Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

BRUSA

Design of a Brushless Separately Excited Synchronous Motor

Enzo Illiano

Development of a Brushless SSM

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Institute of Machine Tools and Manufacturing

ETH
Eidgenössische Technische Hochschule Zürich
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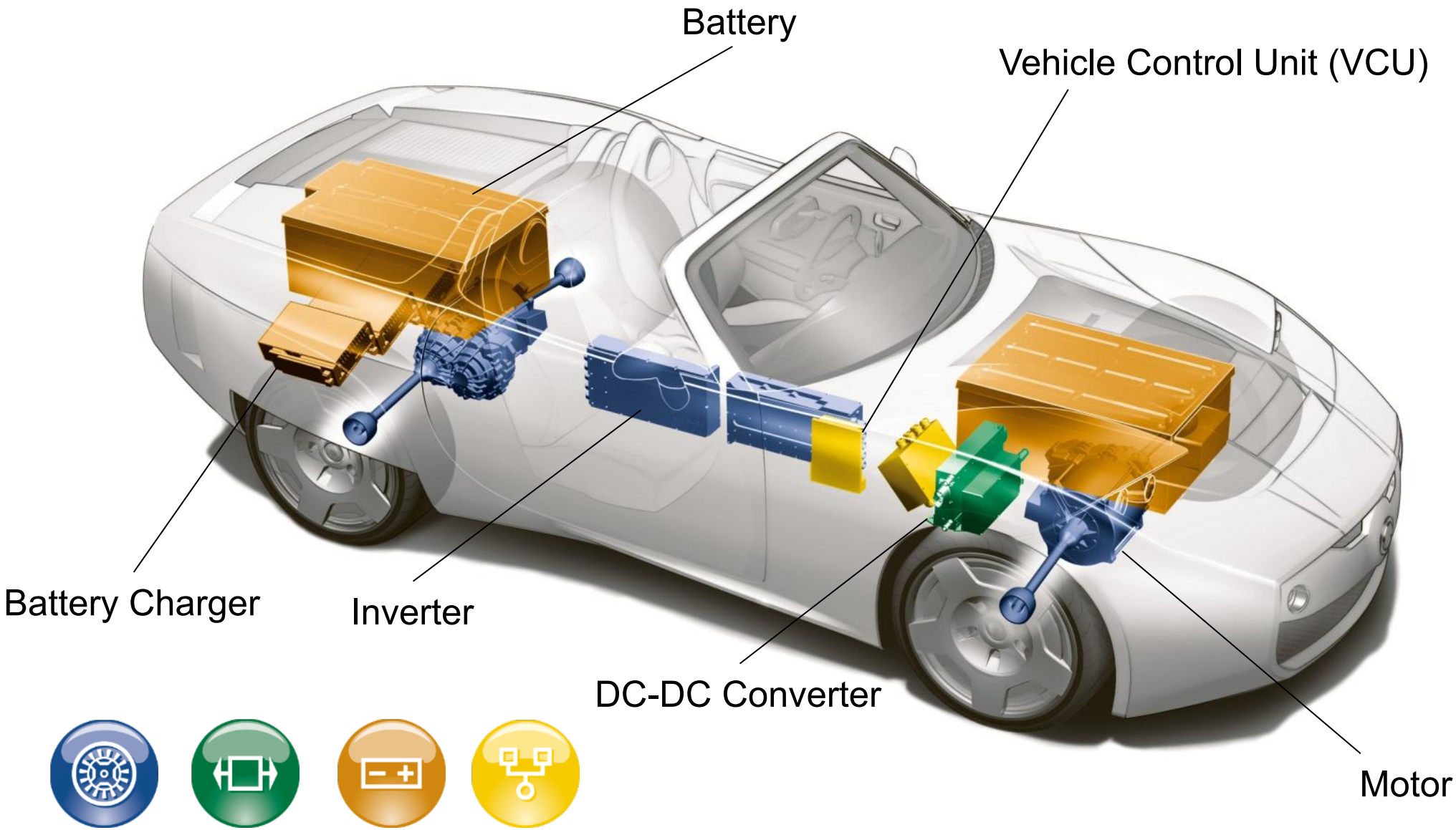
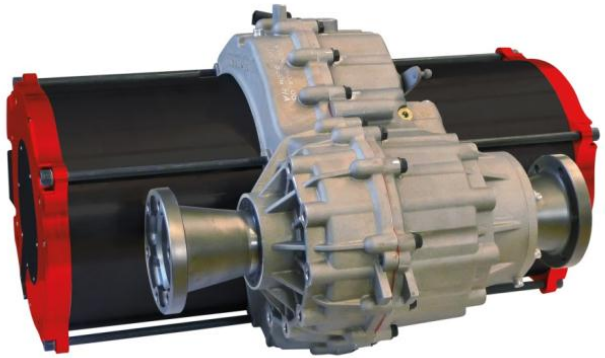
BRUSA Products

