Mechatronic

Motors

Mechatronics - energiflow

Structures of the energy conversion system (< 1 h)

Primary energy to output

Electrical as intermediate

Power electronic converters as components (< 3 h)

AC/DC/AC

Modulation

Power Units (50 Hz / SMPS / Integration)

Passive components / Integration of passives

Electromechanical converters as components (< 3 h)

Conv. machine types

Elektrostrictive/magnetostrictive converters

Cooling

Power and Energy density

Energyconvertsre as construction elements (< 1 h)

Laminated steel / powder pressing / injection moulding

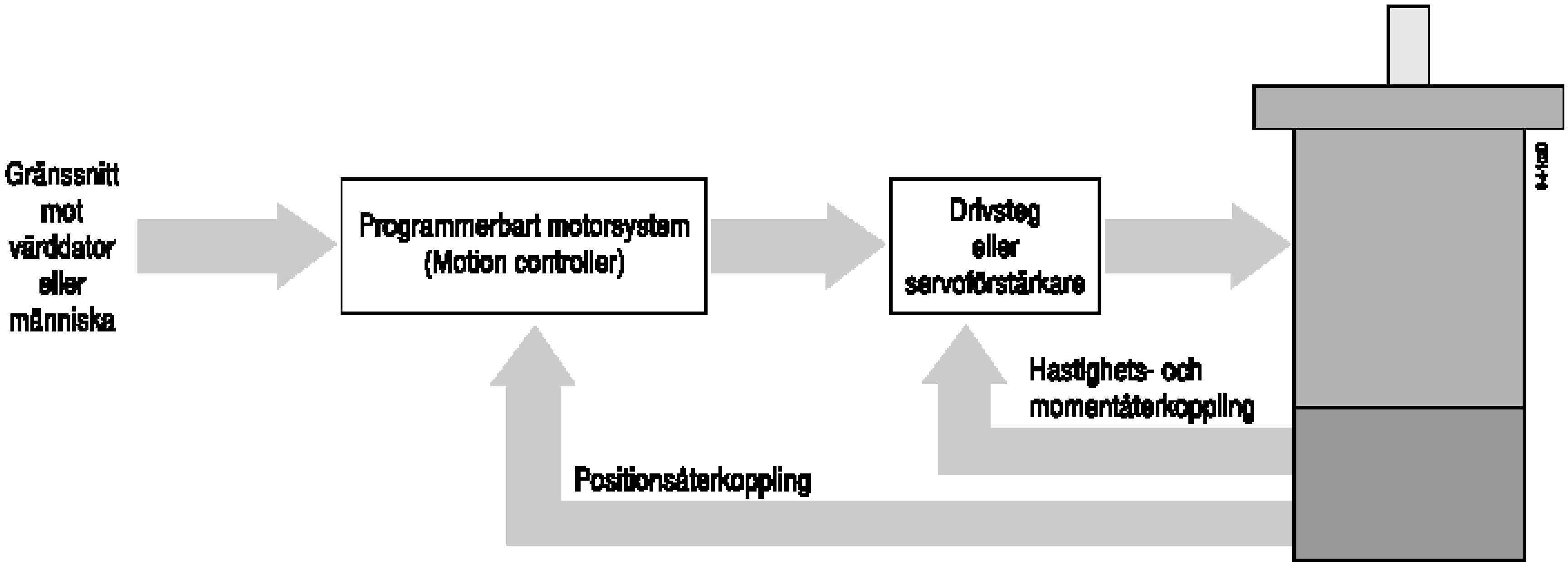
Powerelectronic measurements (< 2 h)

Current / voltage / flux

Torque /speed / position

Preassure / flow (in pumps)

What constitutes a drive?



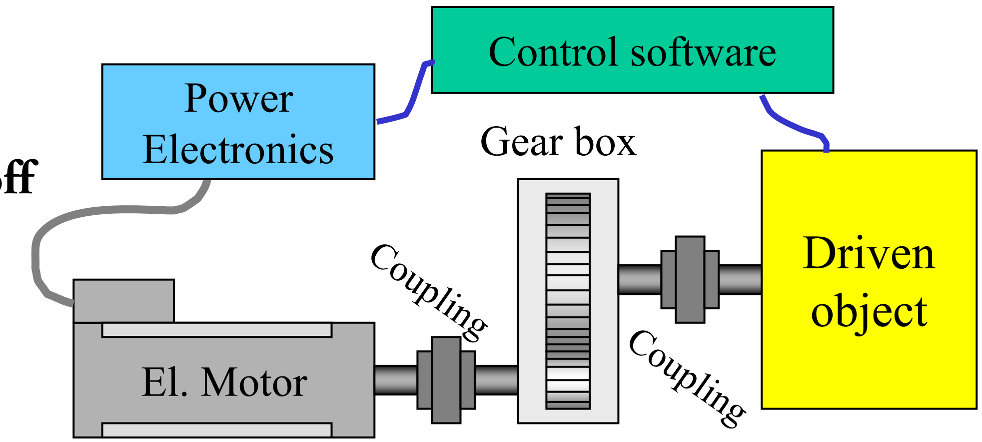
Schematisk bild av ett positioneringssystem

Off the shelf, or tailor made?

- **Off the shelf – complete machine with bearings, housing etc.**
  - This machine is normally connected to the load via a coupling
- **Tailor made**
  - Can be made an integrated part of the driven object.
  - Iron core material can be doubly utilized, magnetic conductor and mechanical design element.

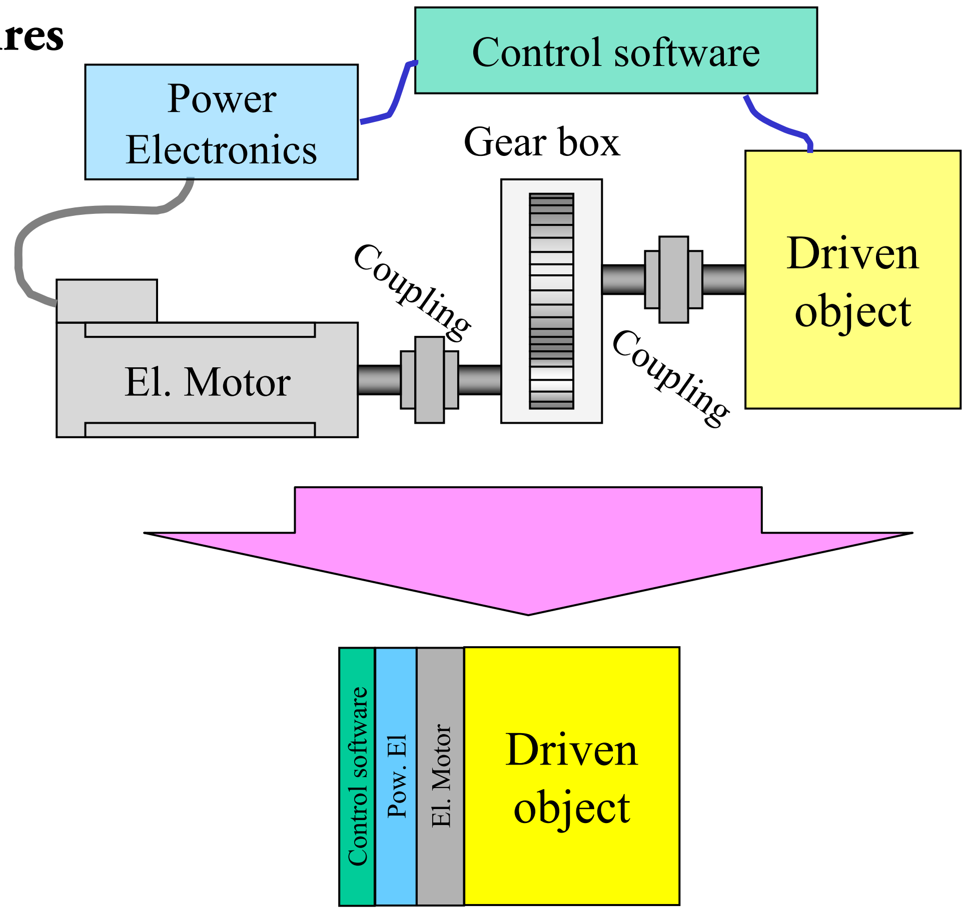
Background

- **Most mechanical designs use actuators**
- **System designs are adapted for "off the shelf"-actuators**



