Aalto University
School of Engineering

AC motors & modeling mechatronic systems

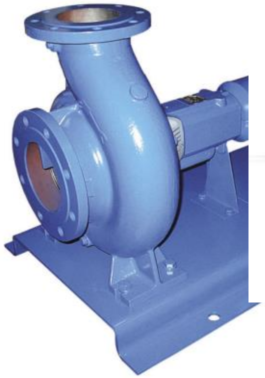
KON-C2004 Mechatronics Basics
Raine Viitala 30.10.2024

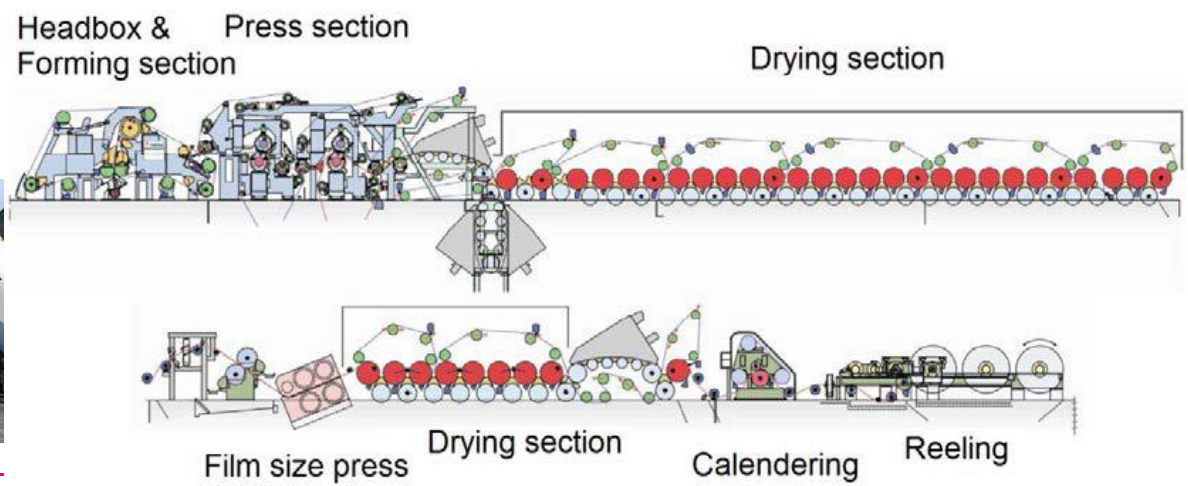
Feedback – Thank you!!

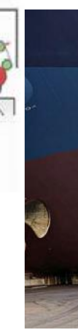
- First round: 7h (2018 8 h, 2019 9 h, 2020 10 h, 2021 8 h, 2022 7h, 2023 7h)

- The lectures are fun and you mange to explain the backgrounds quite well. The slides are well structured and it is easy to follow. Also the exercise was, contentwise, alright but it is too long! 8 hours for an assignemnt are fine for bi-weekly submissions but not for weekly ones. Compared to other courses, that give the same amount of credits and also only last half a semester, the workload definitely needs to be reduced! Also, if answers are requested in SI units, the constants given in the task should be SI units as well. Converting non-SI to SI units does not teach one anything and is a simple waste of time. Last but not least, giving parameters in the tasks, that are not necessary for solving it is an unneccessary confusion.
- Hyvä intro. Automaatio pääaineella kaikki tehtävät olivat tuttuja ja olivat hyvää kertausta. Sähkötehtävät vaativat enemmän muistelua, kun muut tehtävät. Tehtävien MyCo Quiz muoto oli mielestäni hyvä ja tehtävät sai tehtyä hyvissä ajoin muiden kurssien ohessa.
- relax with the amount of questions dawg
- I liked the diversity of the exercises because it challenged to do all be it writing report and calculating.
- looks good
- They were quite fun.
- Simulink warmup exercise instruction could be more clear. For example, it would be helpful to list all items to be submitted separately. Right now, the task description is a bit unclear.

Applications







Electric motors

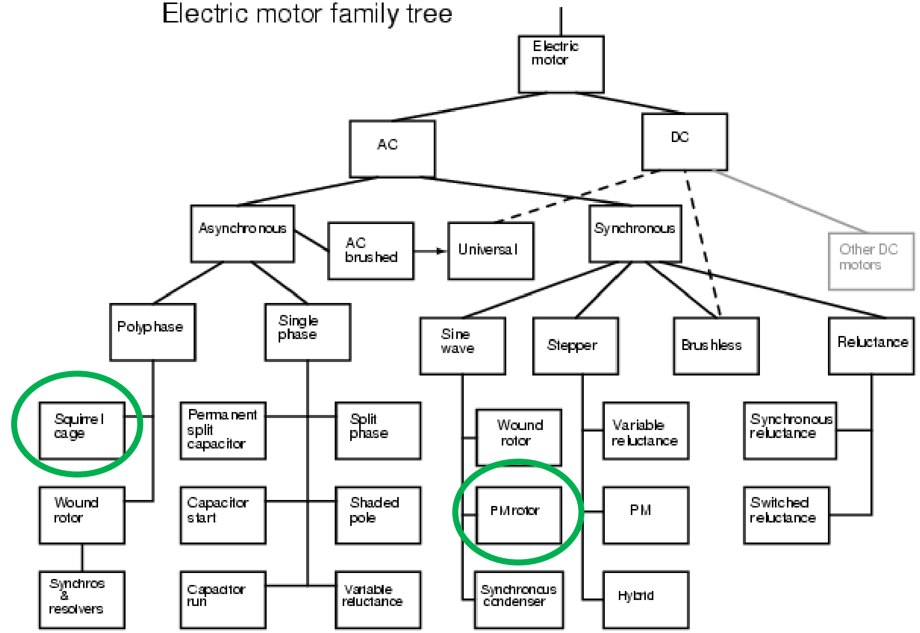
DC

- *Brushed*
- *Brushless*

AC

- *Synchronous*
  - Permanent magnet motor
  - Field excitation
  - Reluctance
- *Asynchronous (Induction)*
  - Squirrel cage
  - Wound rotor

Electric motor family tree



Speed range

http://www.celeroton.com/en/products/motors.html

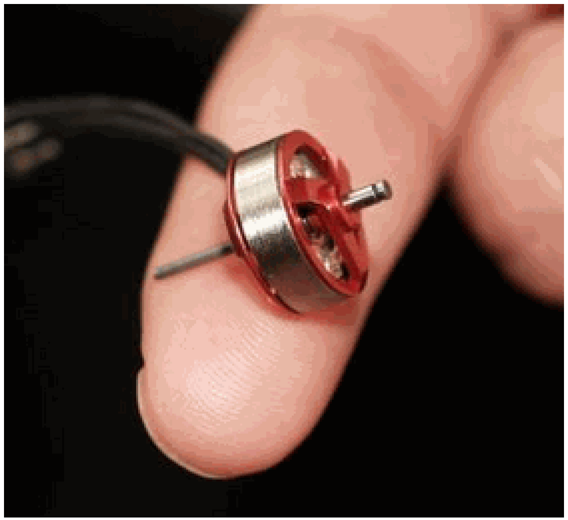
From a couple hundred rpm

http://www.ebikes.ca/learn/hub-motors.html

to hundreds of thousands of rpm

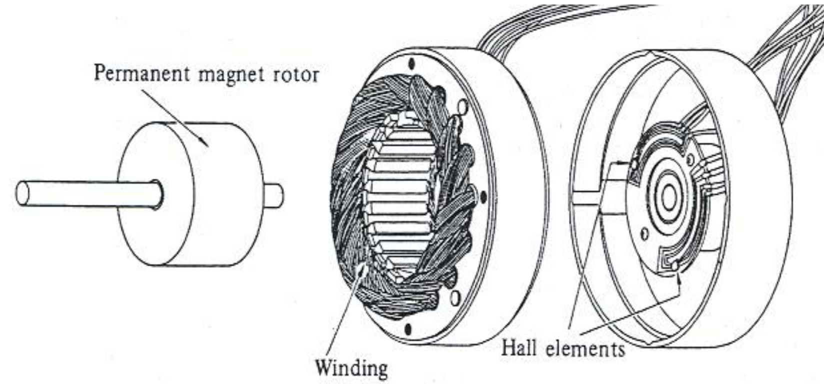
Power range

From some watts



to millions of watts

Brushless DC motor (BLDC)



Permanent magnet rotor

Stator with windings

External commutation

- *integrated position sensors, usually hall sensors*

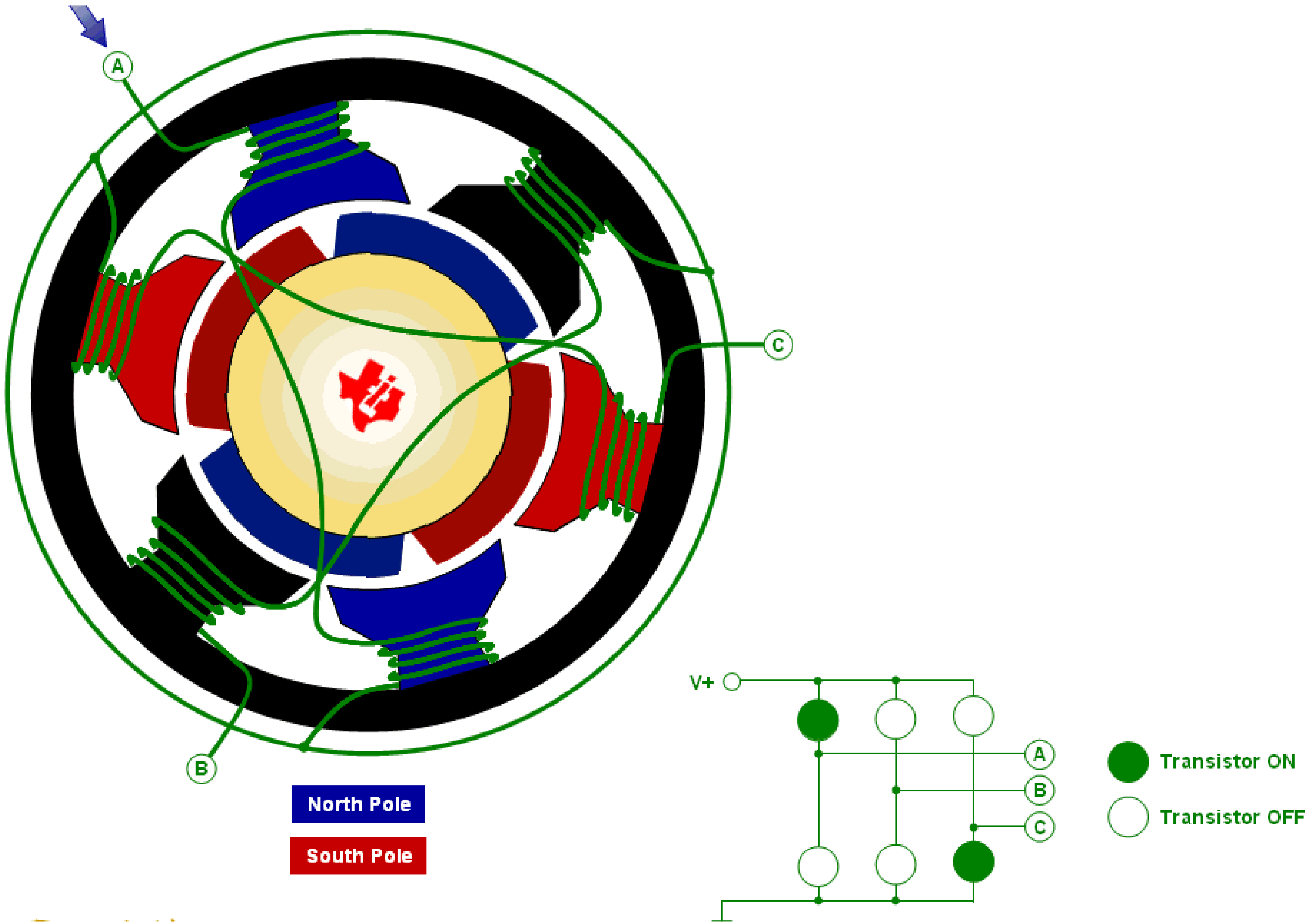
Almost service free

Withstands well short term overloading

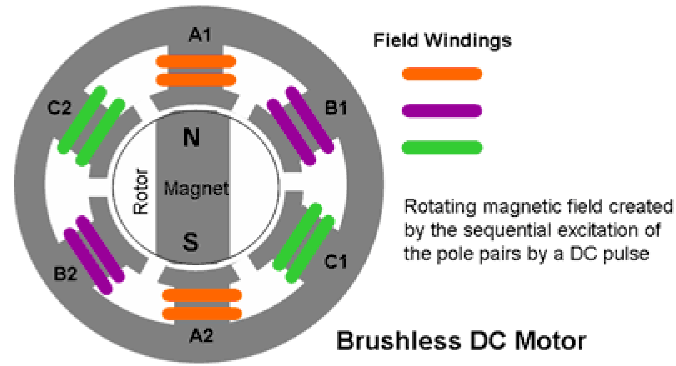
- *heat is transported effectively from the stator into the environment*