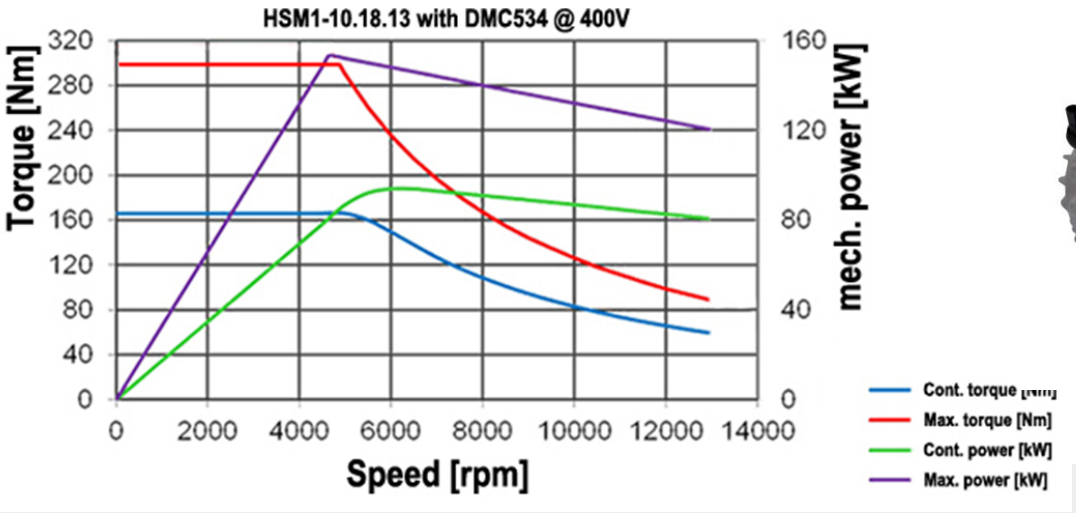


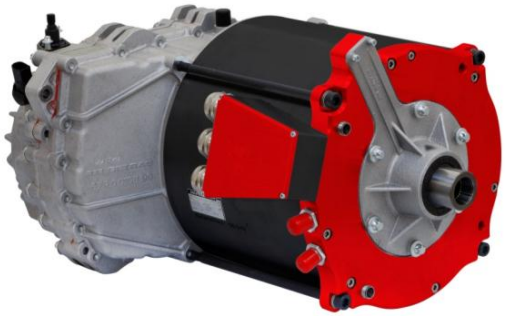
Drive Converter Energy System

Advantages of Electric Drives

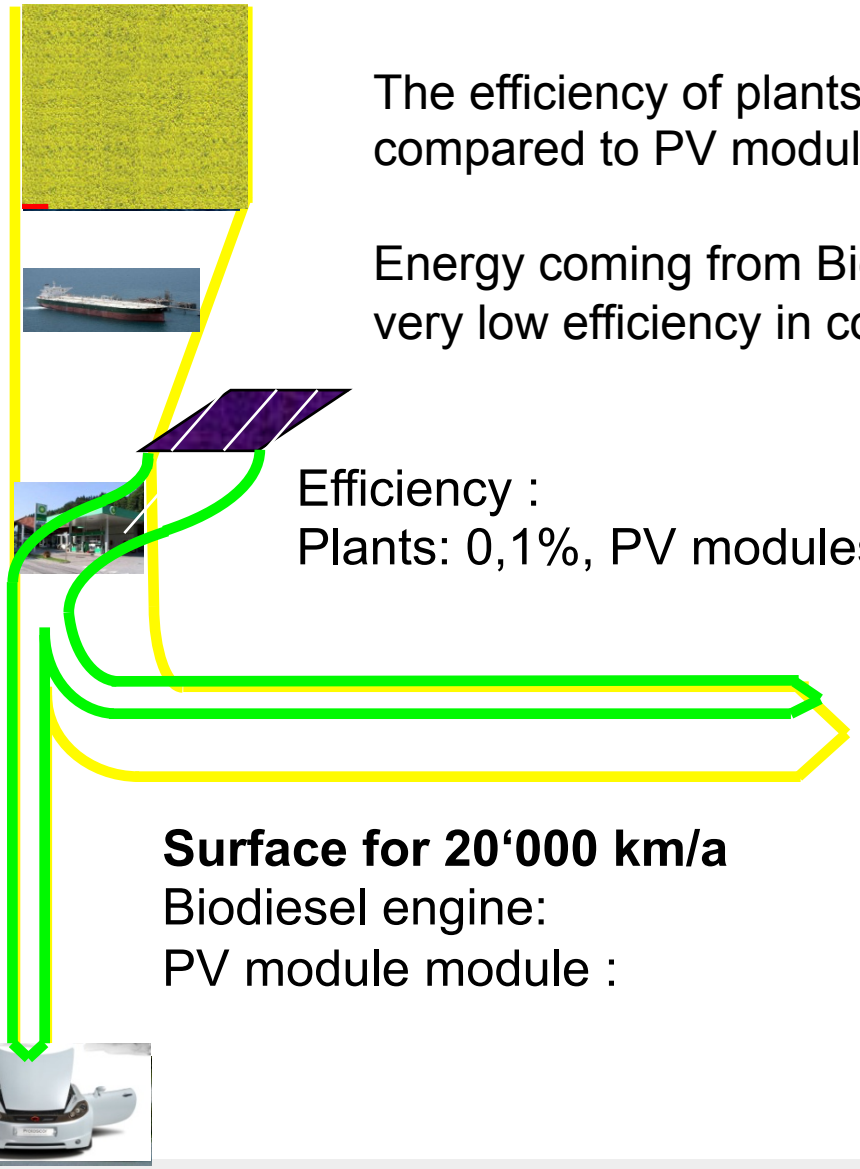


- Kinetic energy recovery
- High Torque @ 0 rpm
- Modulable
- Excellent power curve, no changeable gearbox
- No clutch
- Excellent power density
- Lowest wearing, less maintenance (no oil)





Electric Mobility a Necessary Condition

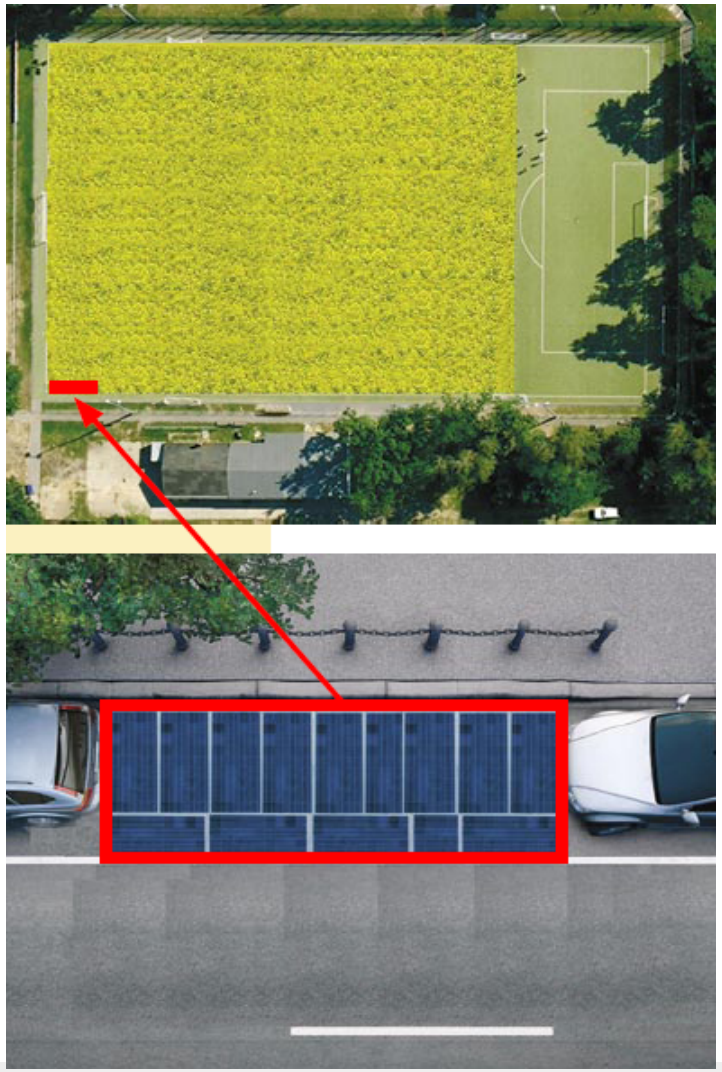


The efficiency of plants is very poor compared to PV modules

Energy coming from Biofuel ist used with a very low efficiency in combustion engines

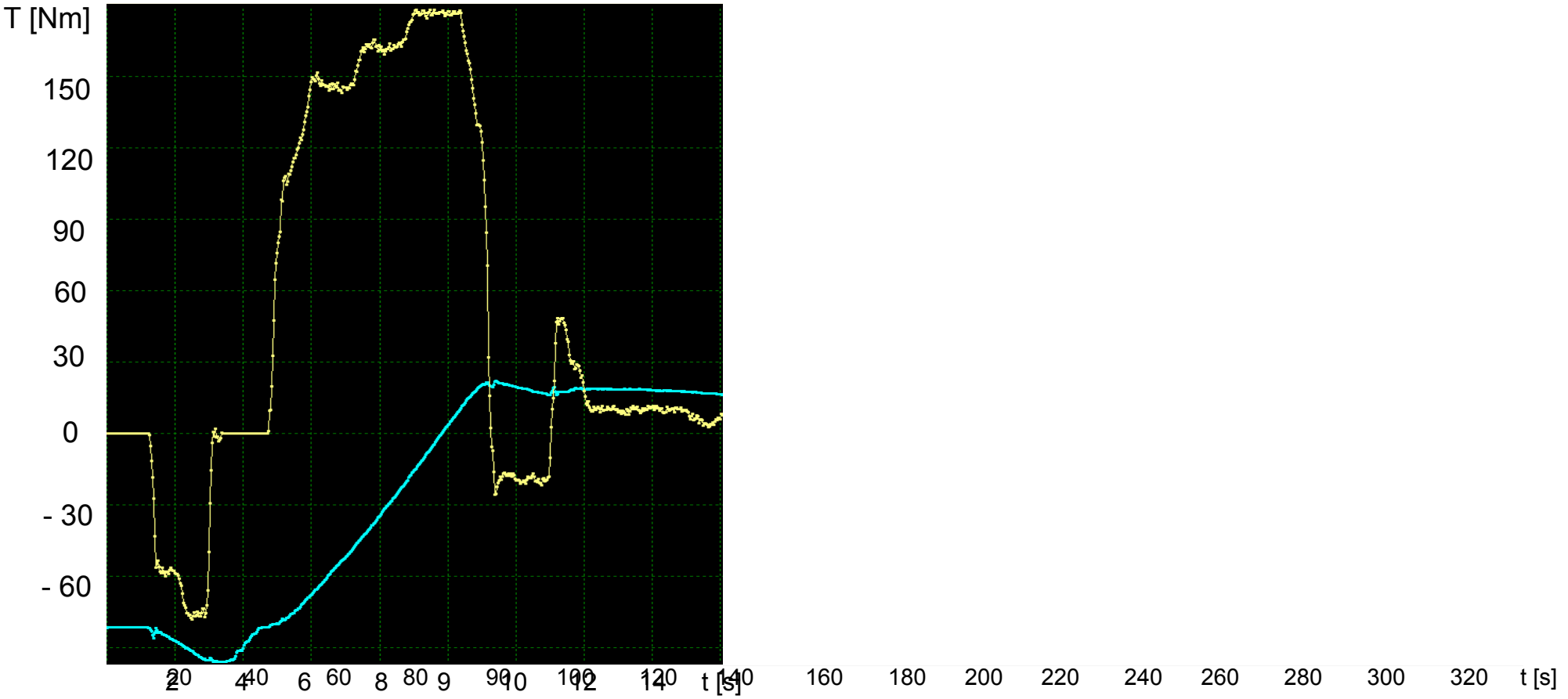
Efficiency :
Plants: 0,1%, PV modules: 15%

Surface for 20‘000 km/a	**in m²**
Biodiesel engine:	3000
PV module module :	20



Don’t forget!! PV modules doesn’t need farmland!!