Integrated designs

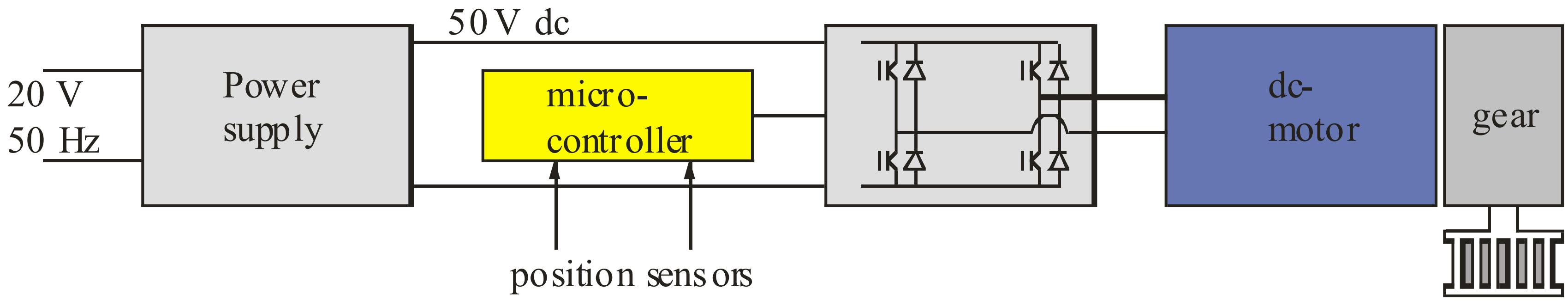
- **Integration of actuators requires …**
  - Actuator design knowledge
  - Production method expertise
- **… and gives**
  - Smaller size and lower weight
  - Lower energy consumption
  - Lower EMC-problems
  - Lower cost



Design task

1. Choose geometry
2. Estimate response time and dynamics
3. Select motor drive
4. Calculate electrical power need
5. Design power supply
   - 20 V / 200 W trafo available

System layout



There are at least two design flaw's at this stage:

1. A standard transformer is used, should be eliminated in the power supply, but is kept for simplification in the power supply design.
2. A gear box may not be the best solution, and any alternative drive has not been investigated yet.

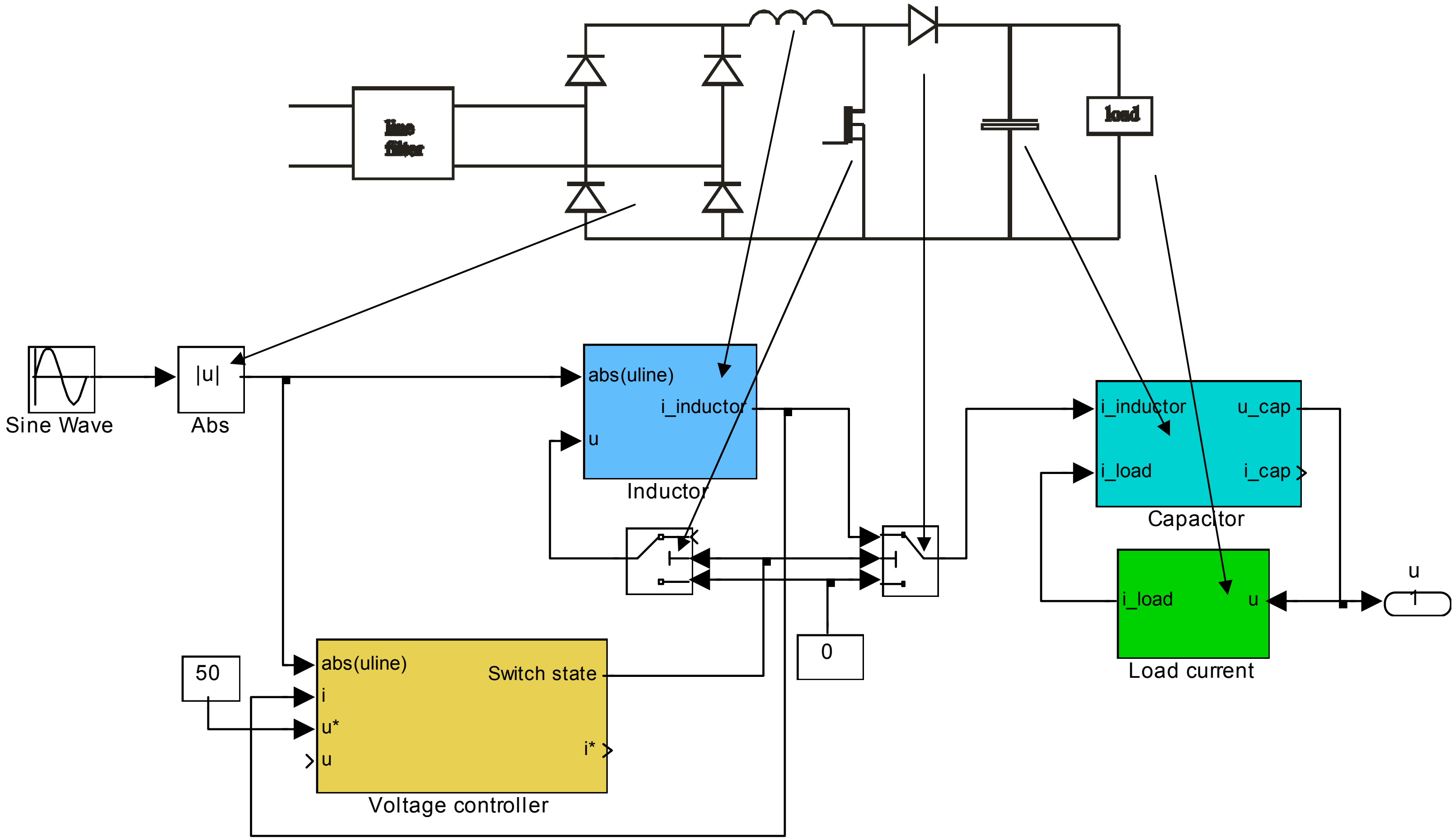
Power requirements

- **To design the power supply, we need to know the maximum power requirements.**
- **These come from the drive power and the control electronics power consumption.**
- **The drive power results from**
  - the mechanical work in normal operation
  - the additional work related to speed changes
  - Losses in the gear, motor and power electronics
- **To evaluate the drive power, a drive system model in dynamic simulation is convenient to build, for two reasons:**
  - It will force us to develop the position and speed controllers
  - It will give us all instantaneous speed and force values to calculate instantaneous mechanical power.