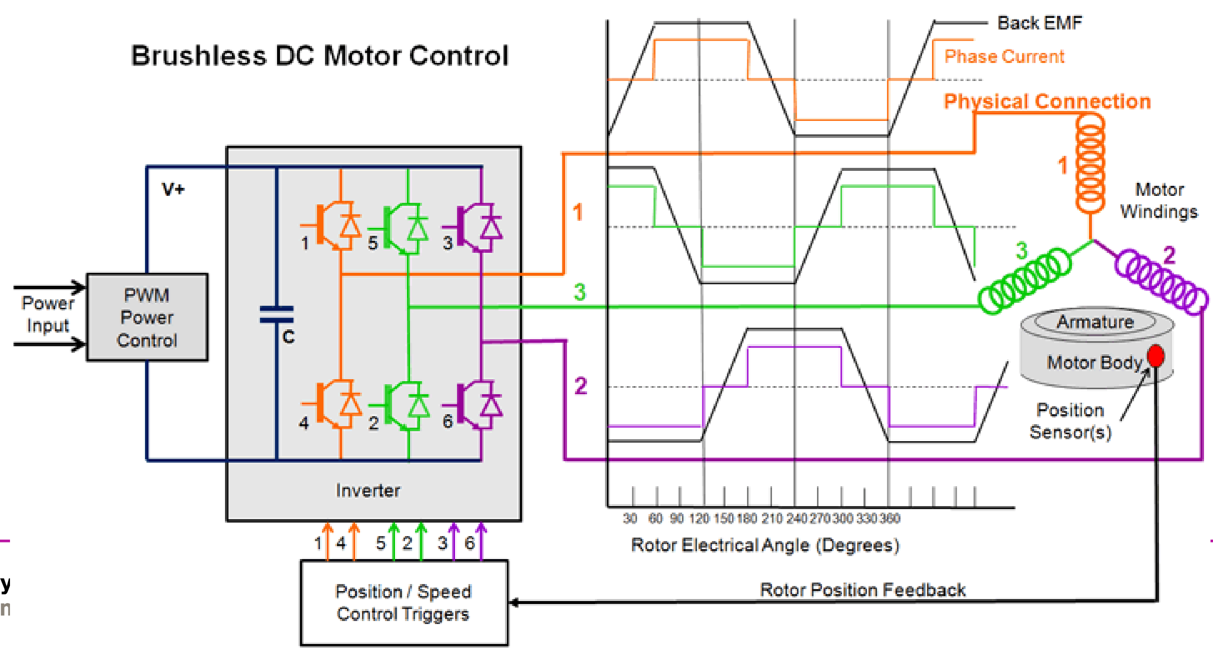
More complex control system

BLDC commutation



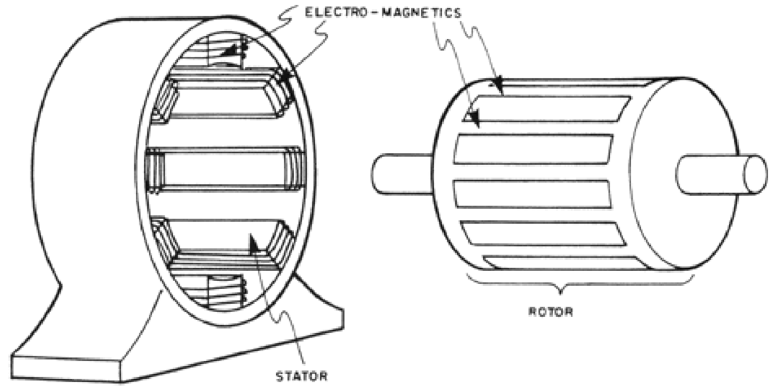
BLDC commutation





http://www.mpoweruk.com/motorsbrushless.htm

AC motor



Two categories

- *Asynchronous*
- *Synchronous*

Input usually three phase sinusoidal AC voltage

Only bearings need service

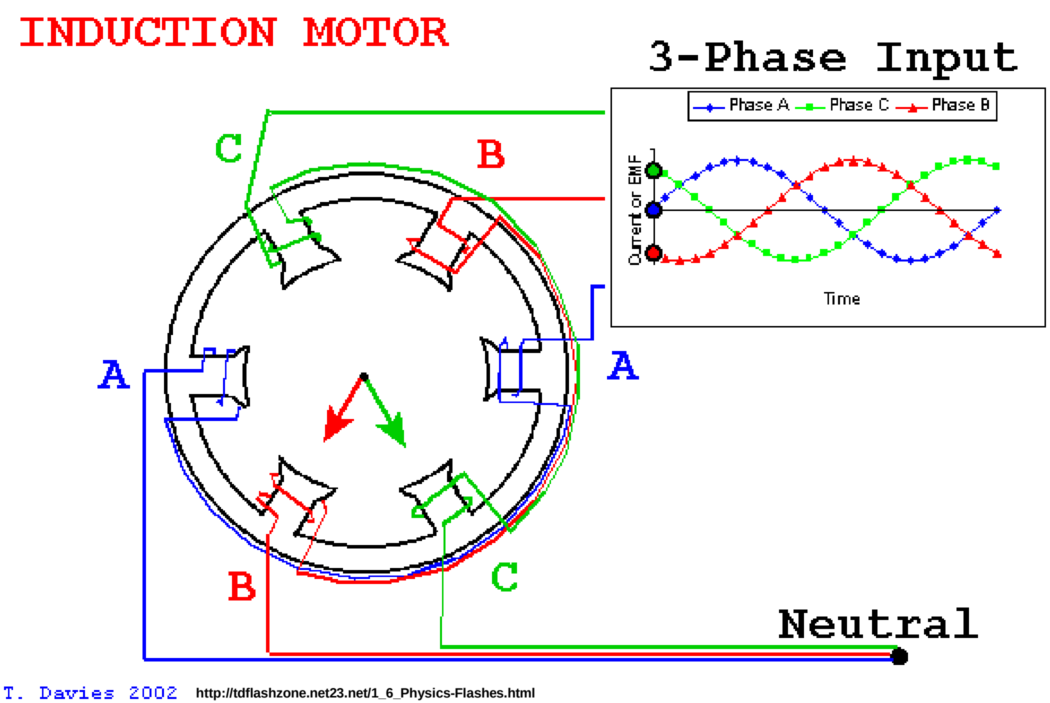
Control with variable frequency drive

http://www.pump-zone.com/topics/motors/ac-motors-part-two-three-phase-operation/page/0/1

AC field generation

Three field coils (per pole pair)

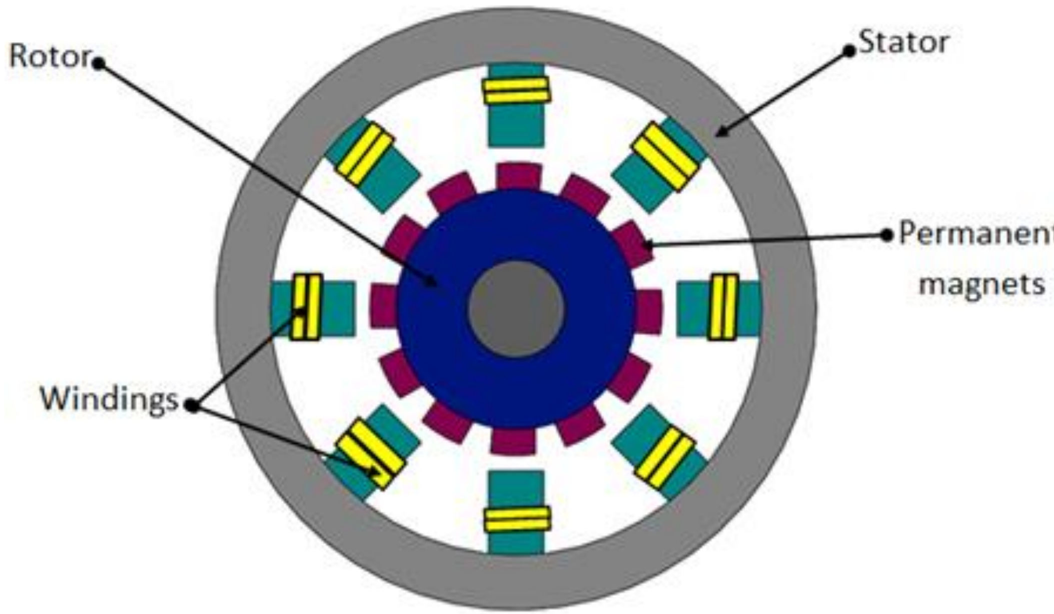
- *120 ° phase difference*



http://tdflashzone.net23.net/1_6_Physics-Flashes.html

Synchronous AC: Permanent magnet

Permanent magnet AC motor is almost the same as BLDC.



Synchronous AC: Permanent magnet

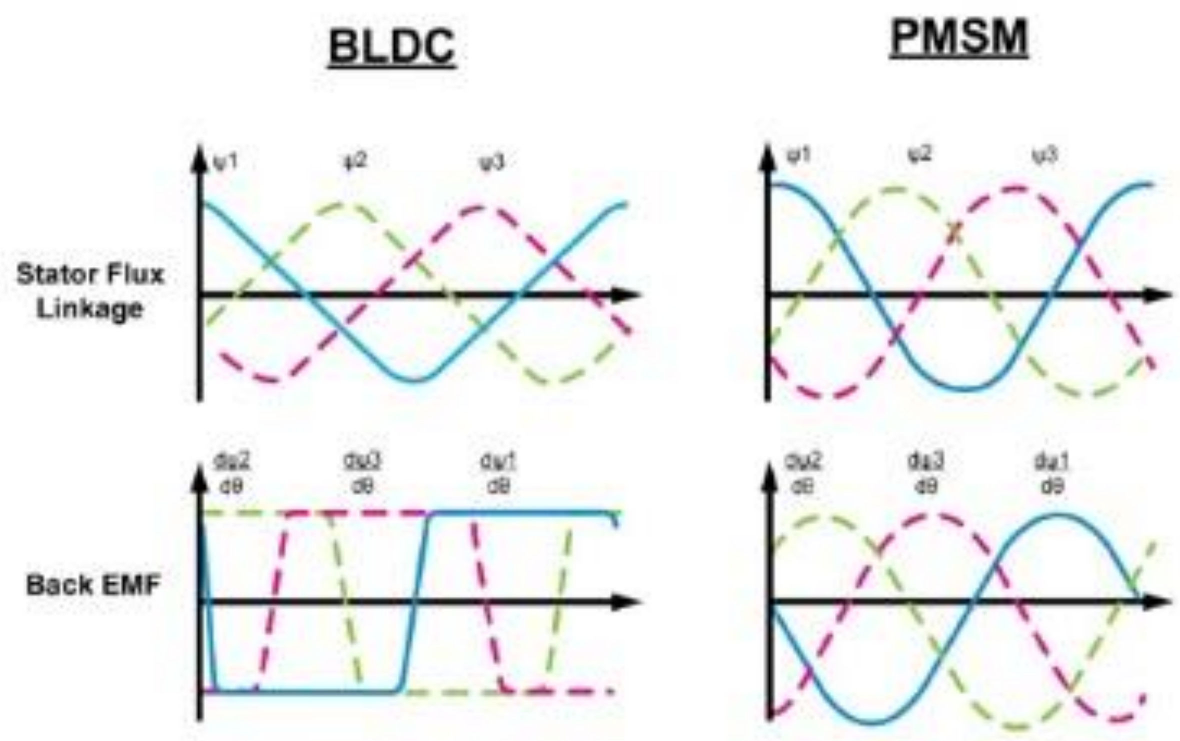


Figure 1. PMSM vs. BLDC BEMF Waveforms

https://www.ecnmag.com/article/2009/10/comparing-motor-control-techniques

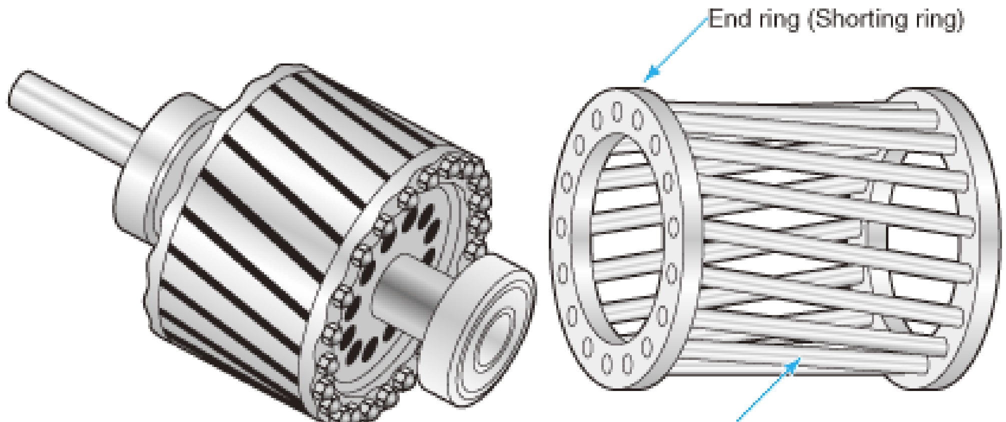
Asynchronous AC: Induction

Stator field induces current in the bars which causes torque

- *Requires slip to create induced currents*

Types

- *Squirrel cage*
  - Rotor made of conducting short circuited bars in steel frame
- *Wound rotor*