Characteristics required by a car motor



On the road between Sennwald and Buchs

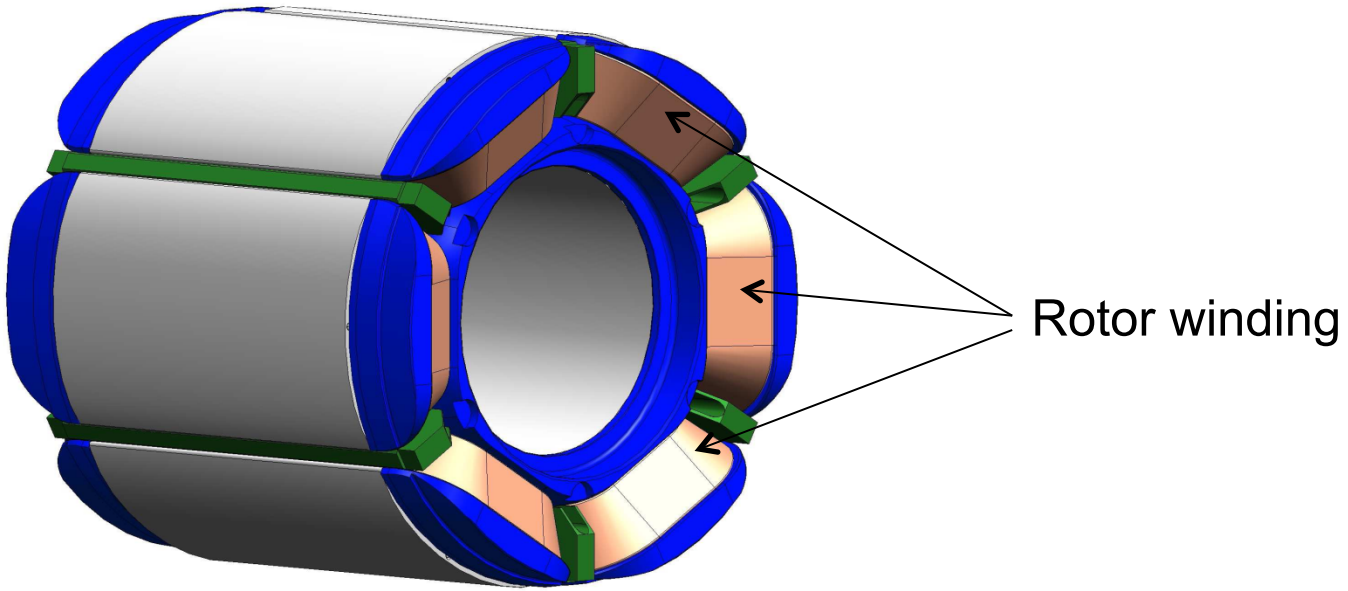
- High efficiency at low torque: Range – CO_2 Balance
- High peak torque / power density: only for driving pleasure
- High continuous power: not necessary

Torque
Speed

Motor: Brusa HSM1-10.18.13
Peak torque: 300 Nm

What is a separately excited synchronous motor ?

A separately excited synchronous motor (SSM) is a topology which is provided with windings in the rotor. The necessary magnetic field needed to produce torque is mainly generatd by these rotor coils. The rotor winding has a function similar to the permanent magnets of PM motors. For this reason the SSM is (usually) magnetless.



The rotor of an SSM is practically a big coil

Candidates as EV drives

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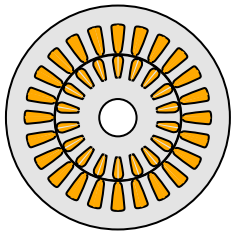
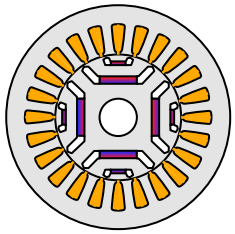
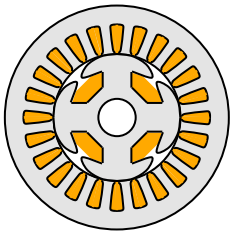
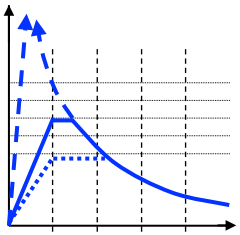
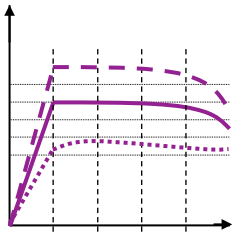
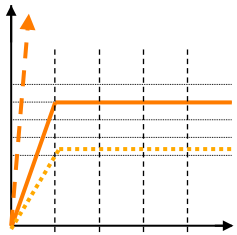
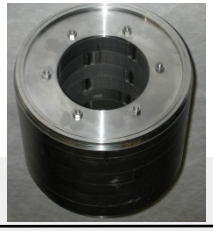
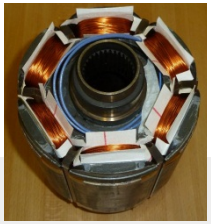
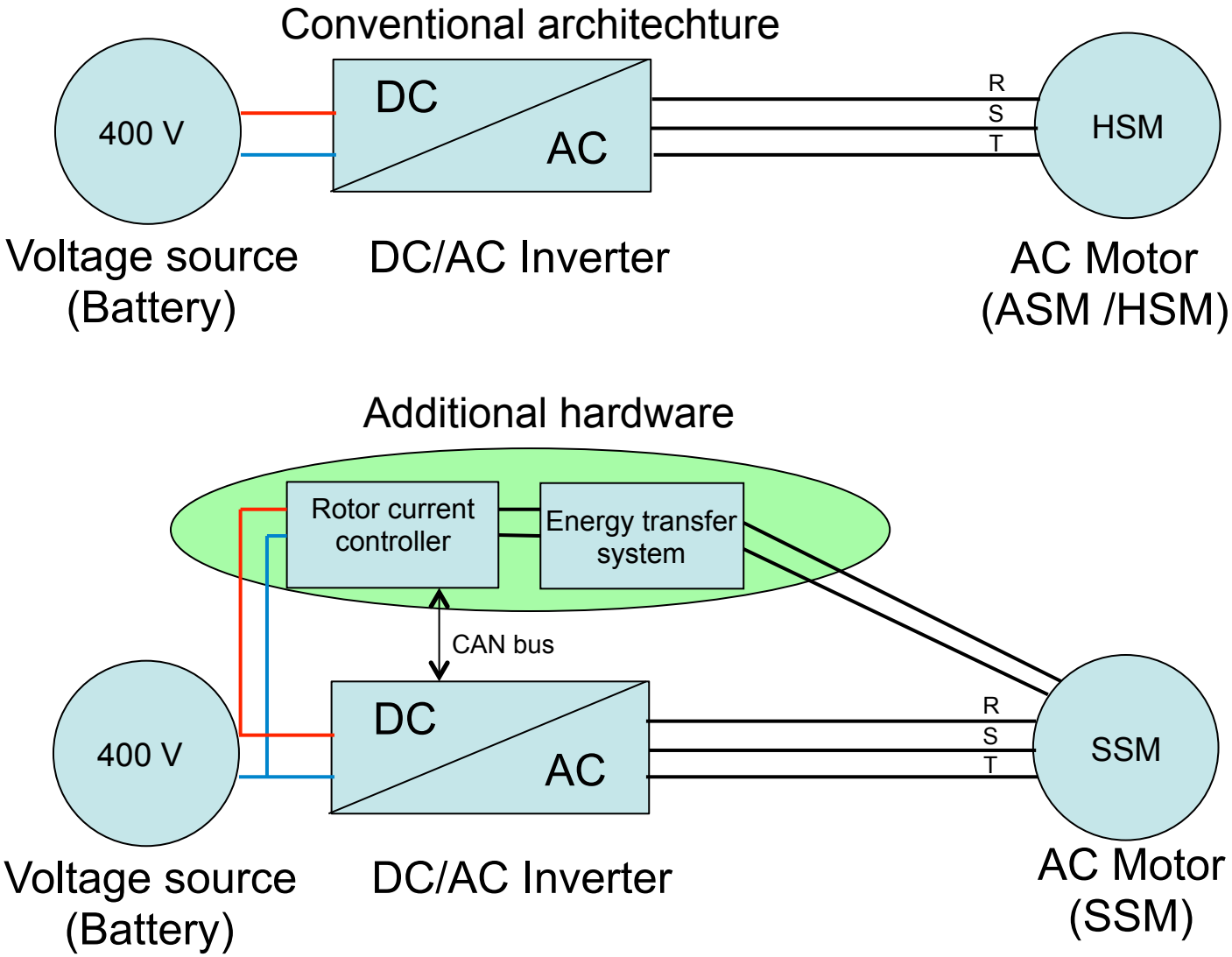
	Asynchronous Motor	Internal perm. Motor	SSM
Principle			
Large speed range with constant power	 NO	 YES	 YES
Magnet needed	No	Yes, 1.5 kg/100 kW Peak	NO
Disadvantage	Poor Power Curve	Magnets	Construction
Advantage	Construction	Good Power Curve	No Magnets, Good Power Curve
Rotor			