Details of the power supply

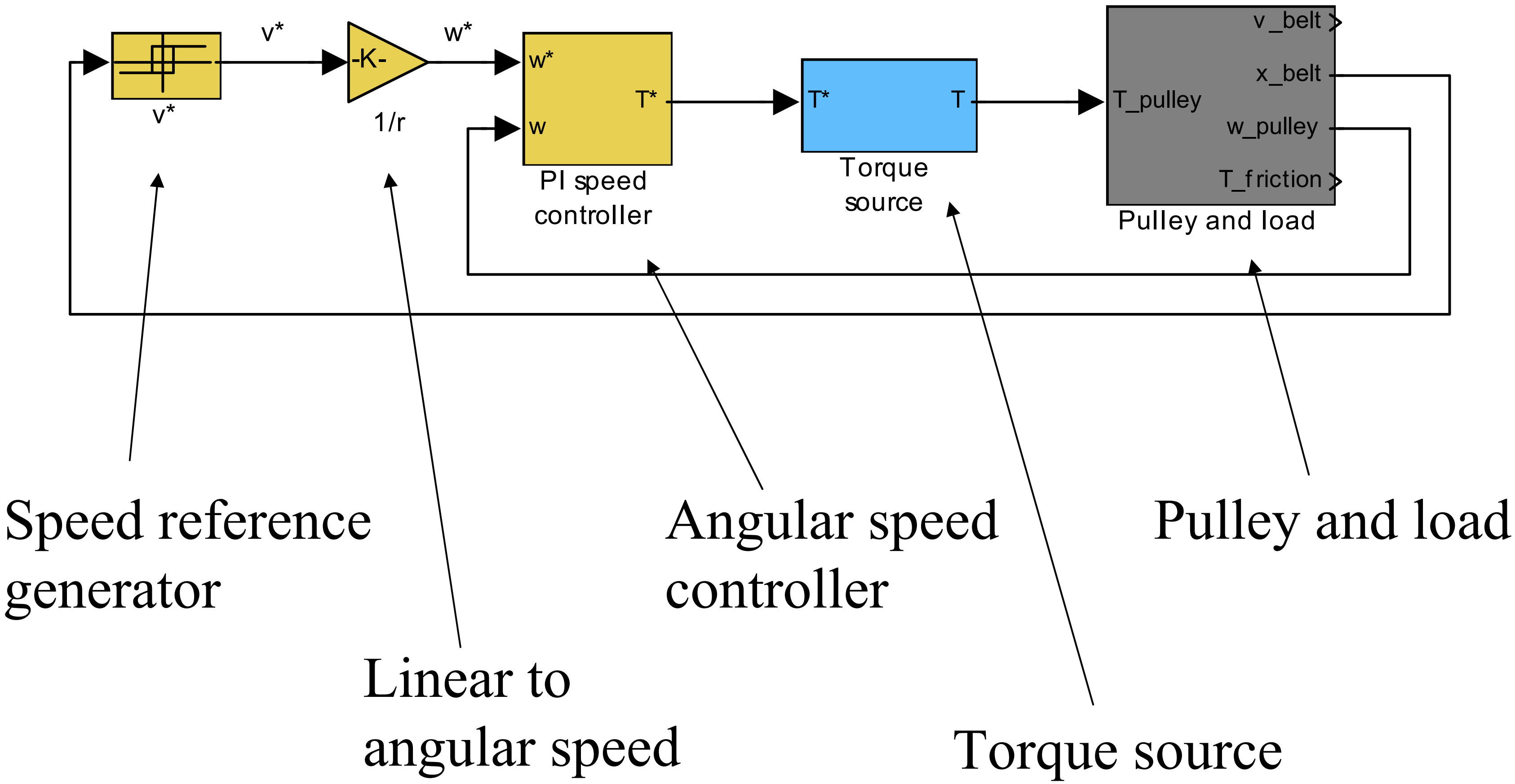
- **Voltage controller**
  - The current reference is scaled with a full wave rectified sinewave in phase with the line voltage but with unity amplitude.
- **Inductor**
  - Includes a small resistive voltage drop
- **Capacitor**
  - Ideal
- **Load current**
  - The load power from the simulation of the mechanical system is use to calculate the load current

Power Supply



Mechanical control loop

- **NB! We do not model the electrical dynamics at this stage, only the mechanical.**



Details of the mechanical control loop

- **Speed reference generation**
  - Shift sign of the speed reference every time it hits an end point
- **Linear to angular speed**
  - Solve the dynamics in angular speed instead
  - Angular speed * Radius = Linear speed
- **Angular speed control**
  - PI-controller
- **Torque source**
  - Does not respond instantaneously – represent as 1'st orde low pass filter
  - Has a limited torque capability – insert corresponding limitation
- **Pulley and load**
  - Estimate equivalent intertia

$$\frac{d\omega_{pulley}}{dt} = \frac{T_{pulley} - T_{friction}}{J_{equivalent}}$$

$$T_{friction} = F_{friction} \cdot r_{pulley}$$

$$F_{friction} = -sign(v_{linear}) * 100 \text{ [N]}$$

Standard machines

- **DC machines**
  - Permanent Magnet
  - Series, Shunt and Compound wound
- **AC servo motors**
  - Permanent Magnet
  - Sinusoidal currents
- **Reluctance motors**
- **Stepper motors**

Electrical Motors properties

- **High torque density**
  - 1…30 Nm/kg
  - Compare combustion motors 1…2 Nm/kg
  - Compare Hydraulmotors 600 Nm/kg
- **High efficiency**
  - ≤ 98%

Motors
Torque and Inertia

One rotor conductor (of all along the airgap surface):

$$F_x = B \cdot i \cdot l$$

$$T_x = F_x \cdot r = B \cdot i \cdot l \cdot \frac{D}{2}$$

Total torque along the airgap:

$$T = T_x \cdot \pi \cdot D = B \cdot i \cdot l \cdot \frac{D \cdot \pi \cdot D}{2} \propto B \cdot i \cdot rotorvolume$$

$$P = \omega \cdot T$$

Inertia

$$J \propto m \cdot r^2$$

The D_{is}^2L Output Coefficient

- **Mechanical power:**

$$P_{mech} = \eta_{gap} \cdot P_{gap} = \eta_{gap} \cdot VA_{gap} \cos(\varphi_{gap})$$

$$= \frac{\pi}{2\sqrt{2}} \omega_{mech} k_1 k_{is} (D_{is}^2 l_{is}) B_{g1} K_{s(rms)} \cdot \eta_{gap} \cdot \cos(\varphi_{gap})$$

Essen's rule

Limited by rotational stresses

Proportional to the rotor volume

Limited by saturation

Limited by losses and cooling

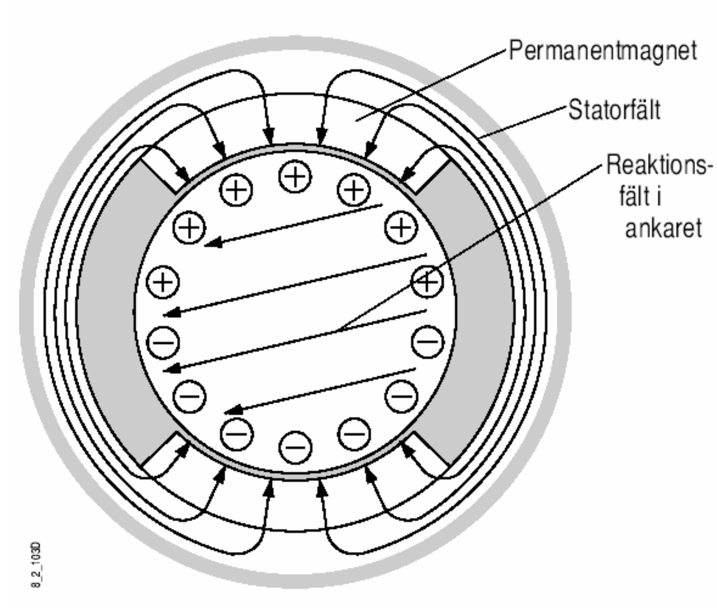
Servo motor - definition

- **Motor for torque, speed or position control**
- **NB! Line start motors and voltage or frequency controlled motors do not qualify as servo motors.**

DC motors

- **Only PM**
- **Mechanical commutation of rotor currents**
- **T=k*ia**
- **Without current feedback risc for over current at start/reversal and permanent magnet demagnetisation**
- **Current feedback protects motor AND load**

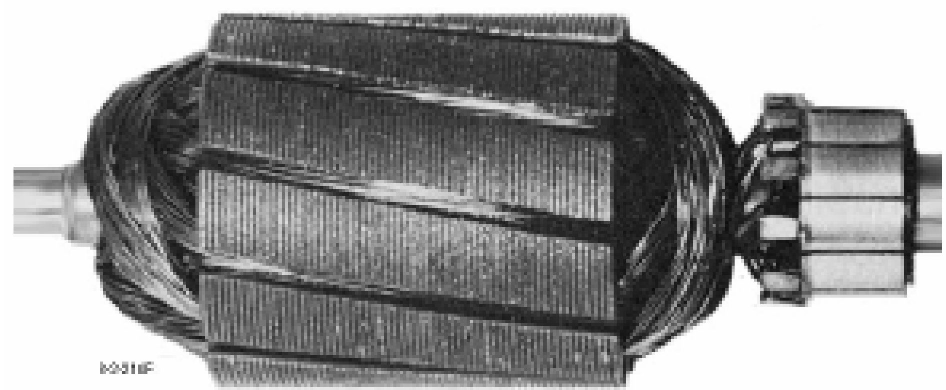
Electro-craft PM-likströmsmotorer



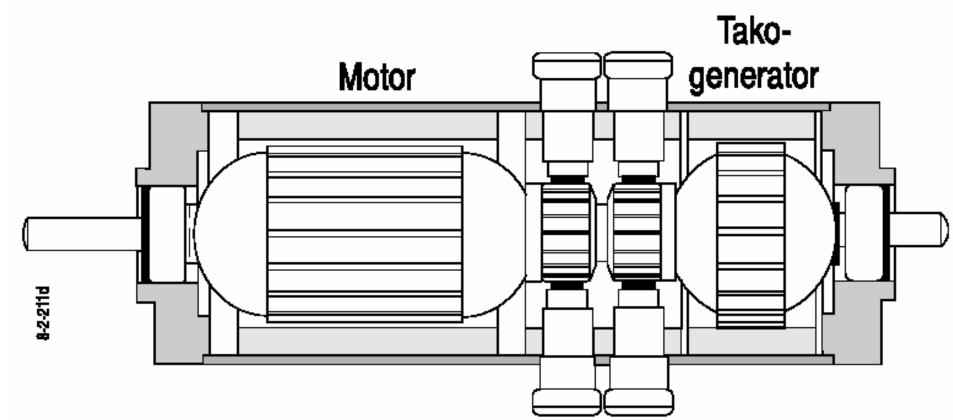
PM-motor i genomskärning

DC Motor as servo motor

- **Smaller and smoother rotor**
  - lower inertia and inductance
  - Shorter torque rise time
  - Faster acceleration
- **Skewed rotor**
  - Smoother torque
- **Built in sensors**
  - Speed
  - Position