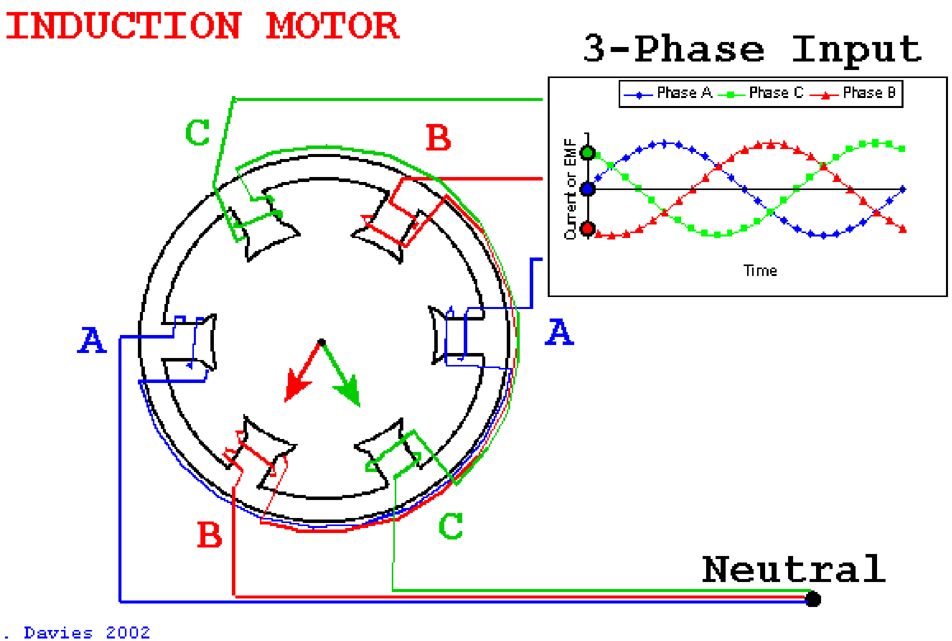
(a) Rotor (b) Squirrel-cage conductor

http://www.nidec.com/en-IN/technology/motor/basic/00026/?prt=1

AC field generation

Three field coils (per pole)

- *120 ° phase difference*



Speed
For a 50 Hz three phase supply:
2 poles or 1 pair of poles = 3,000 RPM (minus the slip speed = about 2,750 RPM or 6 -7% *n*)

$$n = 60 * 0.93 * \frac{f}{p}$$

http://tdflashzone.net23.net/1_6_Physics-Flashes.html

Lecture task

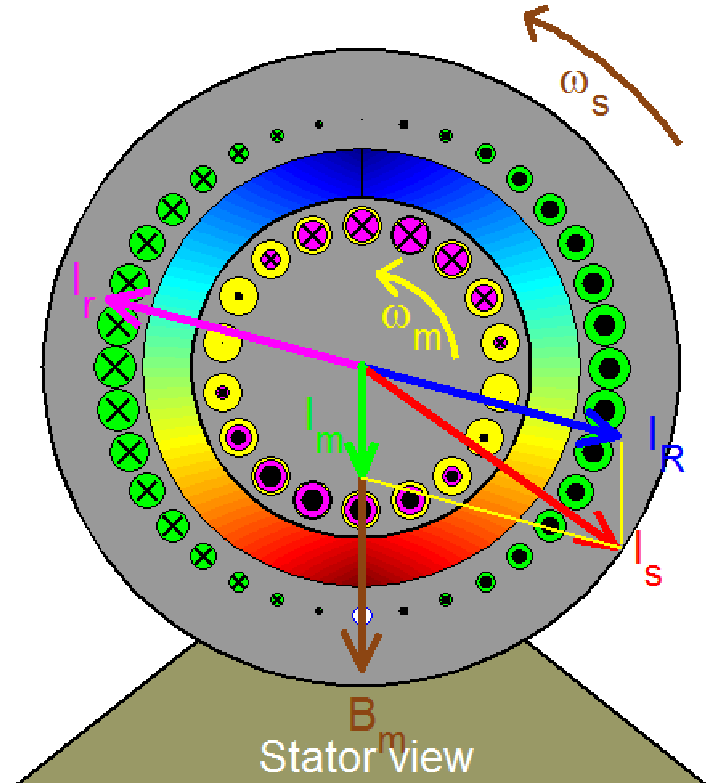
Ensure that your pair or group (2-3-4) understands the induction motor operating principles

- **How the voltage is induced into the rotor?**
- **Torque generation**
- **Slip**

If not, teach!

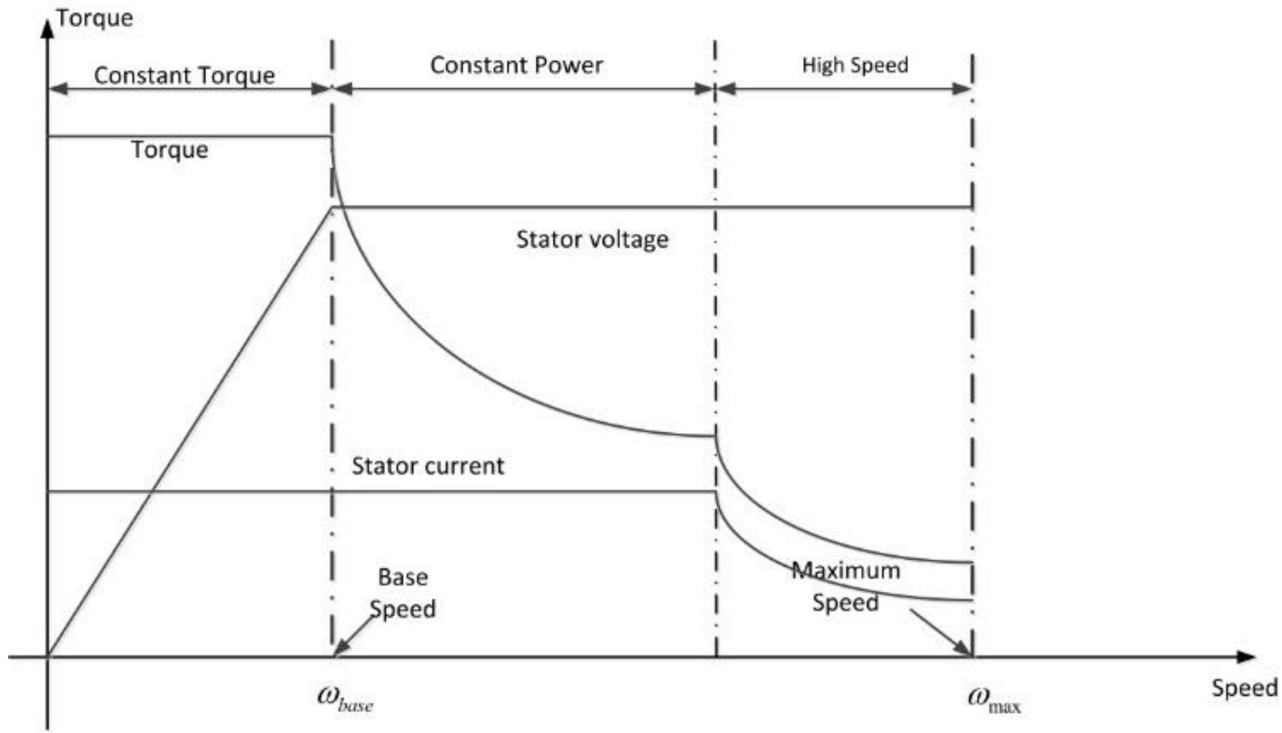
If something remains unclear, write it down and I'll <u>try</u> to answer ☺