Additional hardware needed by an SSM



Conductive vs inductive energy transfer

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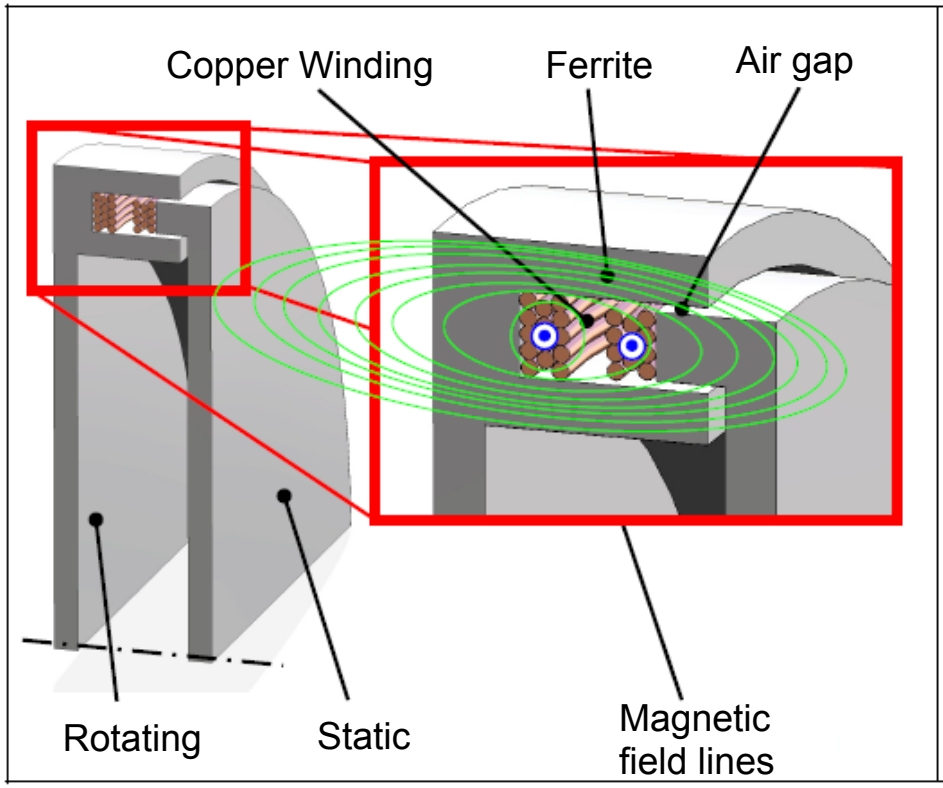
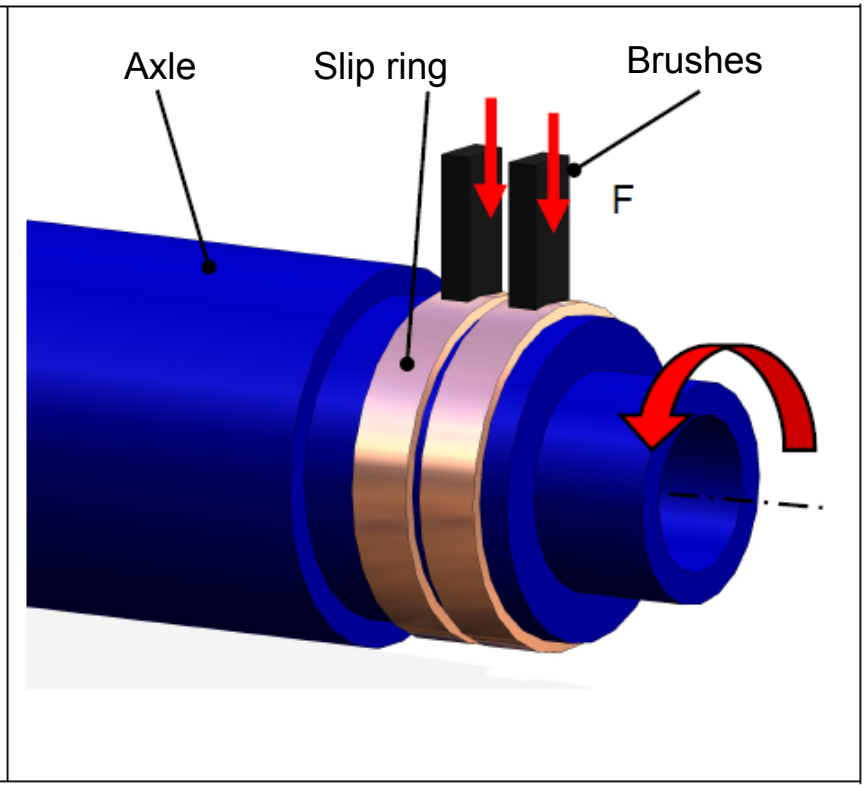
Inductive – Rotating transformer



+ No wearing
- Expensive

Conductive – Brushes and slip rings



+ Cheap and simple
- Wearing
- Dust formation

Improved regulation freedom and safety

The SSM offers more freedom than other synchronous motor topologies. In fact it is possible to force three currents instead of two (I_d, I_q, I_{rotor}). For a proper functionality of a motor only two equations have to be respected.

- Flux equation: the stator flux cannot exceed the flux allowed by the battery voltage

MANDATORY !

- Torque equation: the motor must produce the desired torque

The driver appreciates this

- Optimization equation. For example:
  - Power factor = 1 (minimization of stator copper and inverter losses)
  - Total losses minimization
  - Total losses minimization with weighted rotor losses
  - Rotor losses minimization

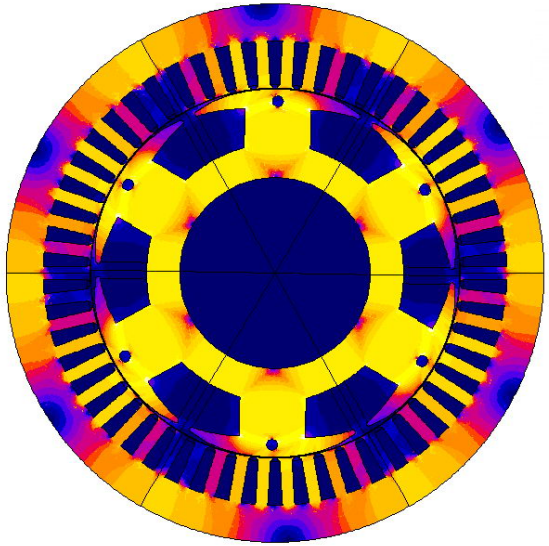
  …..