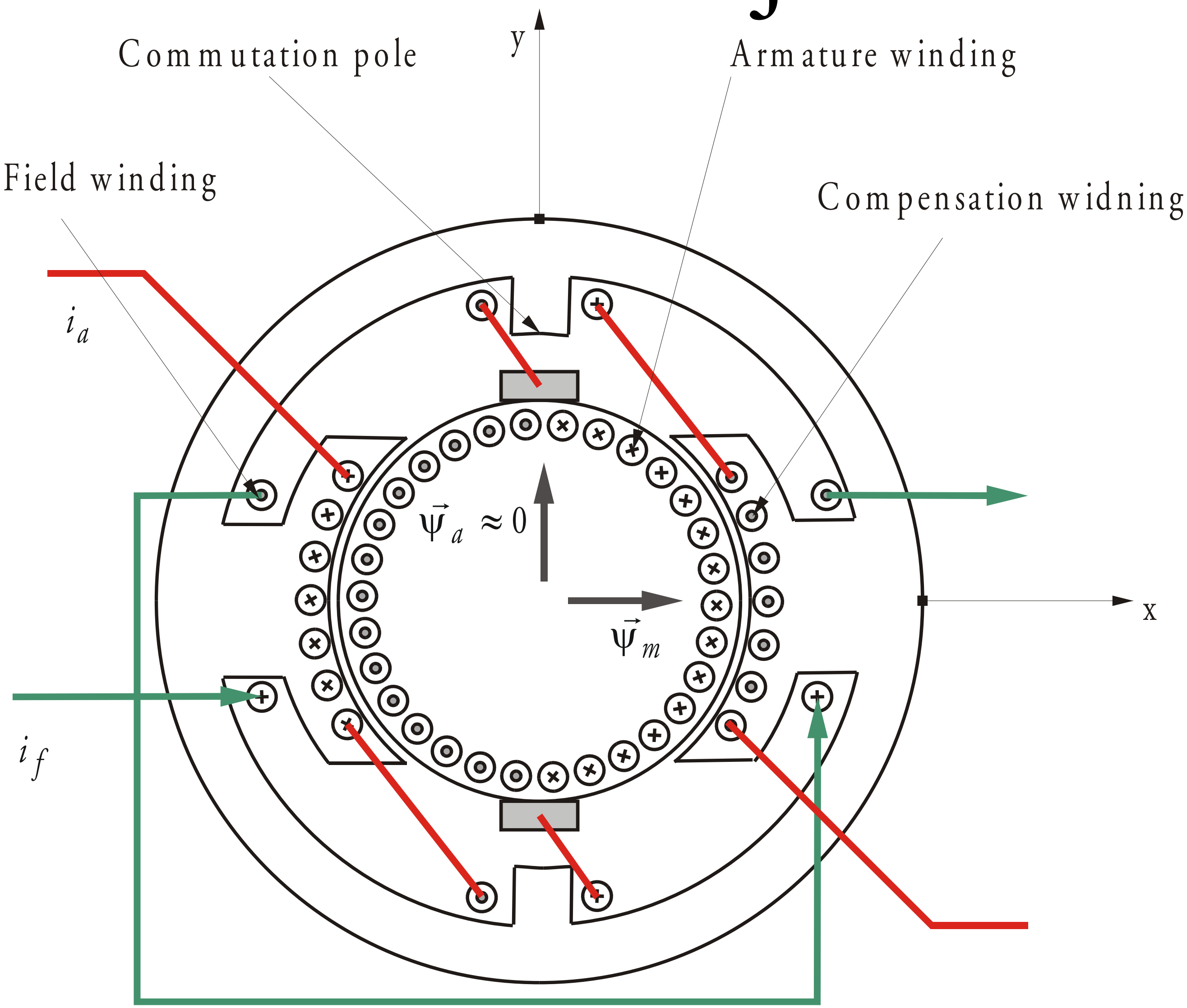


Spårsneddat ankare



DC-servomotor med takogenerator

Mer detaljer



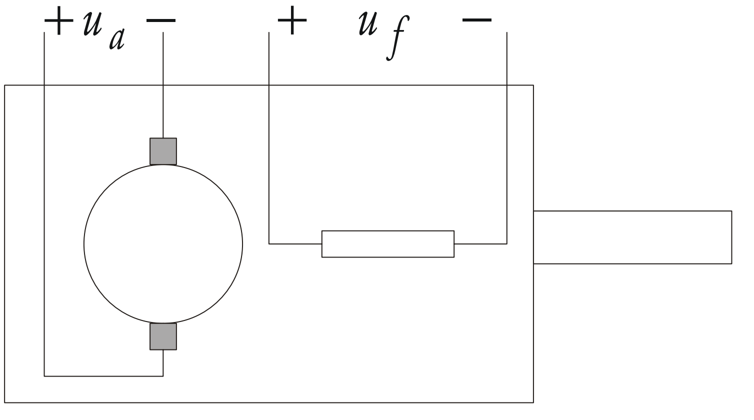
Mathematical model

- **Rotor circuit**

$$u_a = R_a \cdot i_a + L_a \frac{di_a}{dt} + \omega \cdot \psi_m$$

- **Torque**

$$T = \psi_m \cdot i_a$$



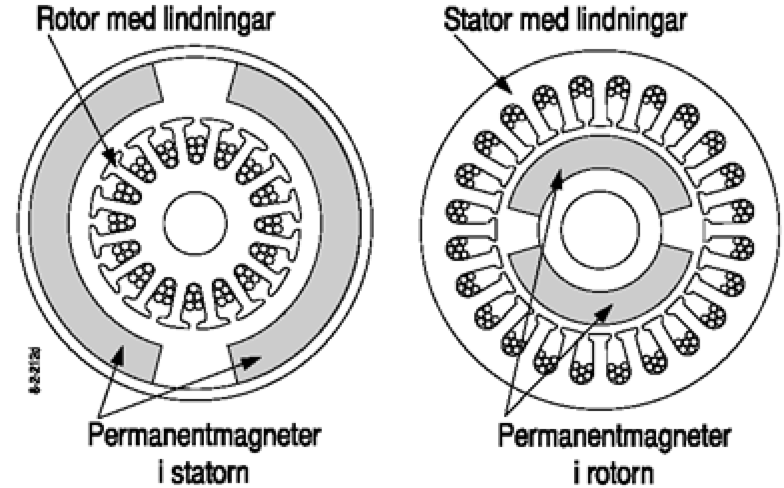
DC motor pros and cons.