Asynchronous AC: Induction

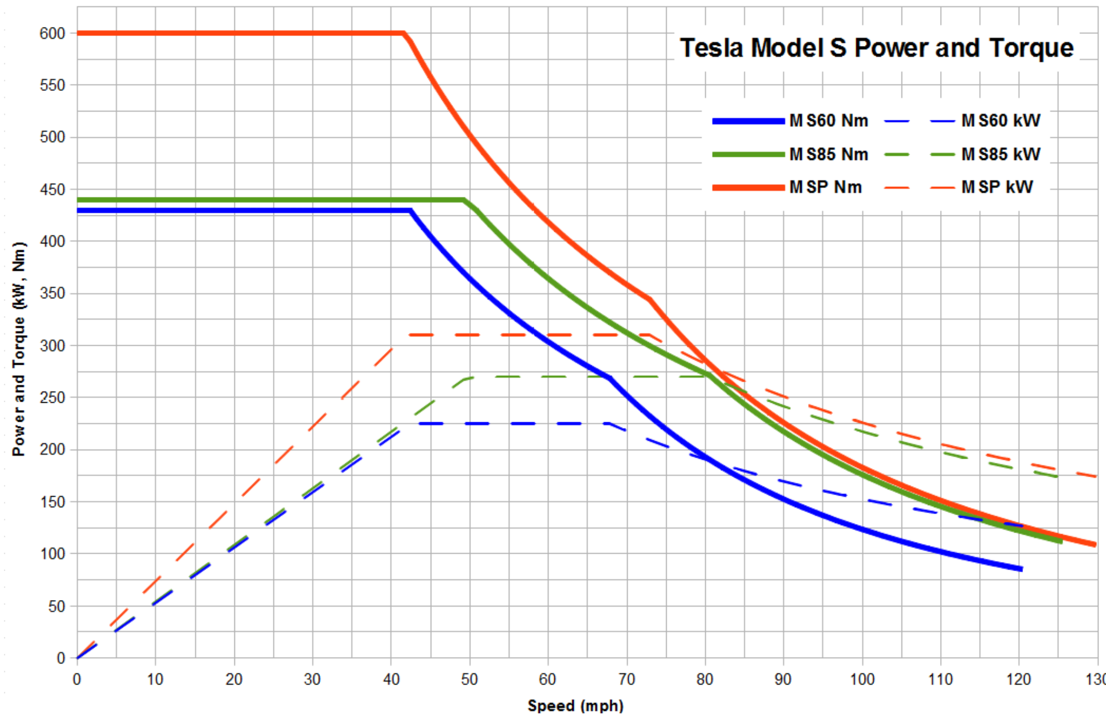


http://people.ece.umn.edu/users/riaz/animations/sqmovies.html

Field weakening

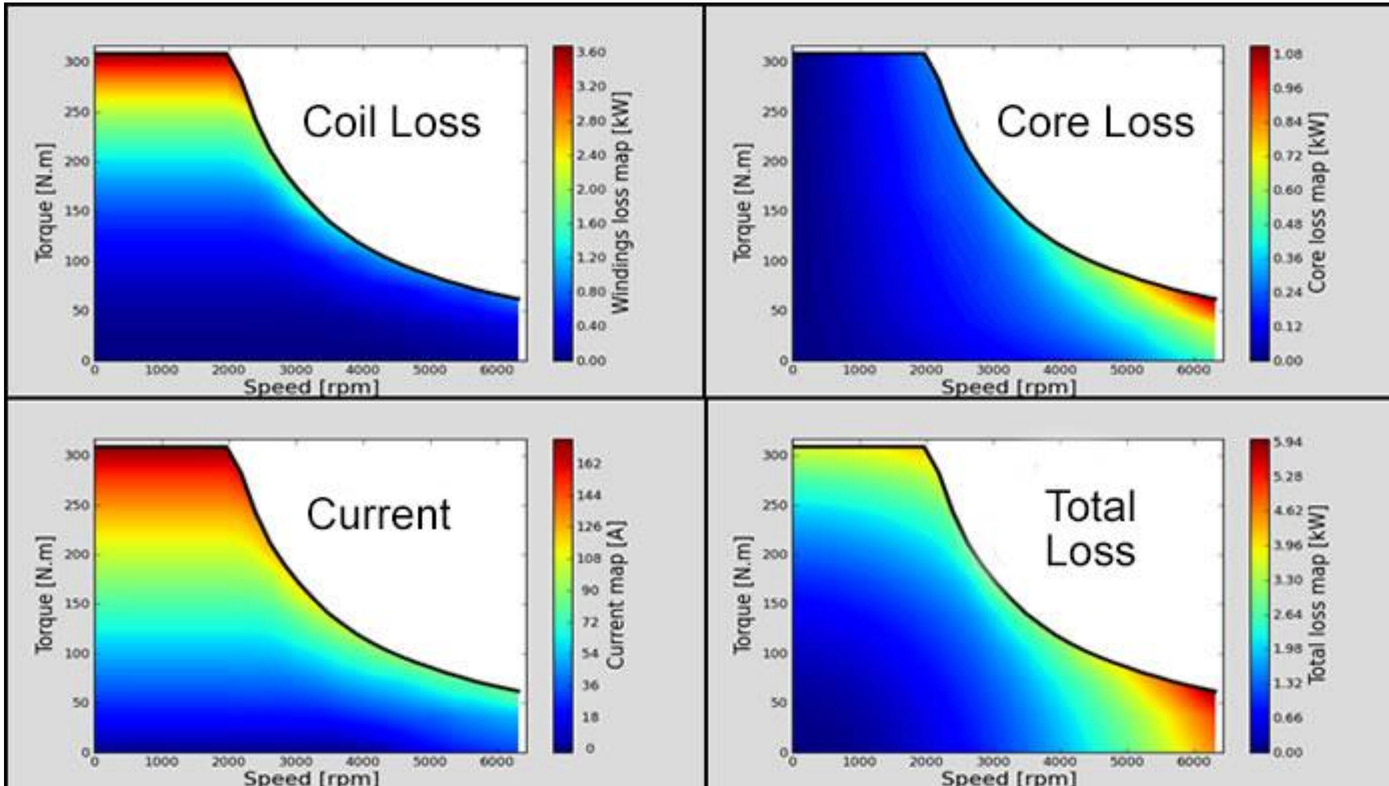


Field weakening



http://ecomodder.com/forum/showthread.php/bsfc-chart-thread-post-em-if-you-got-1466-26.html

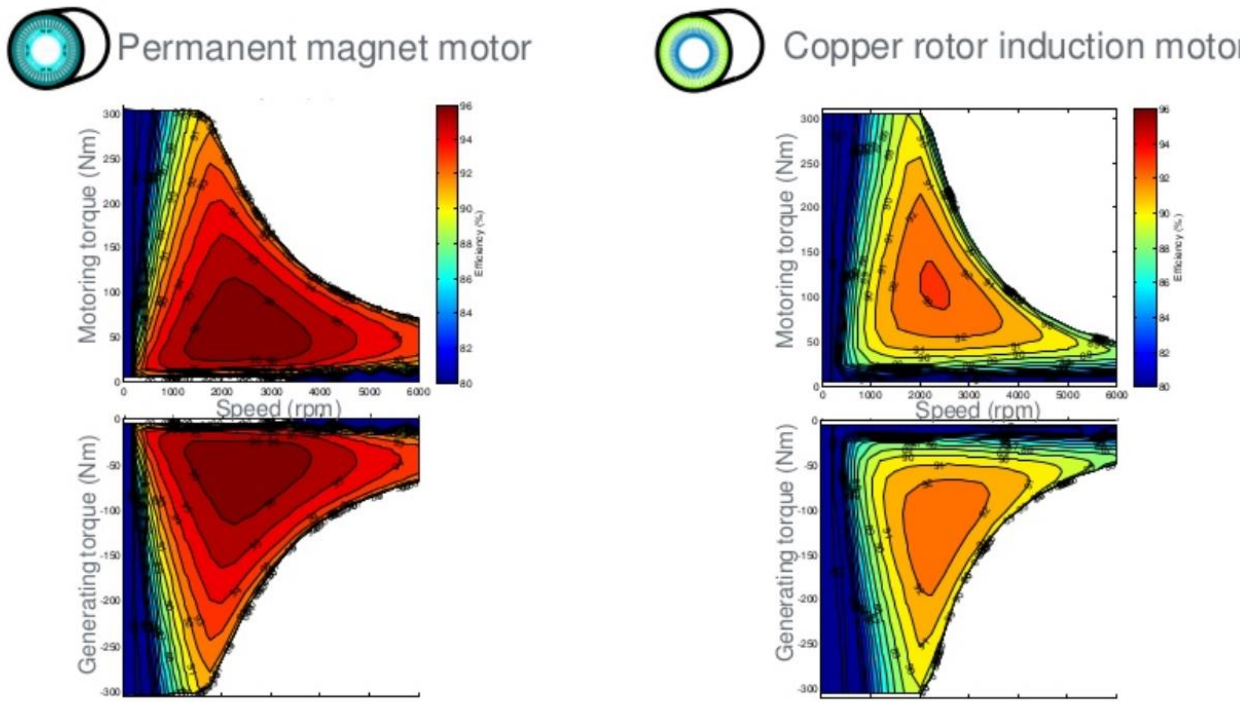
Losses for some PM motor



http://www.ansys.com/de-de/products/electronics/electric-motors

Efficiency

The two motors have similar torque/speed performance, with the induction motor having ~5% lower efficiencies



AC motor control

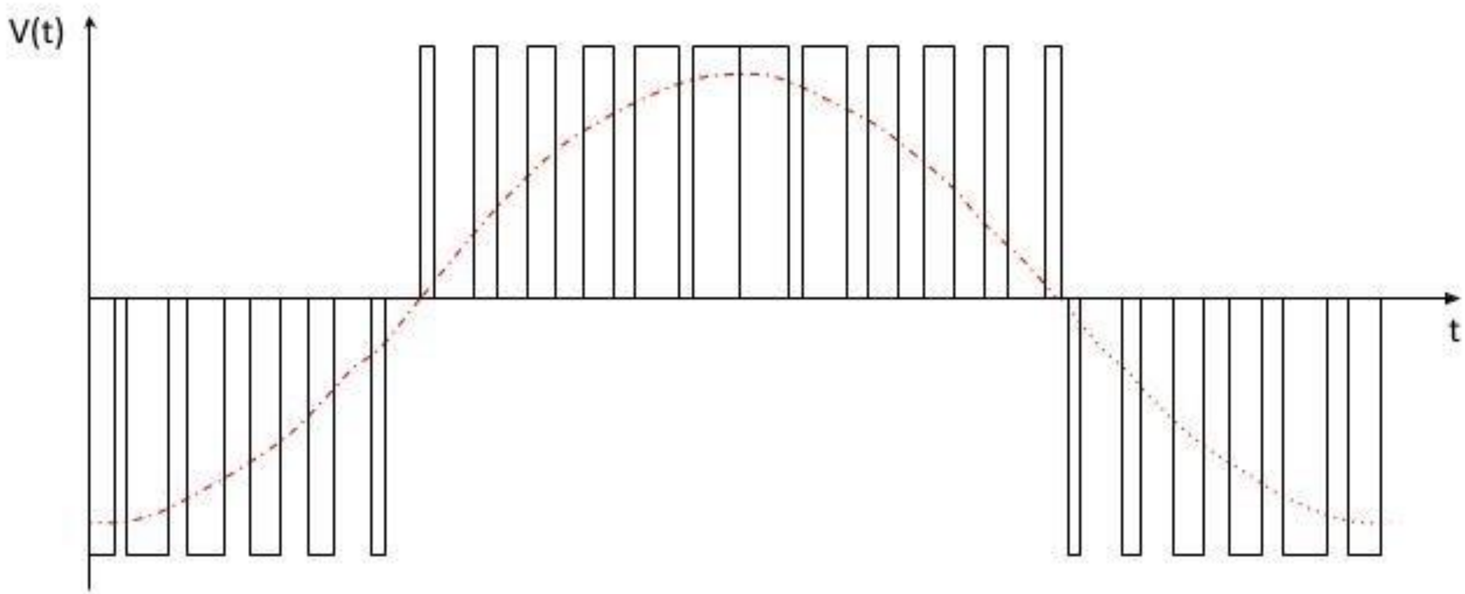
Rotational speed is determined by the frequency of the input voltage

Frequency is controlled with variable frequency drive/inverter (taajuusmuuttaja in Finnish)

- Rectification of the three phase voltage to DC voltage
- The rectified DC voltage is converted e.g. with pulse width modulation (PWM) to AC voltage with the needed frequency
- The AC voltage is fed to one of the three coils of the stator according to the sensors of the control system.

Variable frequency drive DC back to AC

Output AC is the average of pulse width modulated DC voltage



Rated values of an induction motor

Rated values are for continuous duty

- *Rated voltage – winding insulation*
- *Rated current – ohmic resistive losses*
- *Rated field – magnetic saturation of the material*
- *Rated power = T*omega*

For dimensioning a motor for a variable load, it is possible to calculate an equivalent constant load or simulate the system

Summary

Electric motors can be found anywhere and for any power rating

They have excellent efficiency at proper loading conditions

- *Usually this means a large enough rpm*

Output power usually limited by temperature

- *Can be overloaded for a short while*

Maximum rotating speed limited by back emf / supply voltage

Modeling

Model

A simplified representation of a

- *System*
- *Physical object*
- *Process*
- *Thing*

Theories are models of reality

Is used to

- *Estimate*
- *Predict*
- *Explain*
- *Describe*
- *Design*

Better understanding leads to better results

Several areas to be modeled

Control code

- *Logic*
- *Control algorithms*

Electronics

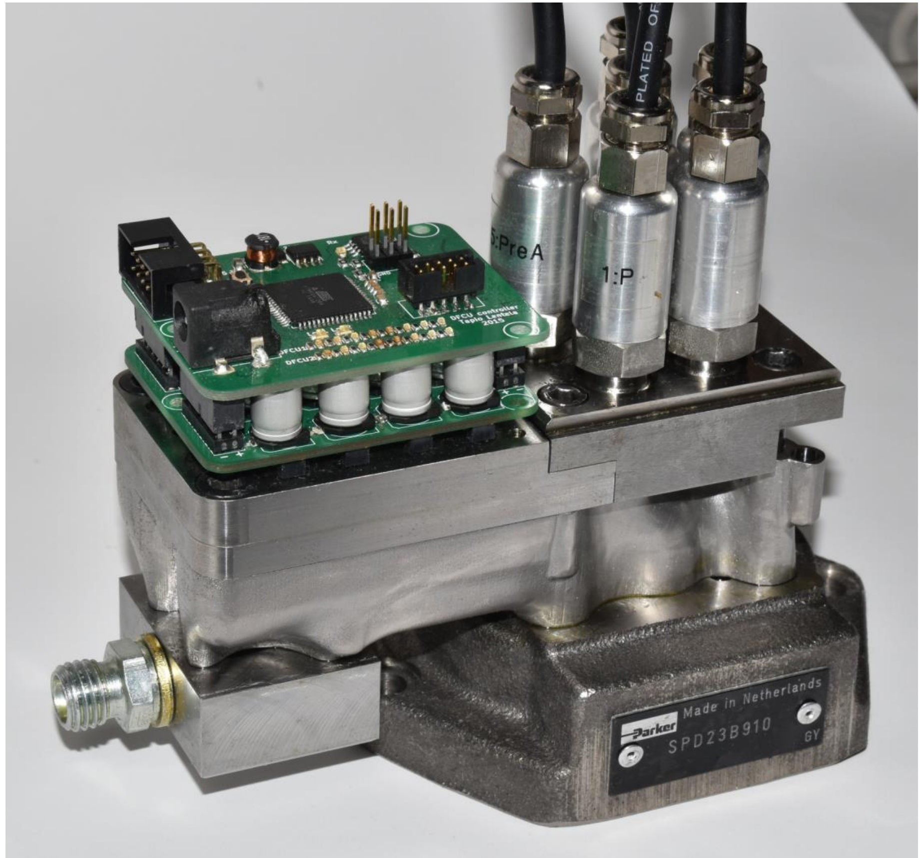
- *Input circuits – amplifiers, filters*
- *Output circuits – power electronics*