Nice to have

In case of short circuit or inverter failure it is possible to quickly remove the rotor excitation
After this time no dangerous braking torque and induced overvoltage can be produced

High efficiency at high torque operation

Maximization of the magnetic flux through saturation



$$M = \frac{3}{2} \cdot p \cdot \psi \cdot I \cdot \cos(\varphi)$$

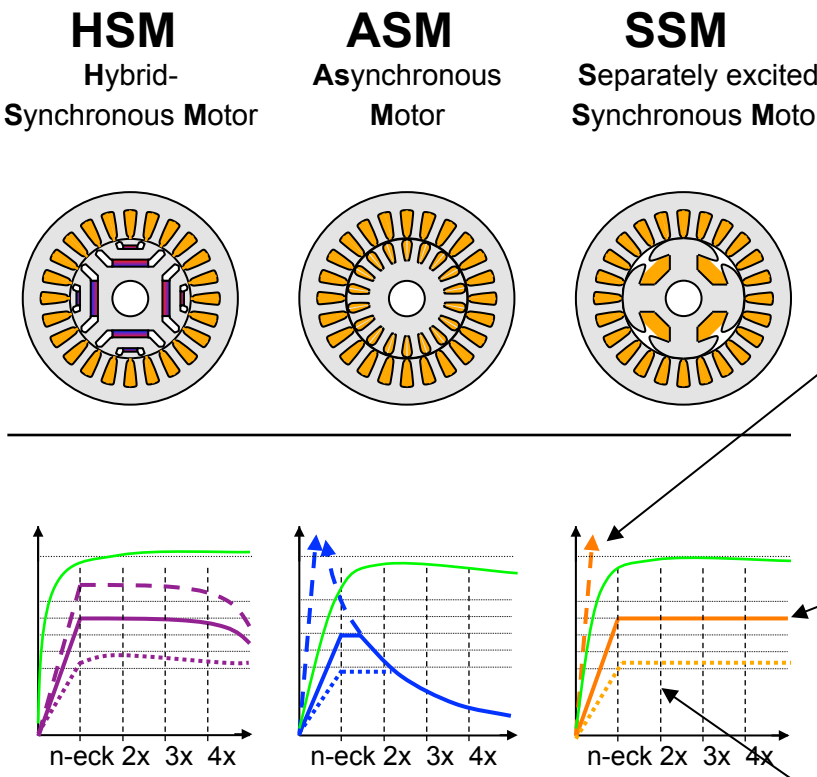
The power factor of an SSM can be maximized (third boundary condition)

M: Torque
p : Number of pole pairs
cos (φ) : Power factor
Ψ : Stator flux
I : Stator current
R : Stator copper resitance

$$P_{loss} = R \cdot I^2$$

- An optimization of the power factor allows a minimization of the current necessary for a required torque. **More power from the inverter!**
- A minimization of the current in the stator windings is useful to improve the efficiency at high torque operating points because power losses depend on the square of the current.

Power curve comparison



Continuous power: dotted line
30 s Power: full line
2 s Power: dashed line
Efficiency : green full line

No torque limit determined by magnetic characteristics. Peak torque theoretically not limited if enough current can be pumped in the motor.

Permanet magnet motors have a limited peak torque.

Large speed range with constant power

This is the most significant advantage compared to the more popular asynchronous motor.

High efficiency at high torque and low speed because of the good power factor.

High efficiency at low torque and high speed because of the controllable excitation
-> low magnetic losses

Magnet price

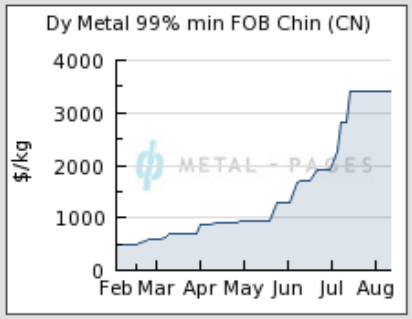
Magnet composition base : 27% Neodymium 1 % Bor 72% Iron

Often part of Neodymium is substituted with Dysprosium (e.g.: 5 %)

Rare earths price explosion 2011

Dy Metal 99% min FOB China

Region	
Last updated	2011-08-11
Previous	3,400.00 - 3,420.00
Latest	3,400.00 - 3,420.00
Change	=



Nd Metal 99% min FOB China

Region	
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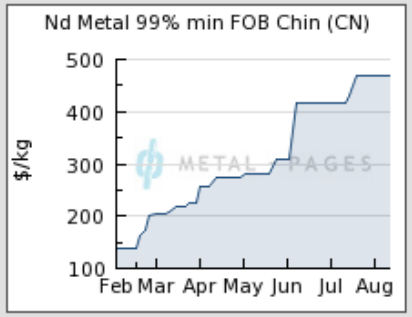
Previous	465.00 - 470.00
Latest	465.00 - 470.00
Change	=

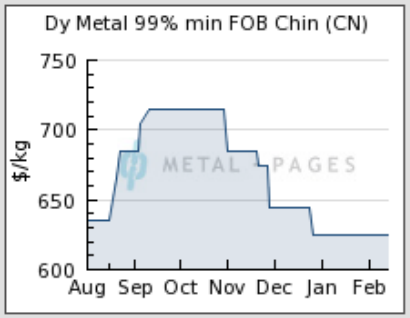


Source: metalpages.com 08.2011

Actual price

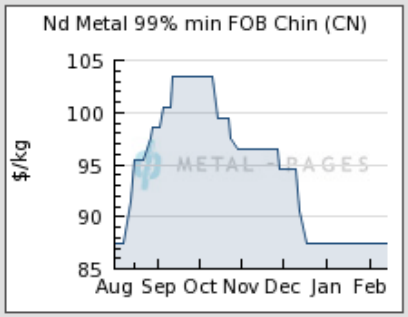
Dy Metal 99% min FOB China

Region	
Last updated	2014-02-13
Previous	Logon to see prices
Latest	
Change	=



Nd Metal 99% min FOB China

Region	
Last updated	2014-02-13
Previous	Logon to see prices
Latest	
Change	=



Source: metalpages.com 09.2013

Price 2006:
- Dy ≈ 80 USD/kg
- Nd ≈ 30 USD/kg

Peak 2011:
- Dy ≈ 3500 USD/kg
- Nd ≈ 460 USD/kg

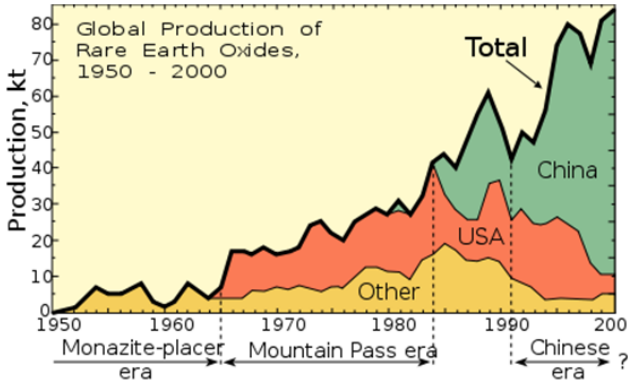
Price 2014:
- Dy ≈ 630 USD/kg
- Nd ≈ 90 USD/kg

Actual magnet price: up to 150 Euro / Kg , 2 Kg /100 kW -> **up to 300 Euro / 100 kW**

Environmental problems related to rare earths

- Neodymium is usually obtained by ores such as Monazite or Bastnasite
- Often the ore is opened using acid
- The separation process produces several dangerous composites

  Often the waste product contains Uranium and/or Thorium which are present in the ore
- The largest amount of rare earth is extracted in China (> 95%)
- At present the waste product is often not treated in a proper way with dramatic environmental consequences.