- Established
- Soft operation
- High efficiency
- Cheap
- Quiet

- Wear
- Sparking
- EMC

AC servo motors permanent magnetized

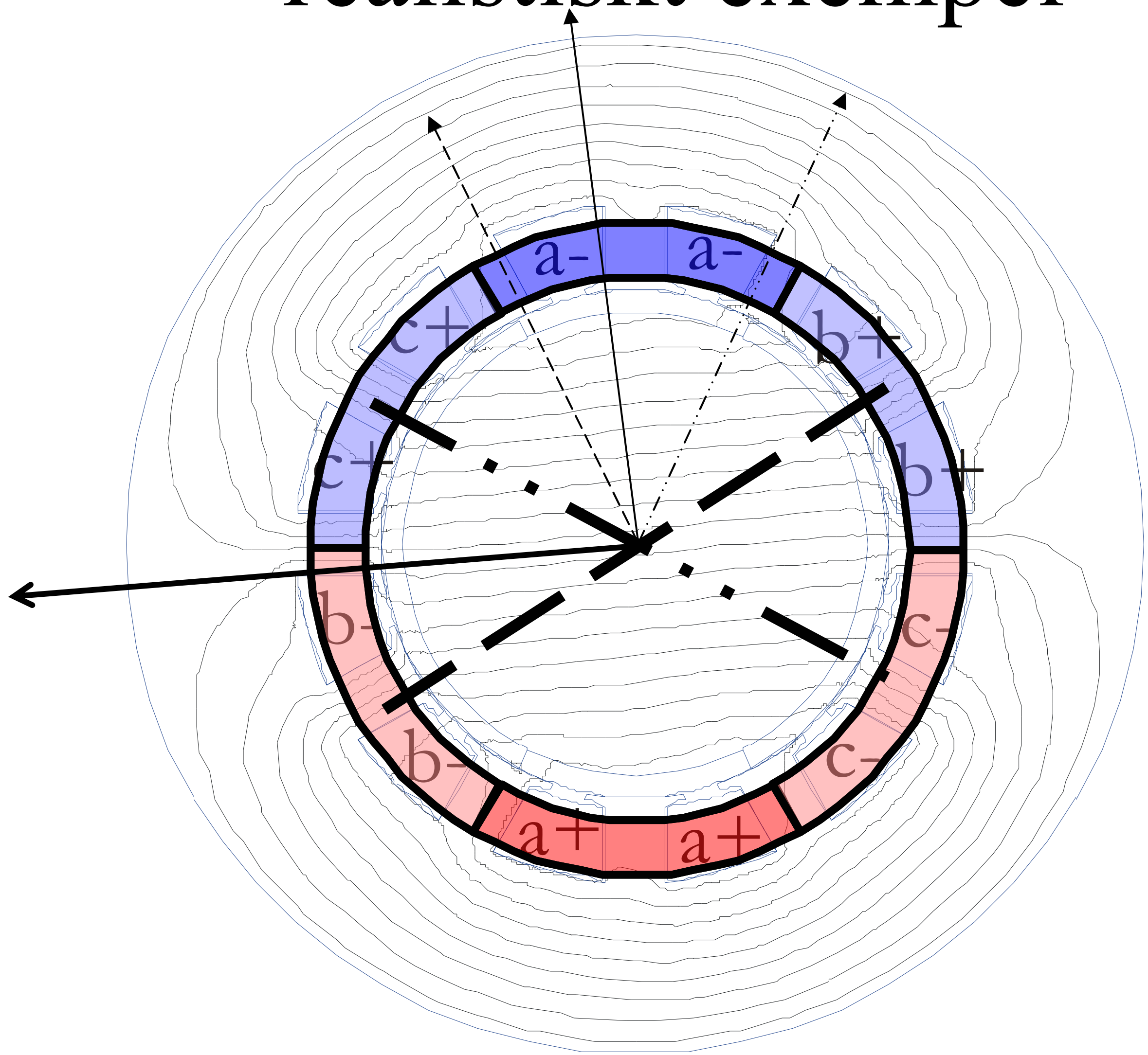
- **Winding in th stator**
- **Electronically commutated**
- **Position sensor needed**
- **High torque density**



T.v. borstförsedd motor, t.h. borstlös synkronmotor

Borstlös synkron servomotor

Trefas löser rotationsproblemet realistiskt exempel



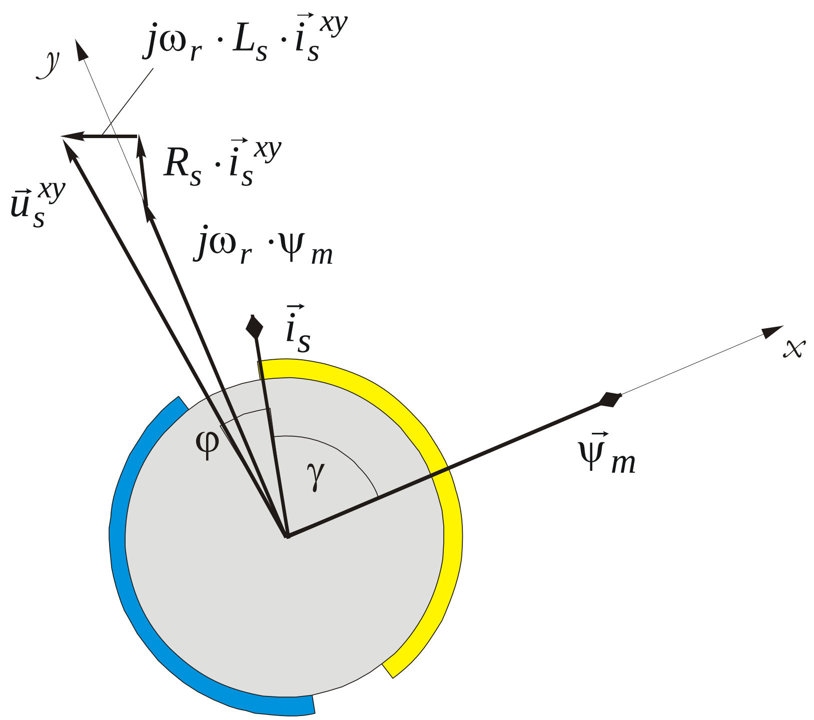
Stationary operating point

Resistive Voltage drop

Inductive Voltage drop

Induced Voltage

$$\vec{u}_s^{\,xy} = R_s \cdot \vec{i}_s^{\,xy} + j\omega_r \cdot L_s \cdot \vec{i}_s^{\,xy} + j\omega_r \cdot \vec{\psi}_m$$

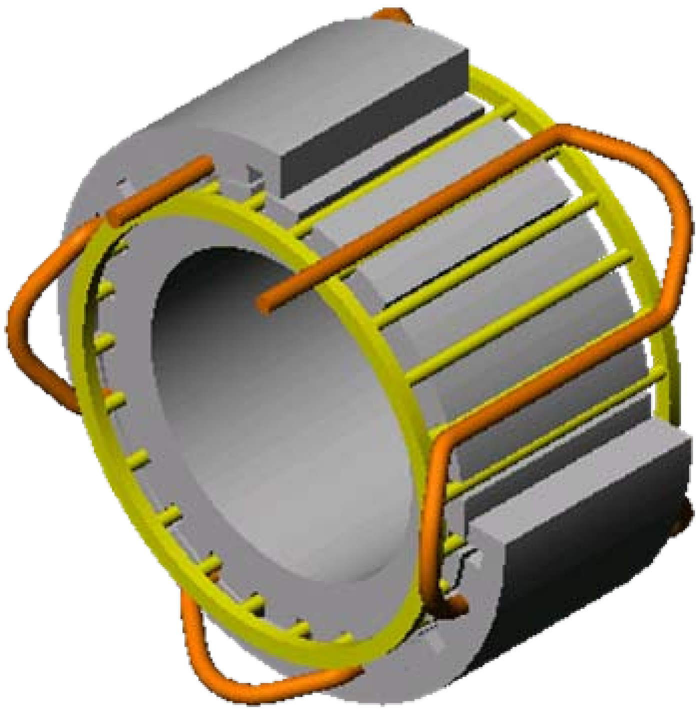


AC servo motor pros and cons.

- **Soft operation**
- **High efficiency**
- **Quiet**

- **Magnet material expensive**
- **Small rotor desired – magnets difficult (expensive) to mount**
- **Expensive control electronics**
- **Position sensor**
- **Can pick up iron dust, sealed**