Mechanics

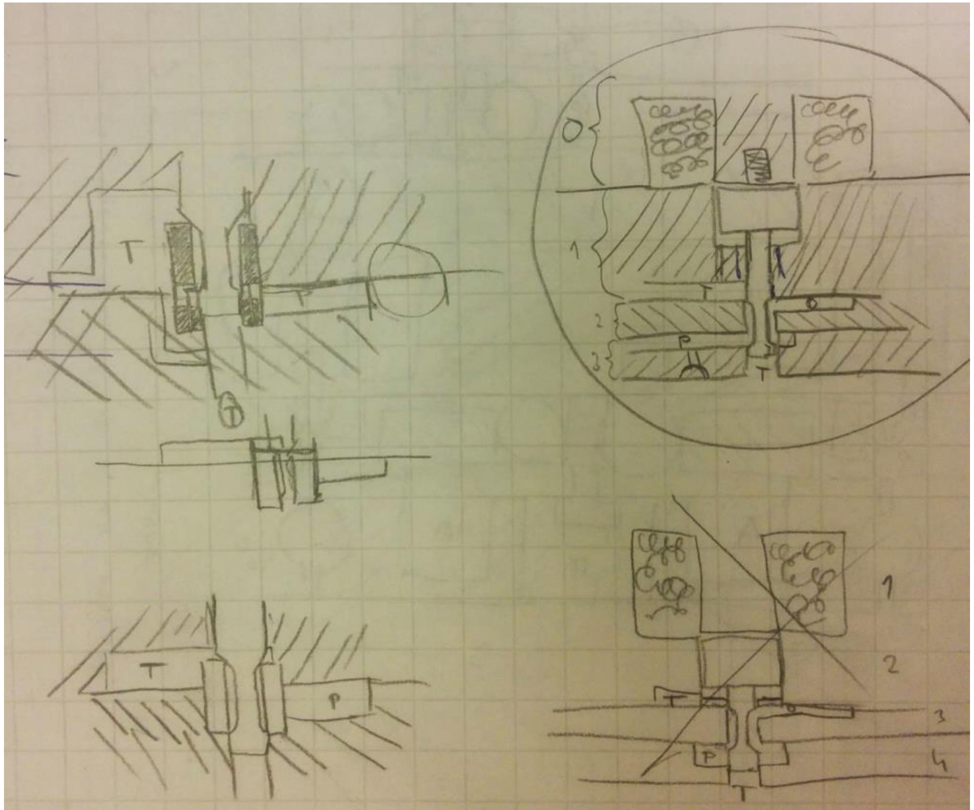
- *Multi-body systems, kinematics, stresses, loads*
- *Rigid body, flexible body, fluid dynamics*

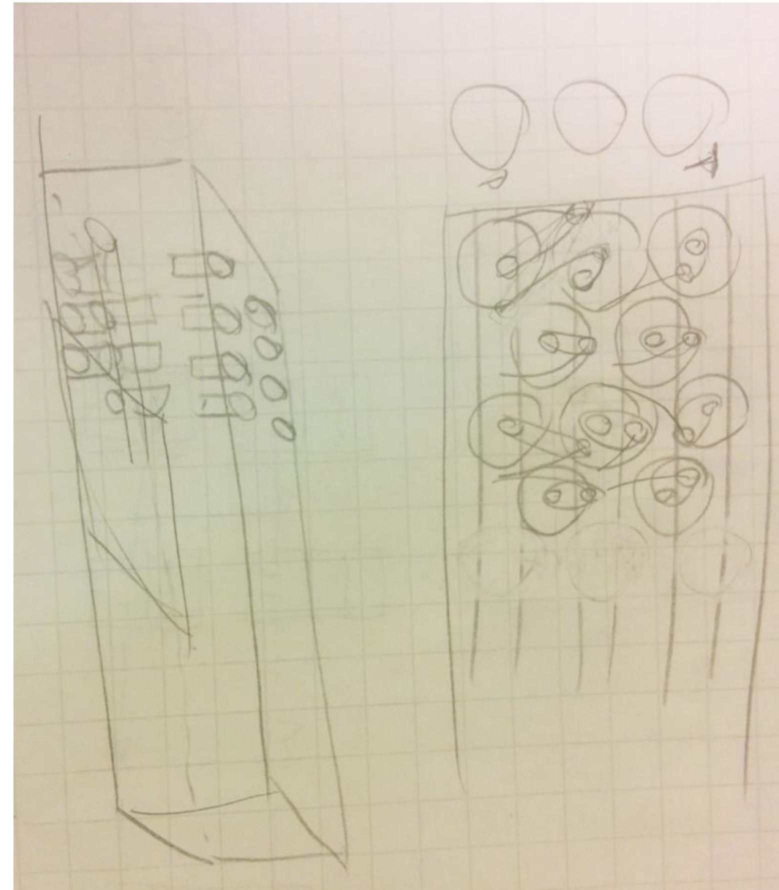
Mechatronic system

- *Interaction between each area and their combined behaviour*


5:PreA
1:P
Made in Netherlands
Parker
SPD23B910

Concept sketching

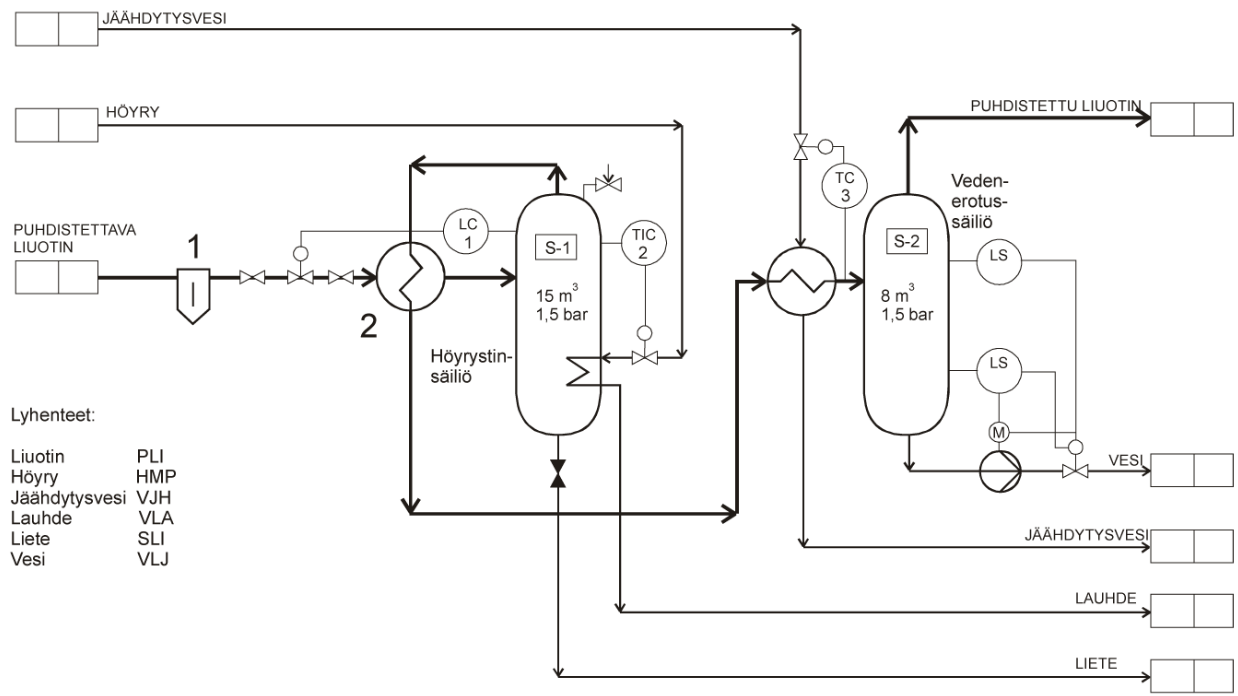




Topology models

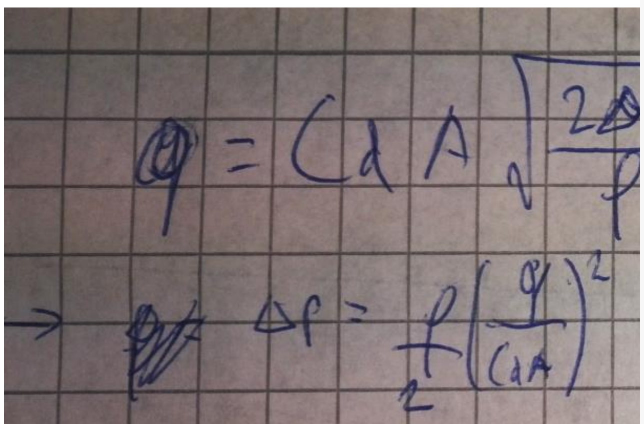
Functional structure

- *Abstract*
- *Describes process*
    - No concrete implementation
- *Helps in thinking different ways of doing the same*



Analytical equations

Easy for static analysis




```
syms A_a A_coil A_out V_valve
areas = [A_a A_coil A_out V_valve];
assume(areas, 'positive')

K_s = 0.4

F_p = pi*D_o^2/4*dp                        %Eq2

F_mag1 = K_F*F_p                           %Eq3

A_a = pi*(D_a/2)^2-pi*(K_s*D_a/2)^2        %Eq4

p_mag = B^2/(2*mu0)                        %Eq5

%F_mag2 = simplify(A_a*p_mag)               %Eq6
F_mag2 = A_a*p_mag                %Eq6

D_a = solve(F_mag1==F_mag2, D_a)           %Eq 7
%D_a = D_a(1)
  pretty(simplify(D_a))
  D_a = D_o/B*sqrt(K_F*2*mu0*dp/(1-K_s^2))
%pretty(simplify(D_a))

l = K_g*D_o                                %Eq 9
```

K_s =

F_p =

$$\frac{\pi D_o^2\, dp}{4}$$

F_mag1 =

$$\frac{\pi D_o^2 K_F\, dp}{4}$$

A_a =

$$\frac{21\,\pi D_a^2}{100}$$

p_mag =

$$\frac{B^2}{2\,\mu_0}$$

F_mag2 =

$$\frac{21\,\pi B^2 D_a^2}{200\,\mu_0}$$

Solve this by hand? ☺

Ix:

restart:

Huom! R=0 niin jäyhyysmomentti on aina nolla.