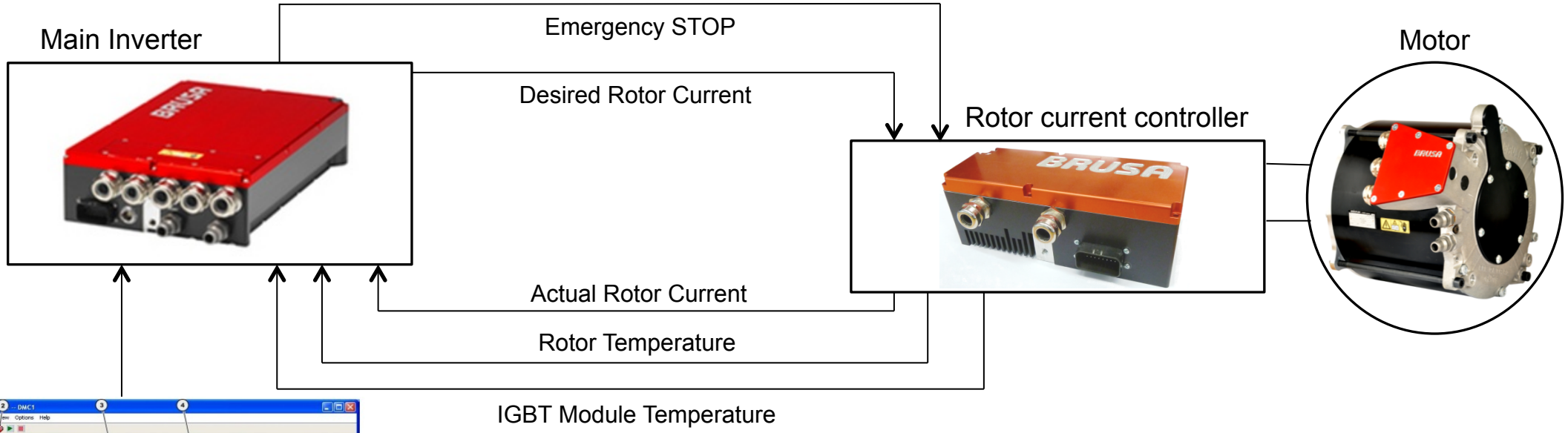


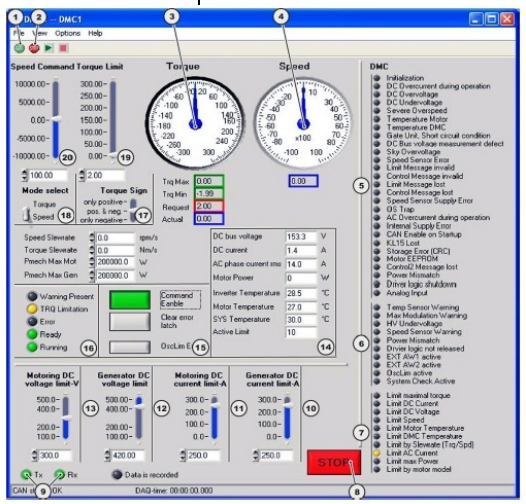
Chinese monopoly since the end of last century

Baotou lake (Chinese Republic). Dramatic environmental consequences of the rare earth industry

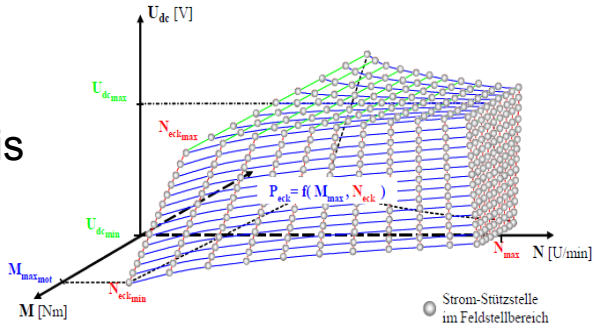
System configuration

Most important information transfer through CAN bus.

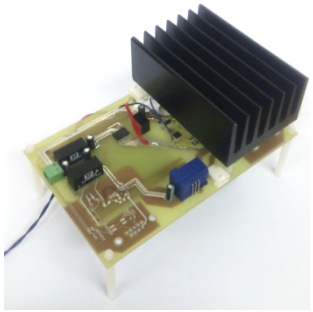


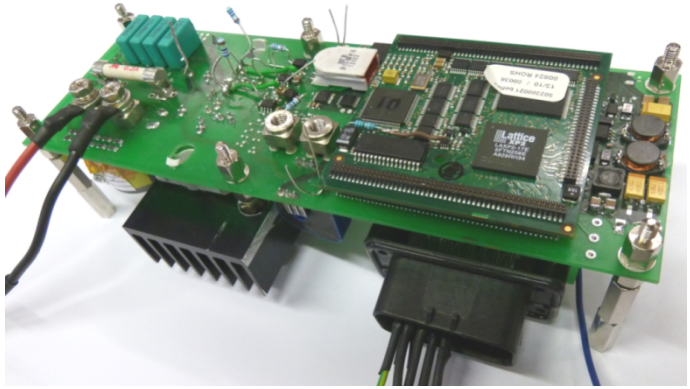


A table with the proper currents I_d , I_q and I_{rotor} depending on speed torque and battery voltage is stored in the main inverter



Rotor current controller A-sample *(completed)*





- Full bridge configuration
- 450 V up to 4000 W
- 2 Kg, 240 x 88 x 90 mm

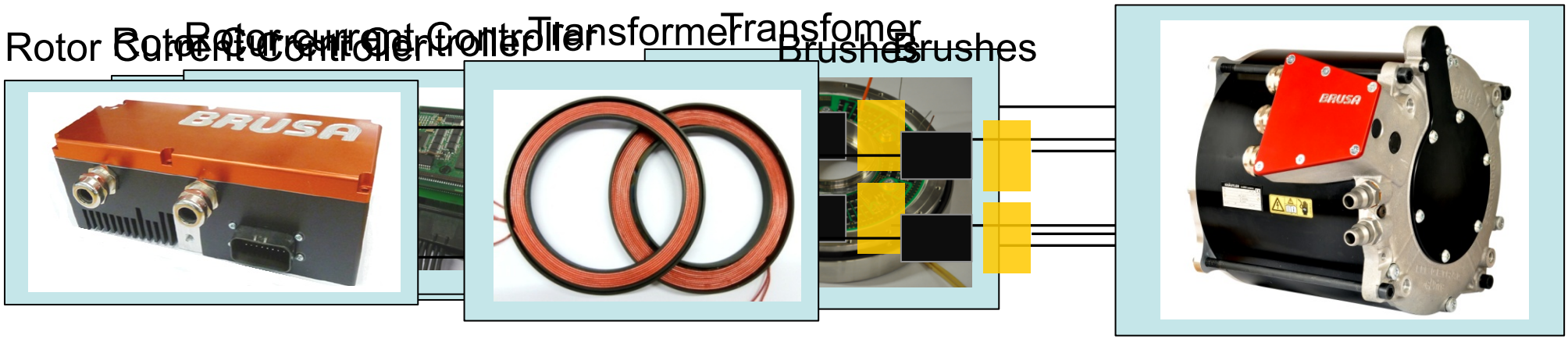
-RS 232 Interface
-CAN BUS communication
-Module temperature measurement
-Board temperature measurement
-Rotor temperature measurement
-HV voltage measurement
-Automotive connectors
-Short circuit protection
-High temperature components