Induction motor



Three phase stator

No magnets

Short circuit, "squirrel cage", rotor

Three phase current in the stator

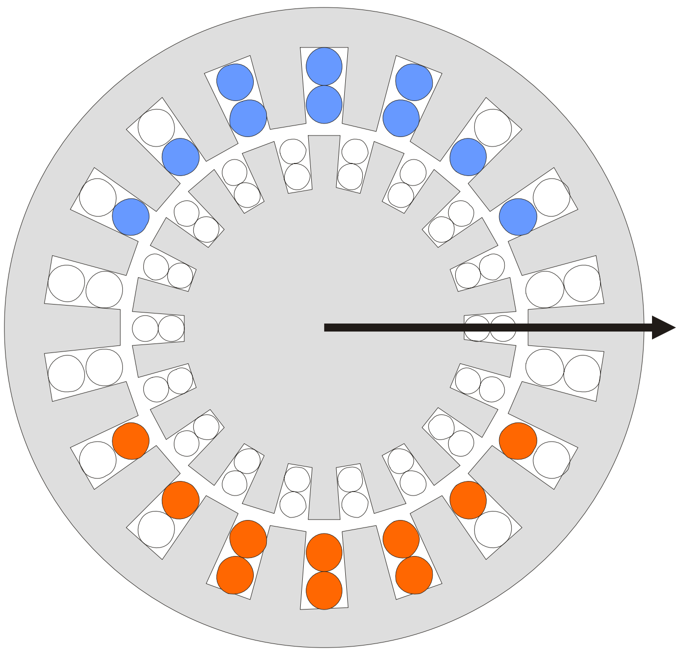
The rotor current must be induced

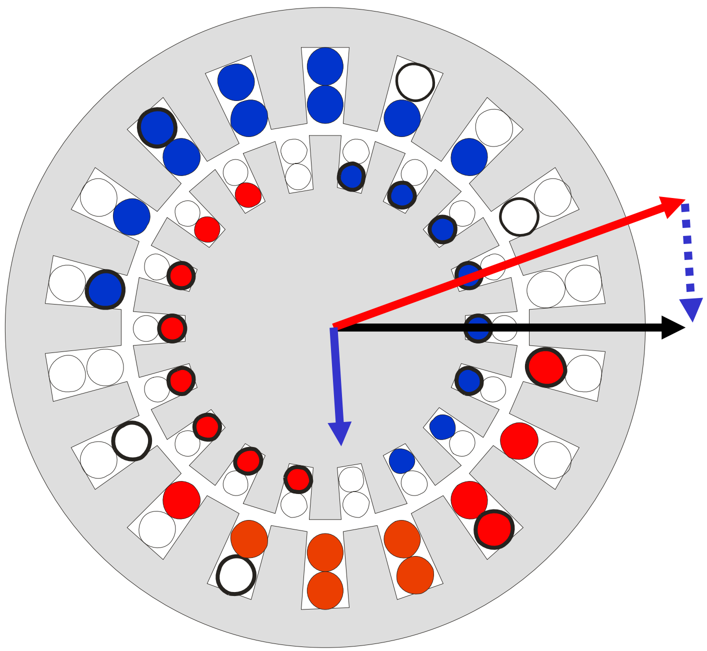
Three phase power electronics

AM - dynamik

Utgångsläge

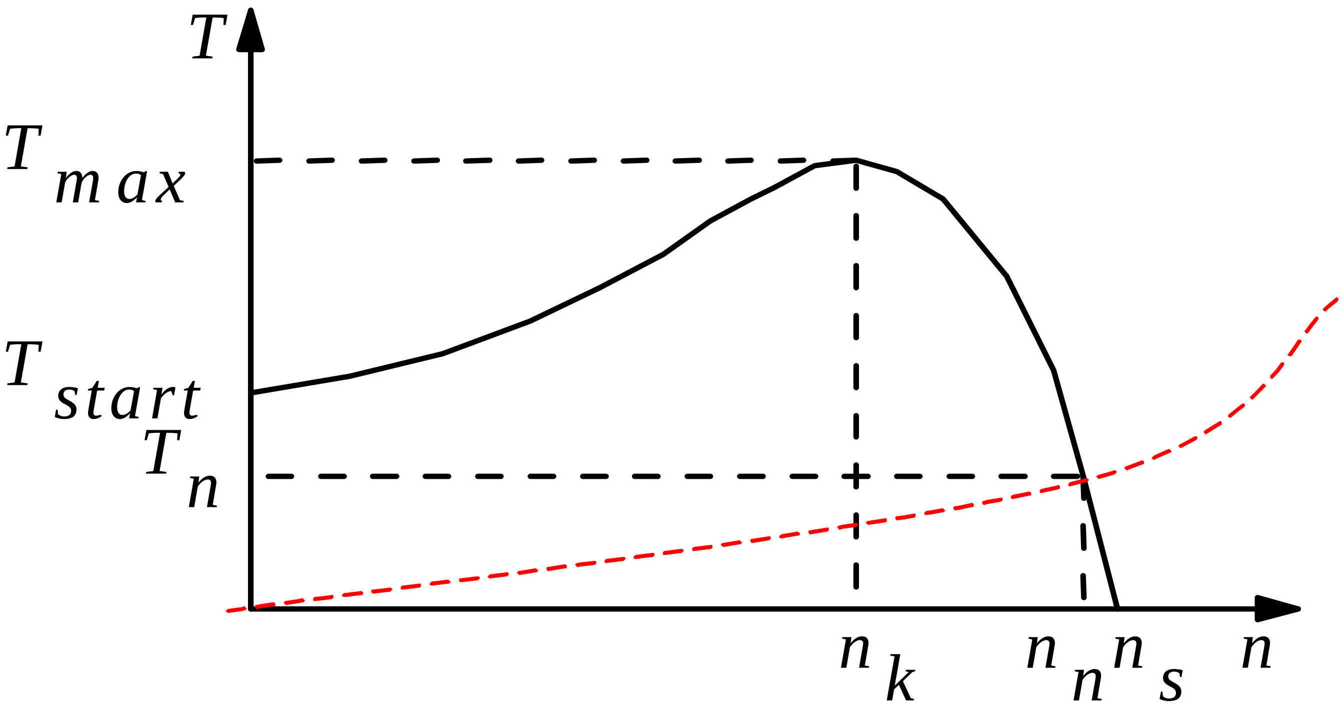
Flytta statorströmmen snabbt ett steg - vad händer i rotorn?





Momentegenskaper

$$T = \psi_s \cdot i_r = (\omega - \omega_r) \cdot \frac{\hat{\psi}_s^2}{R_r}$$



Induction motor pros and cons

- **Can start when connected to the public grid**
- **Robust and reliable**
- **Cheap**
- **Simple to maintain**
- **Standardizsed**

- **Efficiency**
- **Power factor**

Stepper Motors

- **Variable Reluctance**
  - Rotor is made of only (soft) iron with no magnets but salient teeth
- **PM stepper motors**
  - Rotor is made of permanent magnets
- **Hybrid stepper motors**
  - Rotor has both teeth and permanent magnets

Variable reluctance motor

- **One winding at a time is energized.**
- **The rotor takes one ”step” at a time**

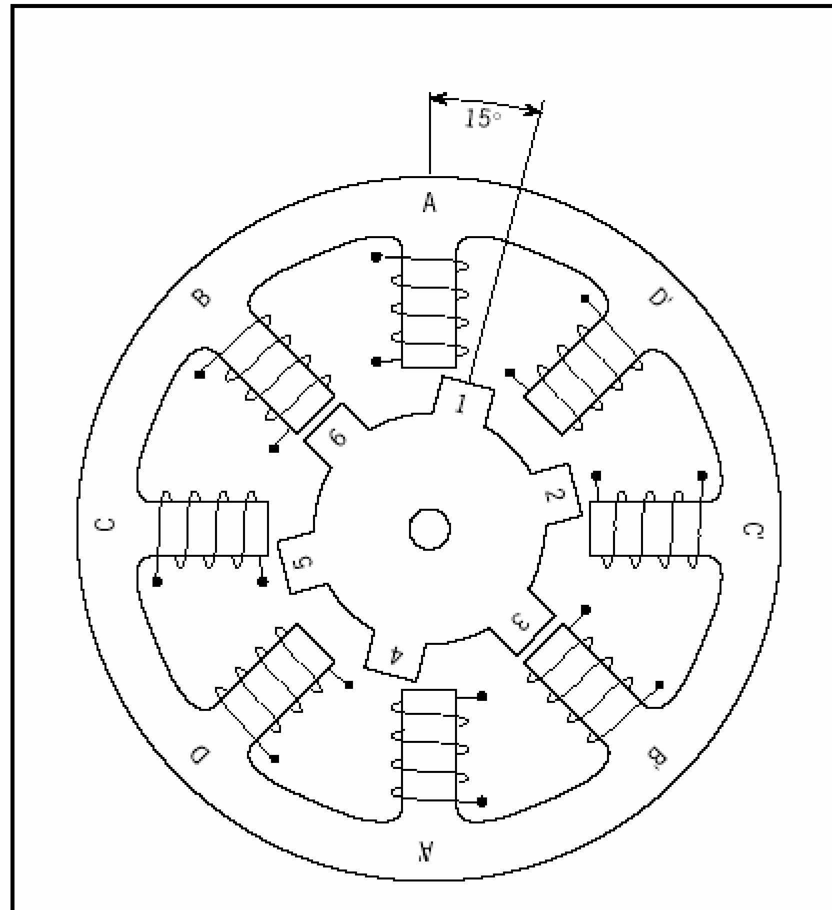


Figure 1. Cross-section of a variable-reluctance (VR) motor.