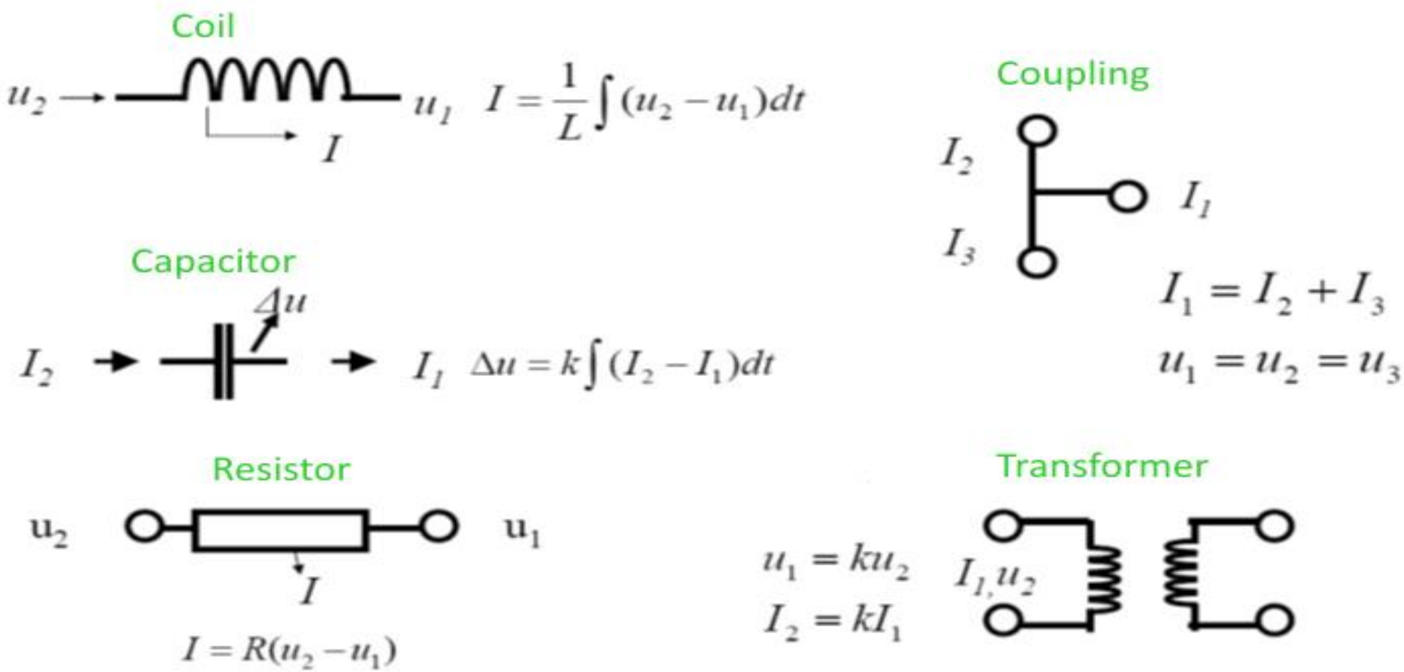
$a := R + A \cdot \sin(k \cdot (\theta + \phi))$

$$a := R + A \sin(k(\theta + \phi)) \tag{1}$$

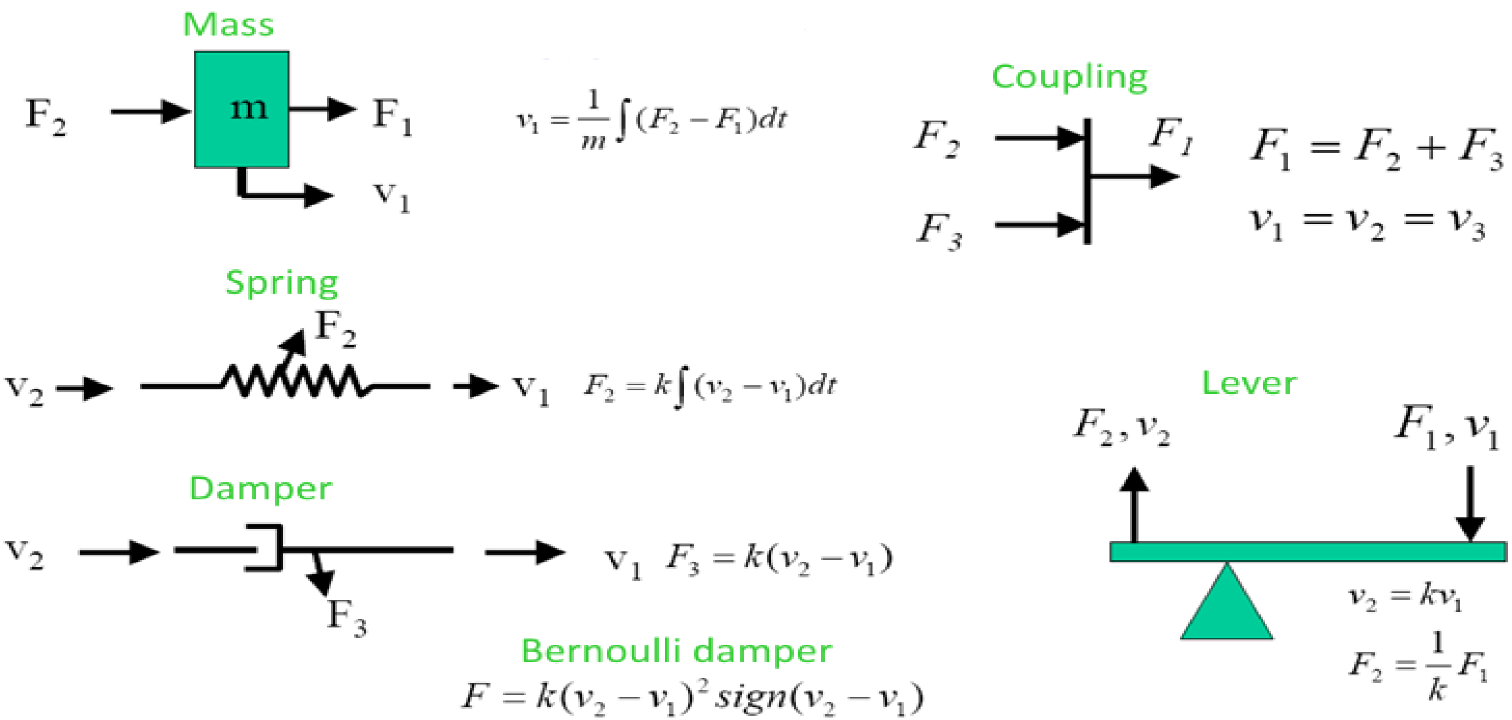
$$\int_0^{2\pi} \int_0^{a} (r \cdot \sin(\theta))^2 \cdot r \, \mathrm{d}r \, \mathrm{d}\theta \overset{\text{combine}}{=}$$

$$\begin{aligned}
&\frac{1}{27648 k^9 - 157440 k^7 + 209664 k^5 - 92160 k^3 + 12288 k} \big(384 A^4 \sin(2 k\phi) - 48 A^4 \sin(4 k\phi) - 864 A^4 \sin(2 k\phi) k^6 + 4056 A^4 \sin(2 k\phi) k^4 - 2496 A^4 \sin(2 k\phi) k^2 \\
&+ 4608 A^3 \cos(k\phi) R + 6144 A \cos(k\phi) R^3 + 27 A^4 \sin(4 k\phi) k^6 - 147 A^4 \sin(4 k\phi) k^4 + 168 A^4 \sin(4 k\phi) k^2 - 512 R A^3 \cos(3 k\phi) + 2304 A^2 \sin(2 k\phi) R^2 + 512 A^3 \cos(3 k\phi) R k^6 \\
&+ 24336 A^2 \sin(2 k\phi) R^2 k^4 - 14976 A^2 \sin(2 k\phi) R^2 k^2 - 2688 A^3 \cos(3 k\phi) R k^4 + 2688 A^3 \cos(3 k\phi) R k^2 - 5184 A^2 \sin(2 k\phi) R^2 k^6 - 41472 A^3 \cos(k\phi) R k^6 \\
&- 55296 A \cos(k\phi) R^3 k^6 + 70272 A^3 \cos(k\phi) R k^4 + 93696 A \cos(k\phi) R^3 k^4 - 33408 A^3 \cos(k\phi) R k^2 - 44544 A \cos(k\phi) R^3 k^2 + 2592 A^4 \pi k^9 - 14760 A^4 \pi k^7 + 19656 A^4 \pi k^5 \\
&- 8640 A^4 \pi k^3 + 1152 A^4 \pi k + 6912 \pi R^4 k^9 - 39360 \pi R^4 k^7 + 52416 \pi R^4 k^5 - 23040 \pi R^4 k^3 + 3072 \pi R^4 k + 20736 A^2 \pi R^2 k^9 - 118080 A^2 \pi R^2 k^7 + 157248 A^2 \pi R^2 k^5 \\
&- 69120 A^2 \pi R^2 k^3 + 9216 A^2 \pi R^2 k + 48 A^4 \sin(8 \pi k + 4 k\phi) - 384 A^4 \sin(4 \pi k + 2 k\phi) + 864 A^4 \sin(4 \pi k + 2 k\phi) k^6 - 4056 A^4 \sin(4 \pi k + 2 k\phi) k^4 + 2496 A^4 \sin(4 \pi k \\
&+ 2 k\phi) k^2 + 147 A^4 \sin(8 \pi k + 4 k\phi) k^4 - 168 A^4 \sin(8 \pi k + 4 k\phi) k^2 - 27 A^4 \sin(8 \pi k + 4 k\phi) k^6 - 2304 A^2 \sin(4 \pi k + 2 k\phi) R^2 + 512 A^3 \cos(6 \pi k + 3 k\phi) R \\
&- 4608 A^3 \cos(2 \pi k + k\phi) R - 6144 A \cos(2 \pi k + k\phi) R^3 - 512 A^3 \cos(6 \pi k + 3 k\phi) R k^6 + 2688 A^3 \cos(6 \pi k + 3 k\phi) R k^4 - 2688 A^3 \cos(6 \pi k + 3 k\phi) R k^2 + 41472 A^3 \cos(2 \pi k \\
&+ k\phi) R k^6 + 55296 A \cos(2 \pi k + k\phi) R^3 k^6 - 70272 A^3 \cos(2 \pi k + k\phi) R k^4 - 93696 A \cos(2 \pi k + k\phi) R^3 k^4 + 5184 A^2 \sin(4 \pi k + 2 k\phi) R^2 k^6 - 24336 A^2 \sin(4 \pi k + 2 k\phi) R^2 k^4 \\
&+ 14976 A^2 \sin(4 \pi k + 2 k\phi) R^2 k^2 + 33408 A^3 \cos(2 \pi k + k\phi) R k^2 + 44544 A \cos(2 \pi k + k\phi) R^3 k^2\big)
\end{aligned}$$