Development steps

Test of the SSM with with conventional brushes

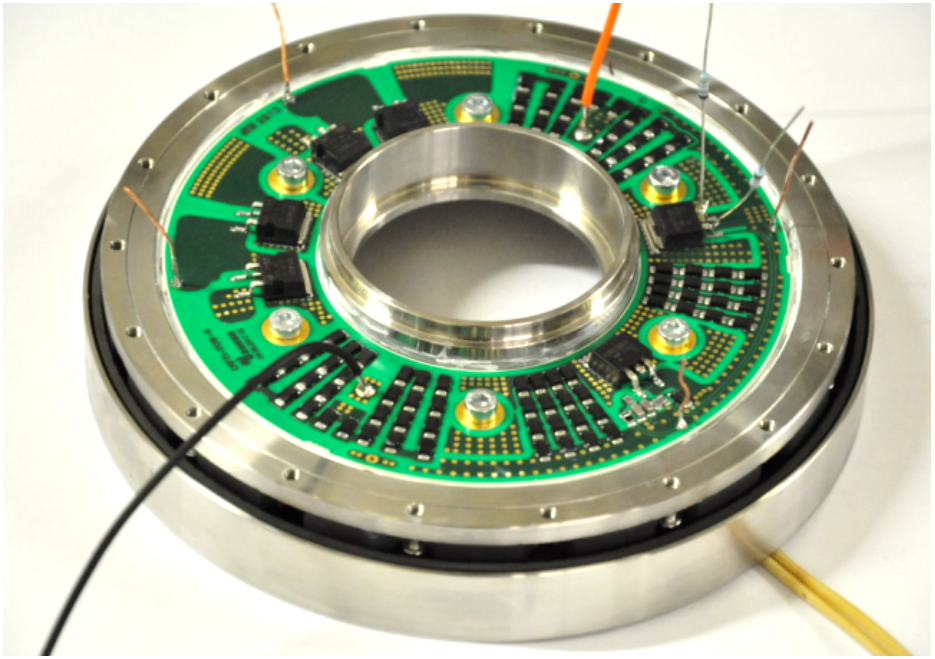
Test of the SSM with a non rotating transformer combined with brushes

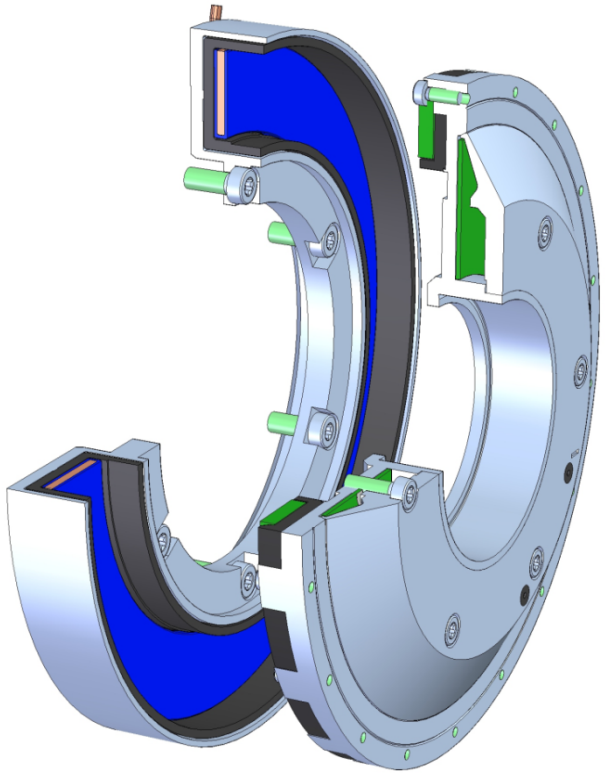
Test of the SSM combined with the rotating transformer

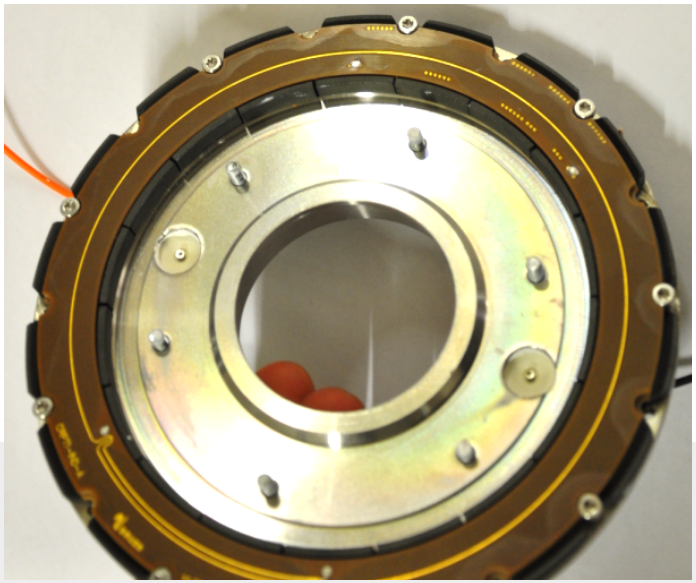


The test of the motor in a vehicle is planned for Spring 2014

The rotating transformer





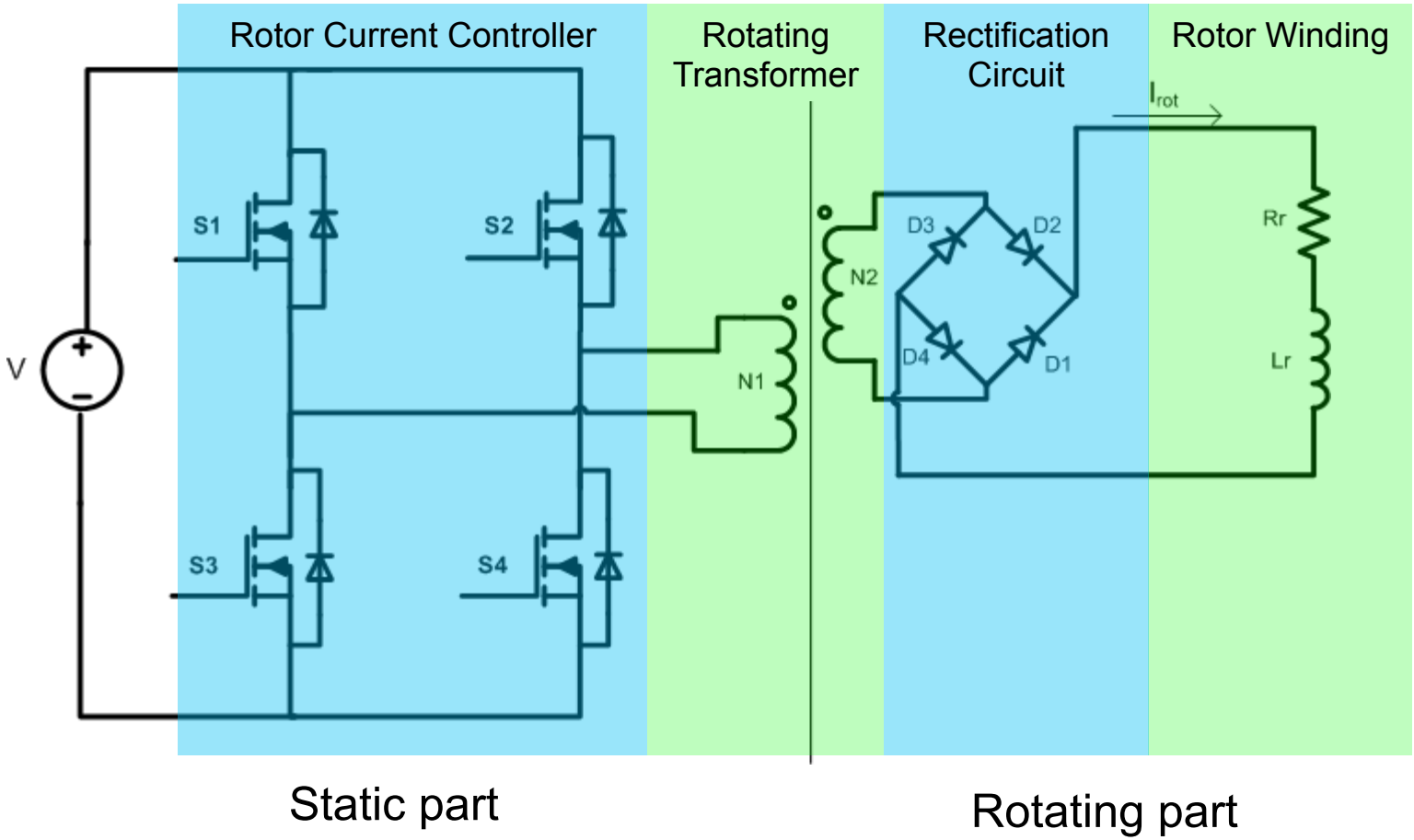


Challenges:

•Accurate rotor current regulation without direct current measurement

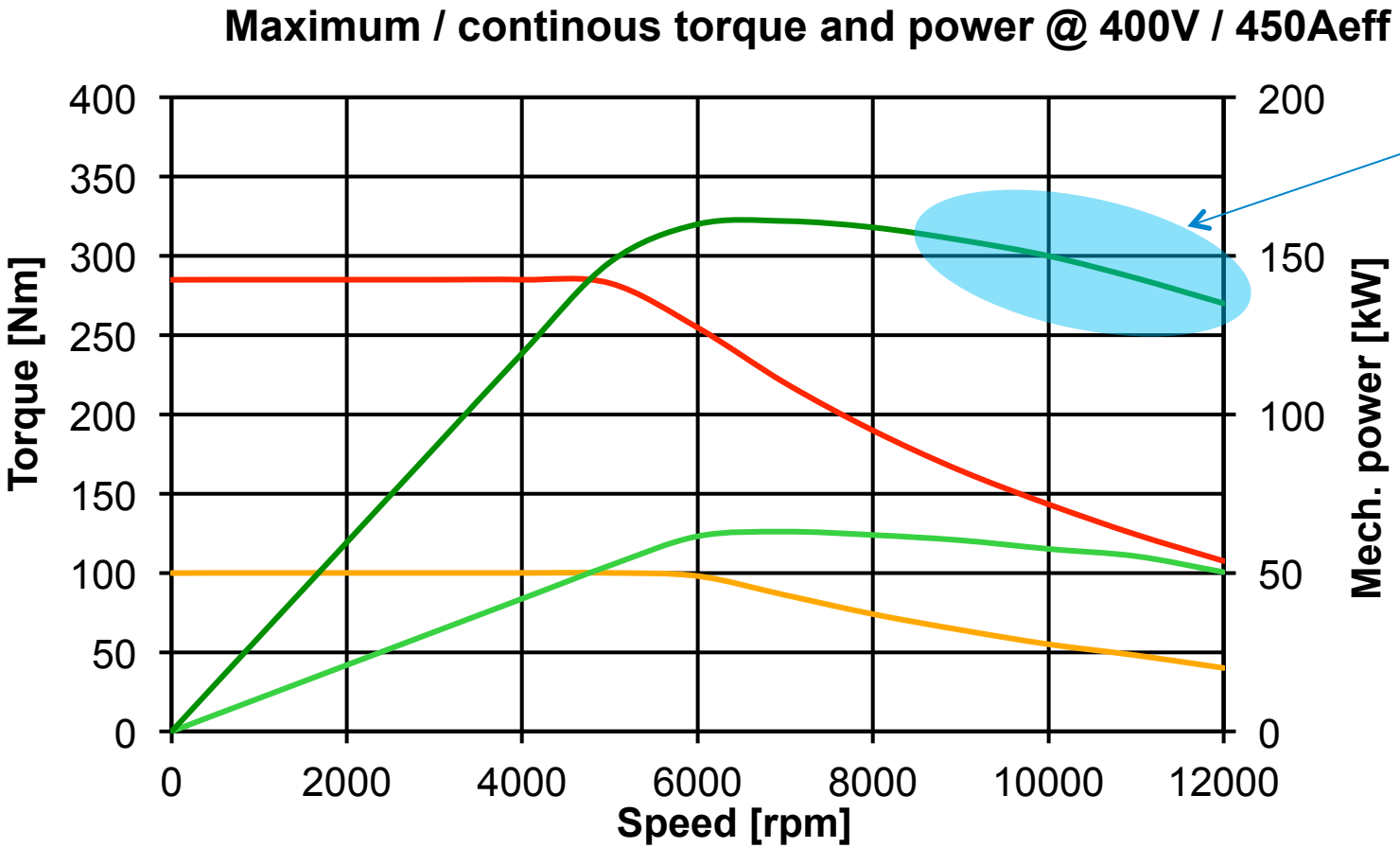
•Withstand centrifugal forces which can exceed 10000 g @ 12000 rpm!!

Power electronic circuit



The basic operation principle is the same of a conventional DC-DC converter. However, the load of the system is represented by the rotor winding.

BRUSA SSM (*on the test bench*)



Reaction time:
50 ms 0-300 Nm

Inverter :	BRUSA DMC534 400 V / 450 A rms
Motor diameter (case) :	270 mm
Motor length (case) :	245 mm
Weight :	49 kg

Integration in the main inverter *(future goal)*

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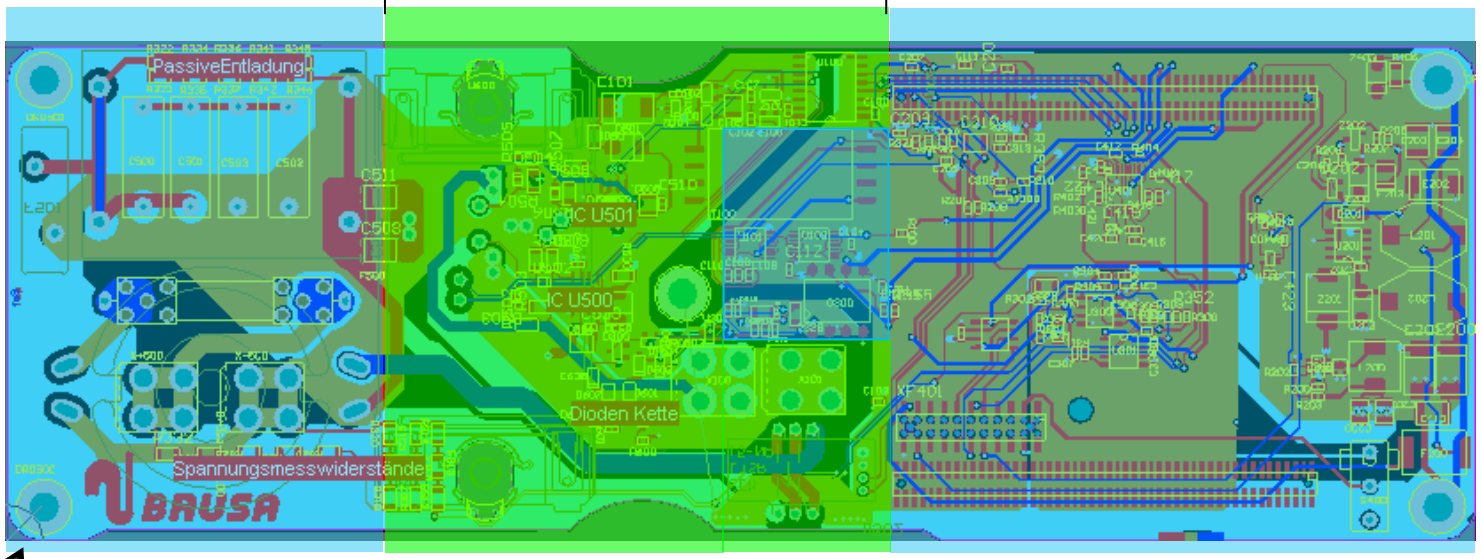
For a series product it makes sense to integrate the rotor current controller into the main inverter. In fact many components are at present doubled in the rotor current controller.



Such a cumbersome Filter is no more needed

FPGA, µC, 5V and 3.3V power supply are already present in the main inverter

After an integration only the green area will be necessary with the advantage of cost complexity and weight reduction

Summary

The current excited synchronous motor:

- Does not need any rare earth permanent magnet
- Has an almost constant power curve over the corner speed
- Offers an impressive peak torque density
- Operates with a high efficiency in the operating points which are most important in a conventional driving cycle
- Allows a quick removal of the rotor excitation

Its main disadvantage is the energy transfer system to the rotor. However, with the present price of rare earth magnets the expected whole additional hardware cost does not exceed the price of the magnets needed by a similar motor.