PM stepper motor

- **The electromagnet of the stator and the permanent magnet of the rotor defines specific positions**
- **By alternating what phase is magnetized, the rotor takes a ”step” at a time**

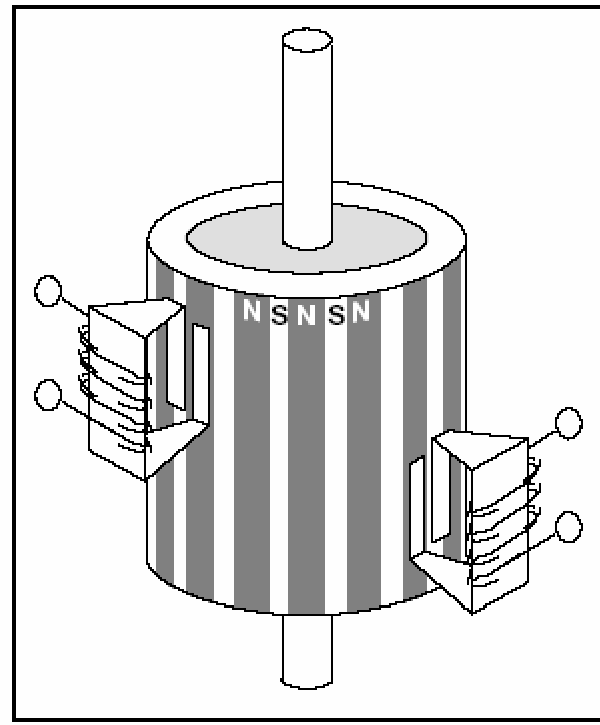


Figure 2. Principle of a PM or tin-can stepper motor.

Stepper motor control

- **Voltage control mode**
  - The current is controller by (pre-)selected voltage – NO CURRENT FEEDBACK
  - Does not work well at higher speeds
- **Current control mode**
  - True current feedback is used.

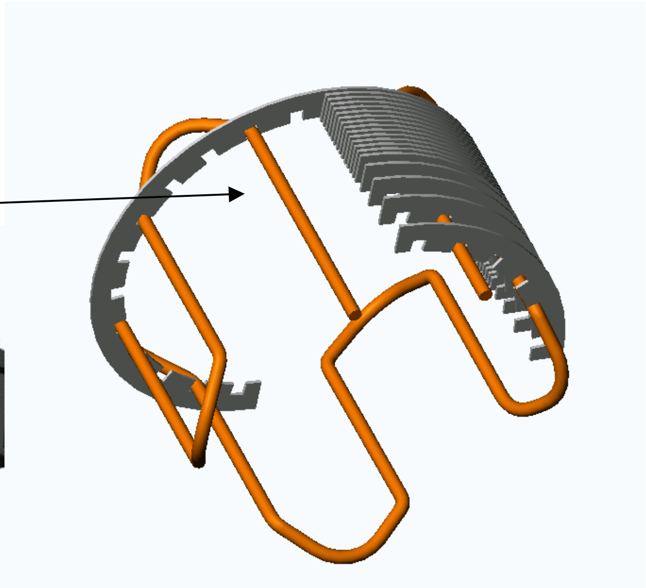
Stepper motor pros and cons

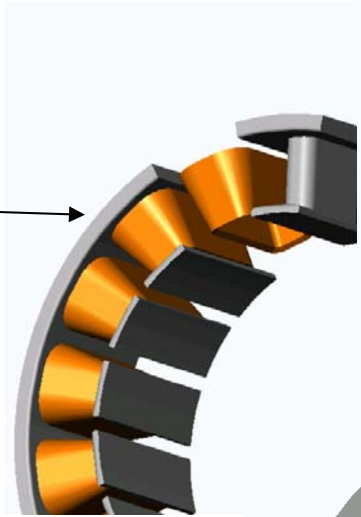
- **Cheap**
- **No position feedback (that's the idea)**
  - Position controlled by counting the number of pulses that is supplied.
- **High torque @ low speed**

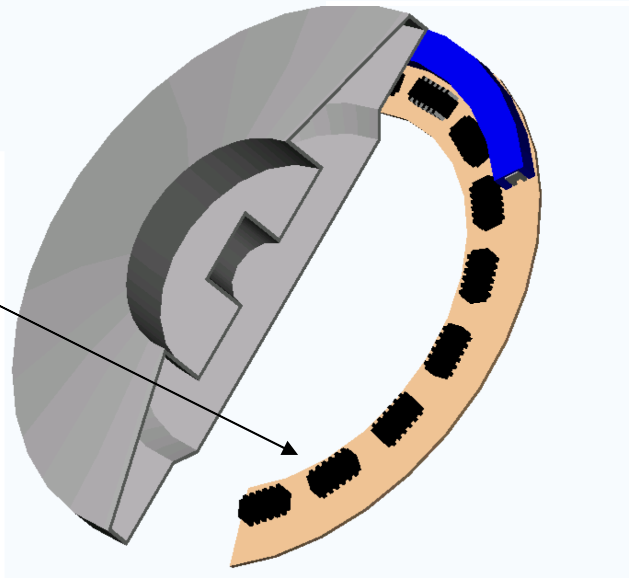
- **Noise**
- **At high acceleration (dynamic) or static load synchronism may be lost. Results in total loss of torque.**
- **Low torque @ high speed**

Production methods

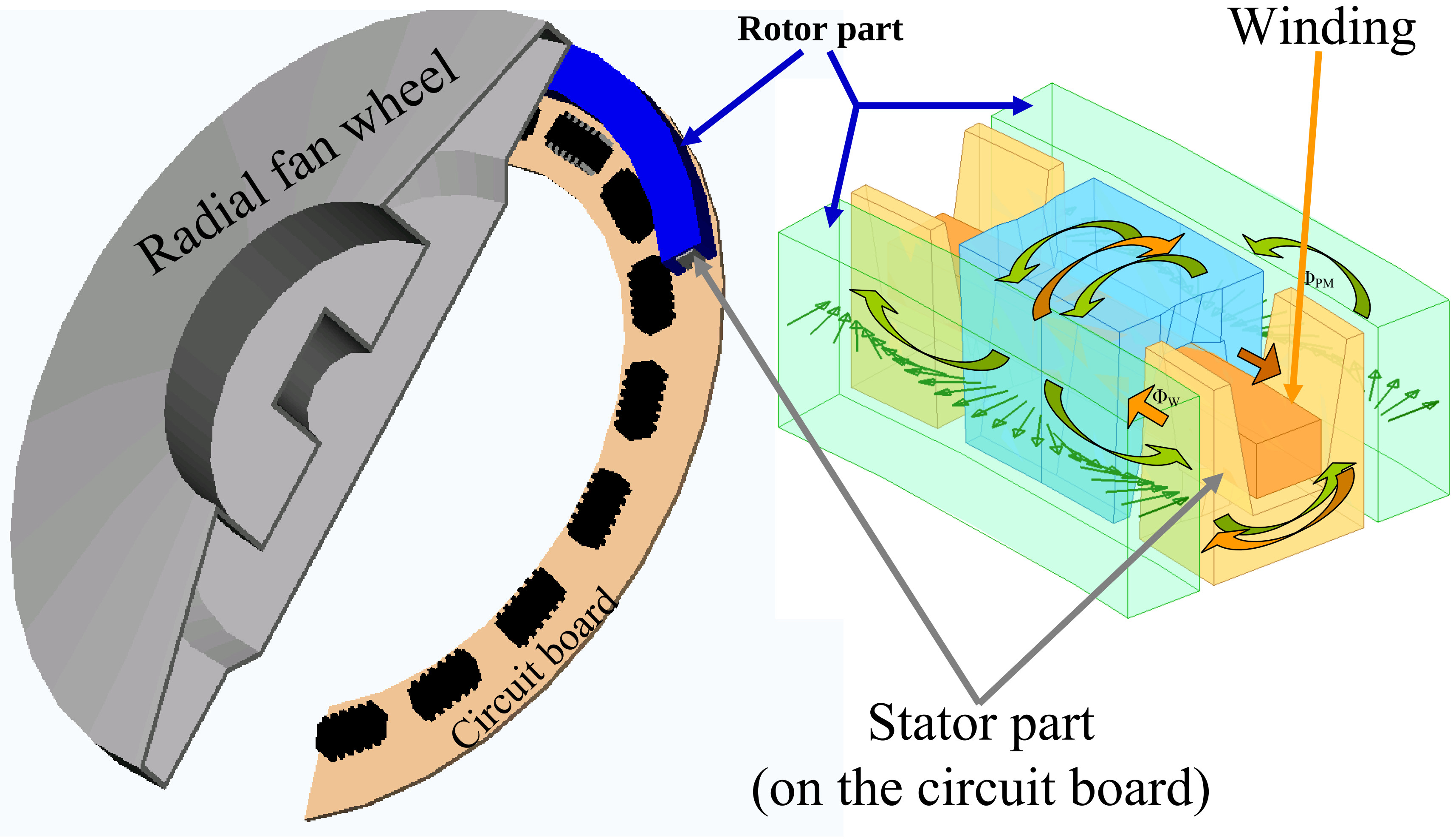
- **Traditionally:**
  - Cut, stack and wind
  - Many production steps, many parts
- **Today:**
  - Press and wind
  - Fewer prod steps, fewer parts
- **Tomorrow**
  - Mould?
  - Single prod step,1 part