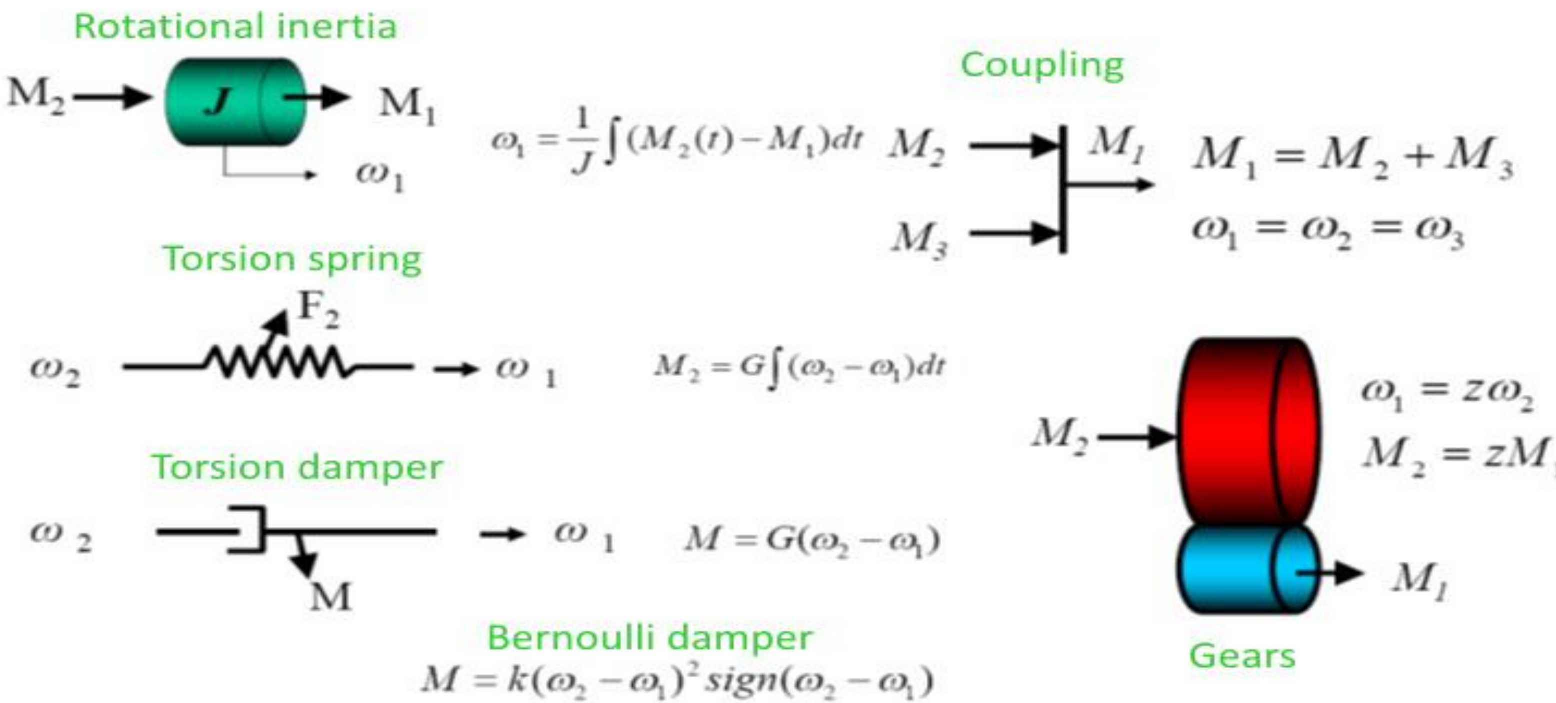
Electrical design elements



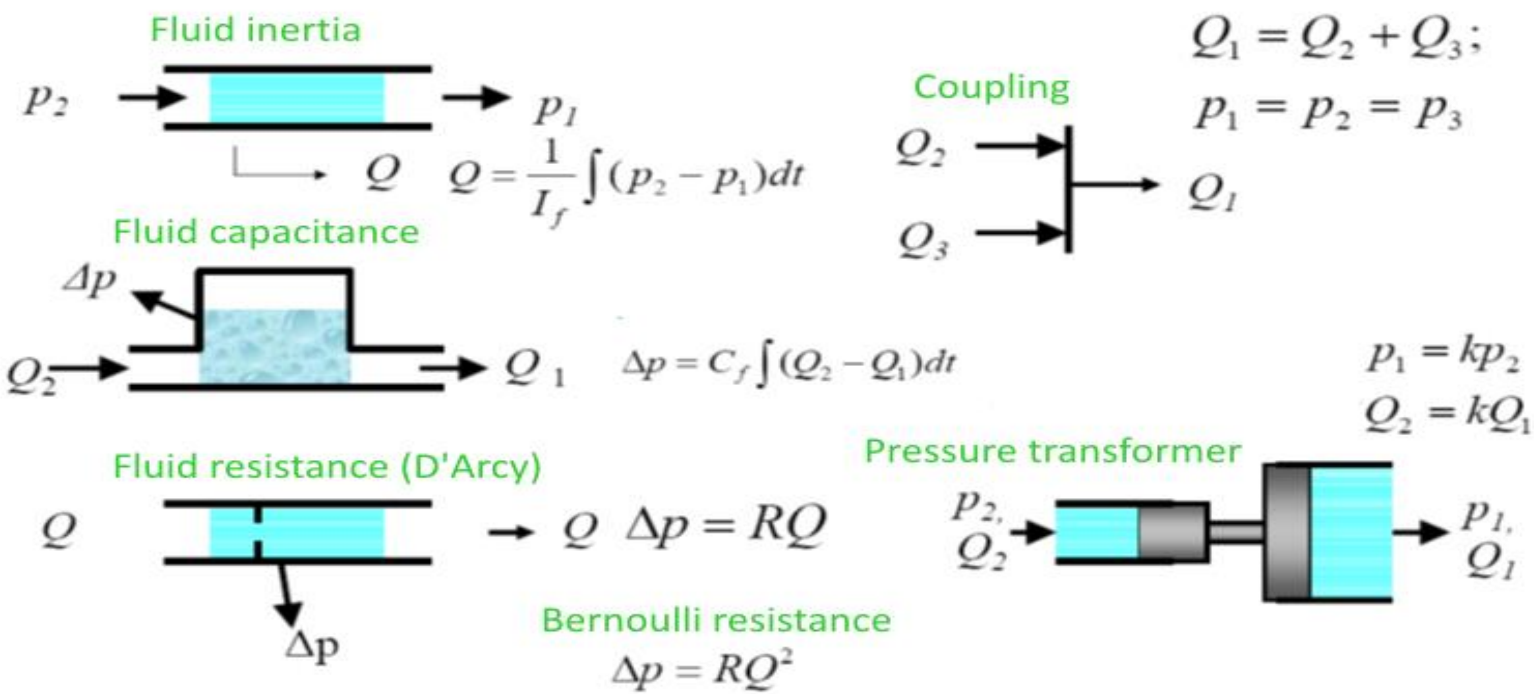
Mechanical design elements 1



Mechanical design elements 2



Hydraulical design elements



Physical analogies

	Intensity	Flow	Inertor	Capacitor	Resistor	Transformer	Gyrator
Electricity	Voltage	Current	Coil	Capacitor	Resistor	Transformer	Electrical motor
Mechanics – translation	Force	Speed	Mass	Spring	Friction	Lever arm	-
Mechanics – rotation	Torque	Angular speed	Moment of inertia	Torsional bar	Friction	Gears	-
Fluid power	Pressure	Flow	Tube	Pressure accumulator	Flow restriction	Pressure transformer	Hydrodynamics

Numerical Models - Simulations

Usually differential equations

- *Not all formulas can be analytically solved!*

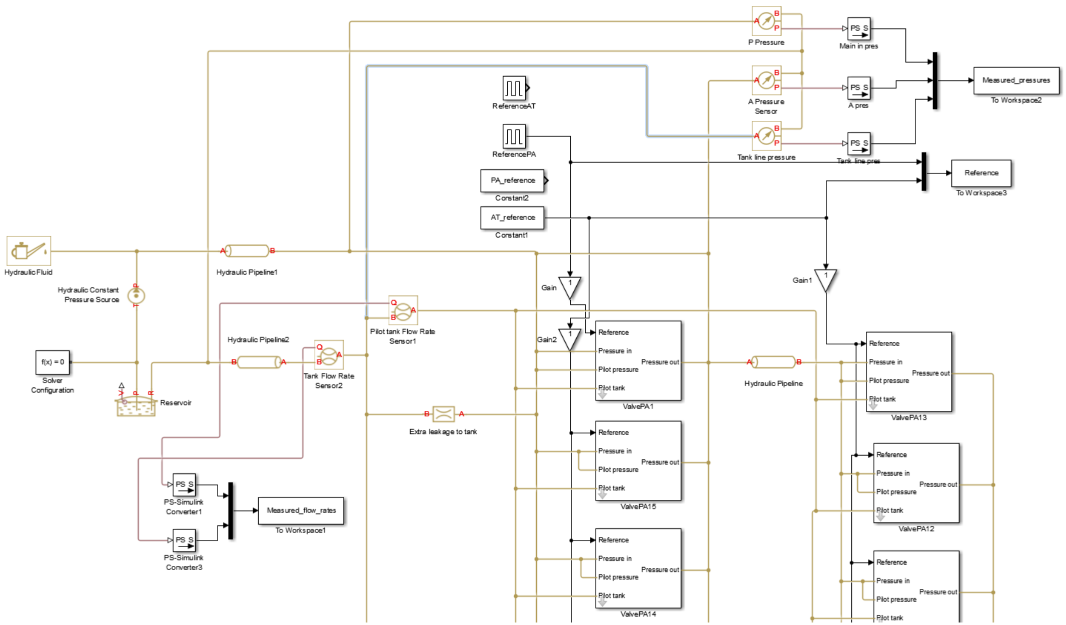
Adding more complexity makes it nearly impossible to solve analytically -> use numerical methods to approximate

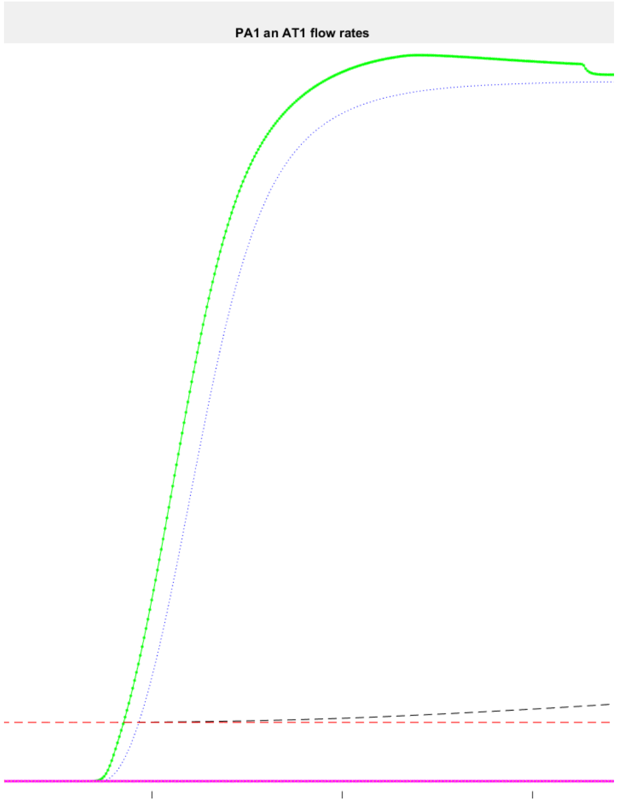
Numerical solvers have their own difficulties