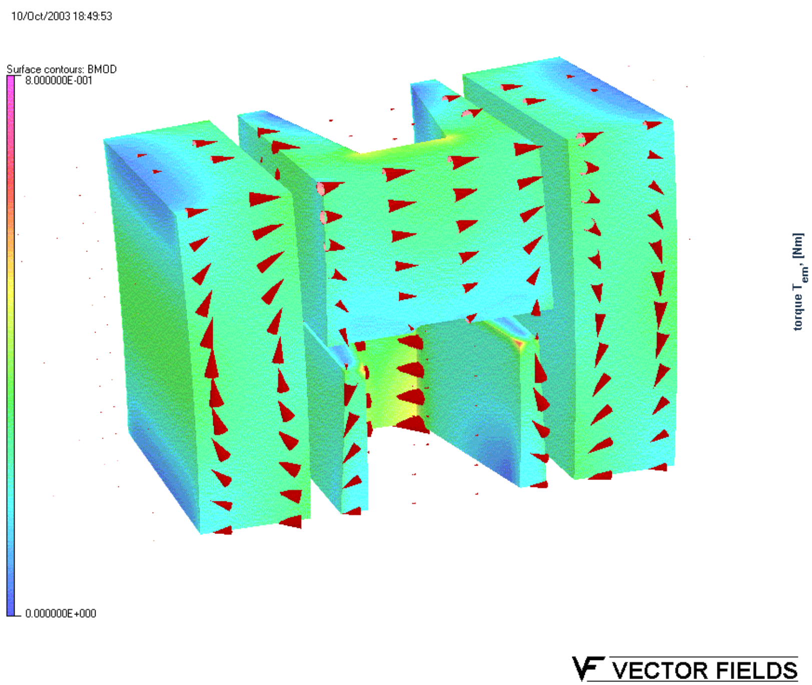


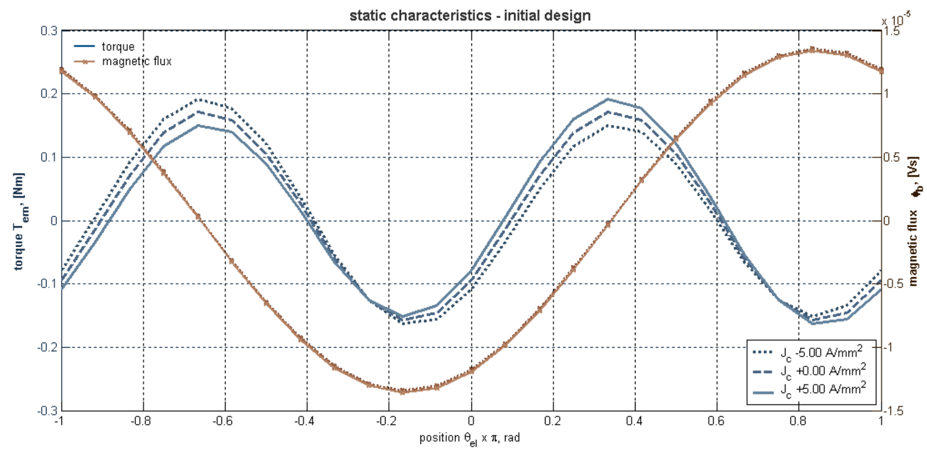


An example of an injection moulded design – in more detail



TFM: double claw-pole simulated

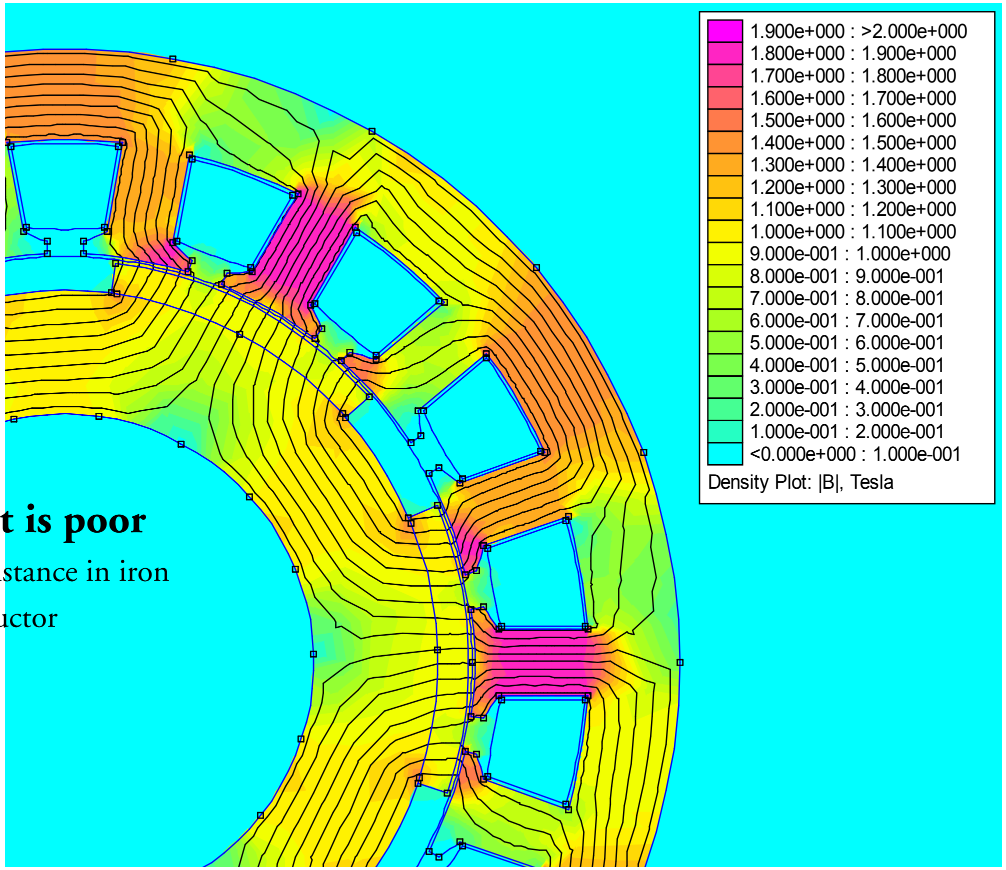




Quantity	Value	Unit
Inner radius, ri	75.0	mm
Outer radius, ro	66.0	mm
Height of core, hp	5.0	mm
Number of poles, Np	72	-
Air-gap, g	0.4	mm
Inner magnet, rpm1	66/68	mm
Outer magnet, rpm2	73/75	mm

Quantity	Value	Unit
Pole clearance, Kp	0.085	-
Tangential tapering, γ1	2.5	deg
Axial tapering, γ2	10	deg
Progressive radius, cyr	0.3	mm
Flank thickness, hf	1.4	mm
Pole thickness, lt	1.1	mm
Current density, Jc	5	A/mm^2

Why not before?



- **In a conventional design the result is poor**
  - The magnetic flux travels a rather long distance in iron
  - Thus, the iron must be a good flux conductor

Torque

2...3

- *Torque = k * Flux density * Air gap radius^2 * Axial length*

4...10

- **When introducing a low permeability material in a conventional design, the Flux density drops a factor 4...10.**

- **This leads to low performance**
  - ***That's why no one has considered this before.***

- **But, if we can increase the air gap radius correspondingly, we can regain the torque**