- *Convergence*
- *Time stepping*
- *Numerical errors*

Dynamic model of the system

Simulink





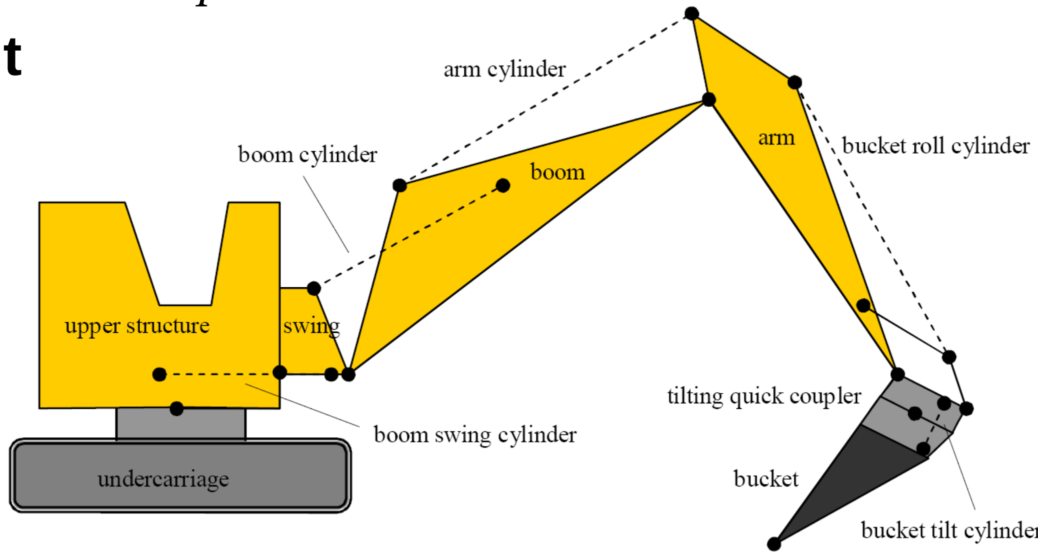
Multibody simulation

Interaction of rigid or elastic bodies

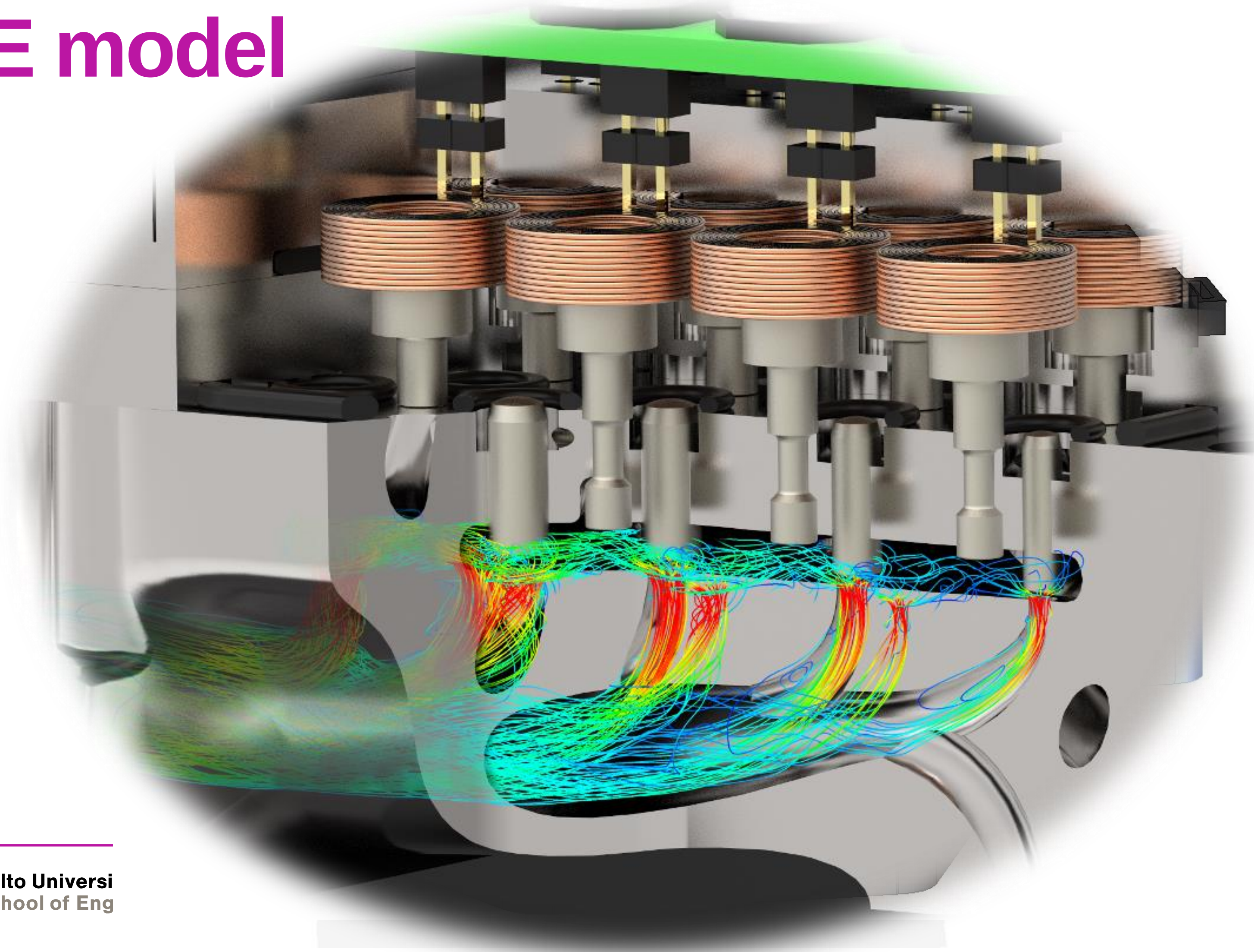
- *Kinematic coinstraints such as joints*
- *Force elements such as springs and dampers*

Shape of part not relevant

- *Only with collision detection*



CAE model



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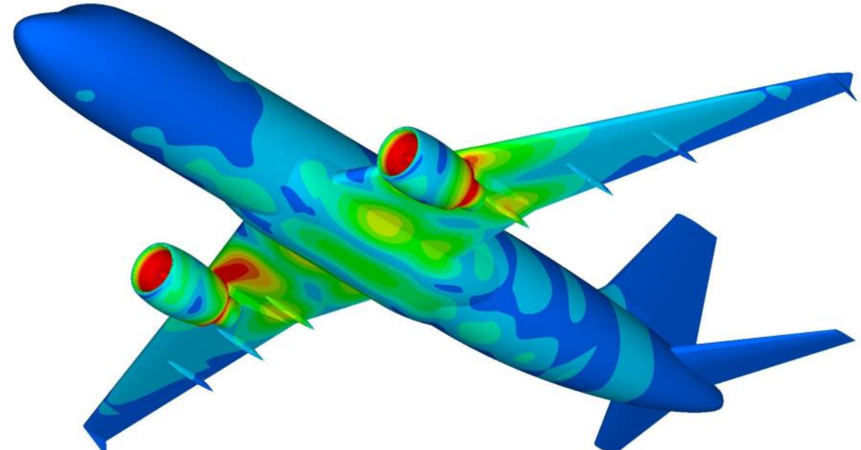
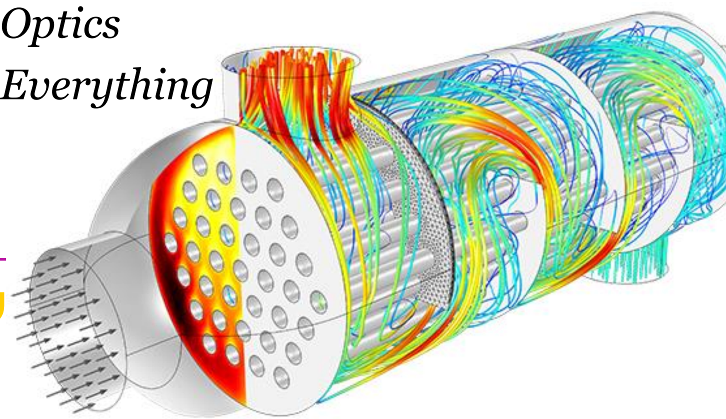
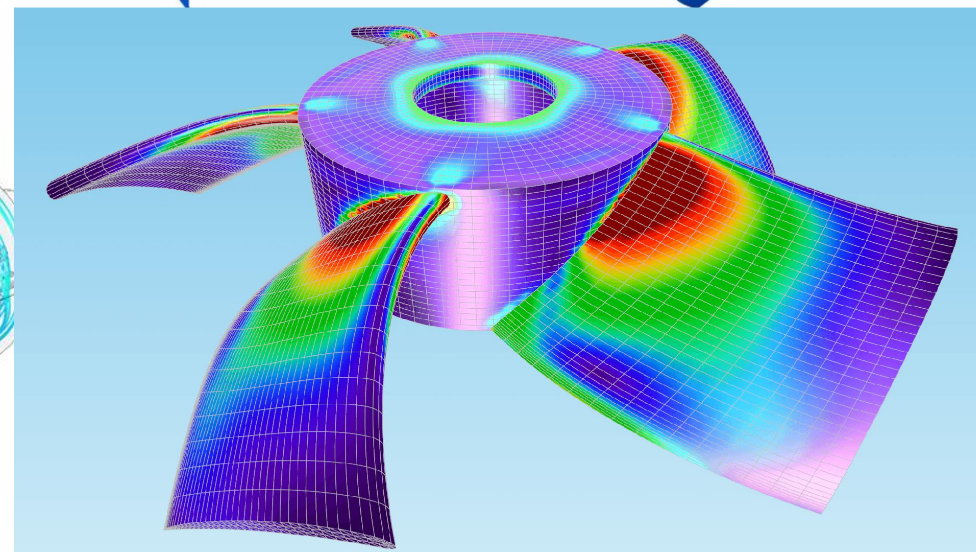
Finite element method

1. **Discretize the volume to tiny cells**
2. **Solve basic equations for each small cell**
    - *Fluid flow*
    - *Electric and magnetic fields*
    - *Mechanical stresses*
    - *Heat flow*
    - *Optics*
    - *Everything*

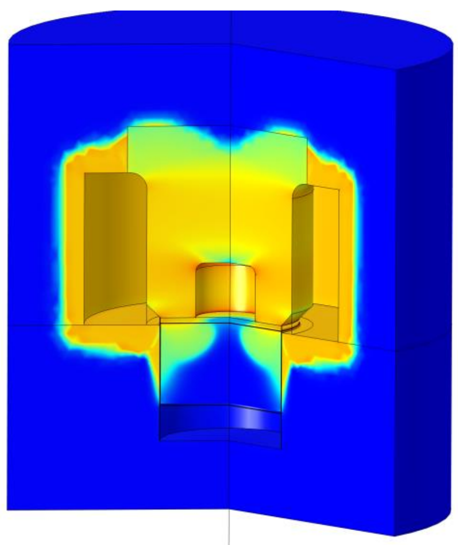


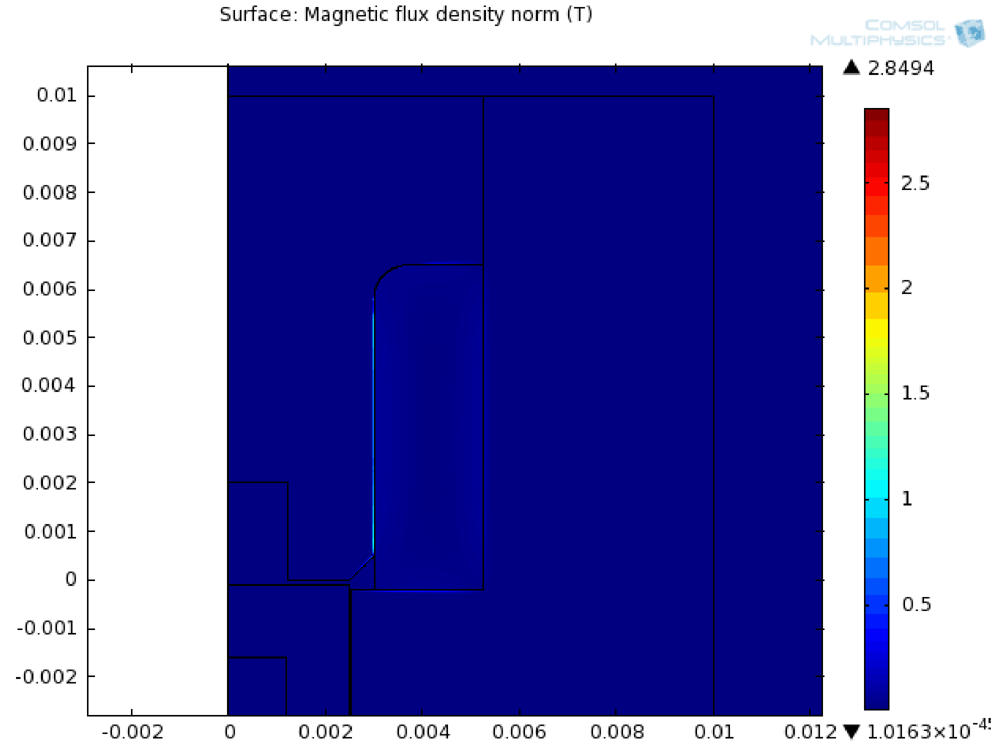




Finite element model of solenoid's magnetic circuit

Comsol Multiphysics





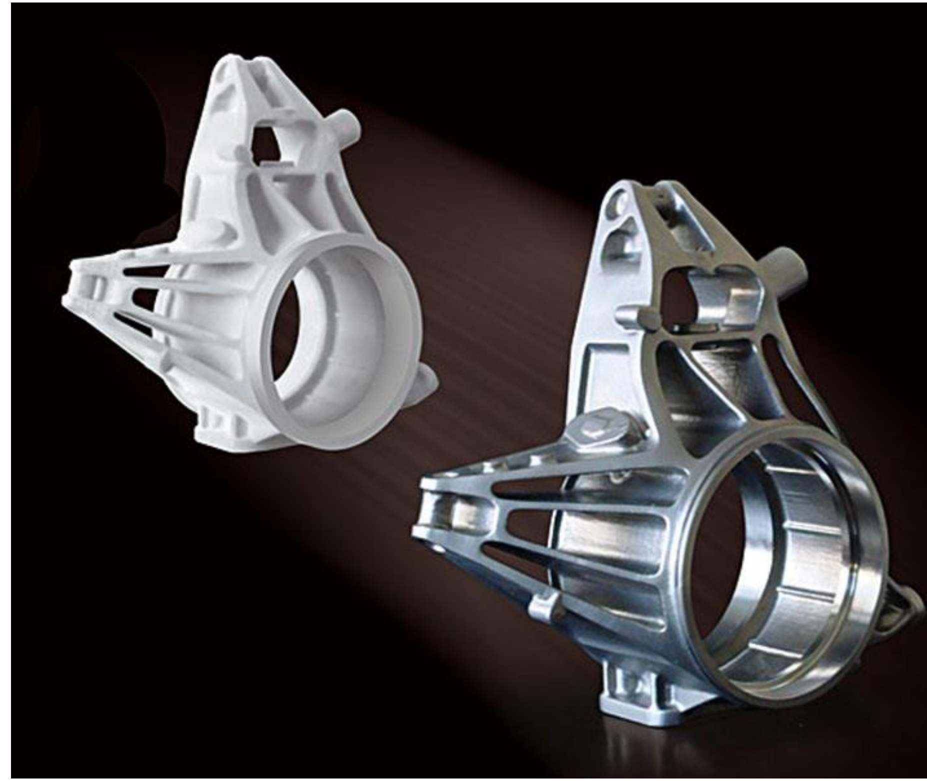
Rapid prototyping

To get a feel of the real part

Can be used for (limited?) testing

- *Depending on the material strength*

3D printing



HIL simulation

Hardware In the Loop

- *The system is partly hardware partly software model*

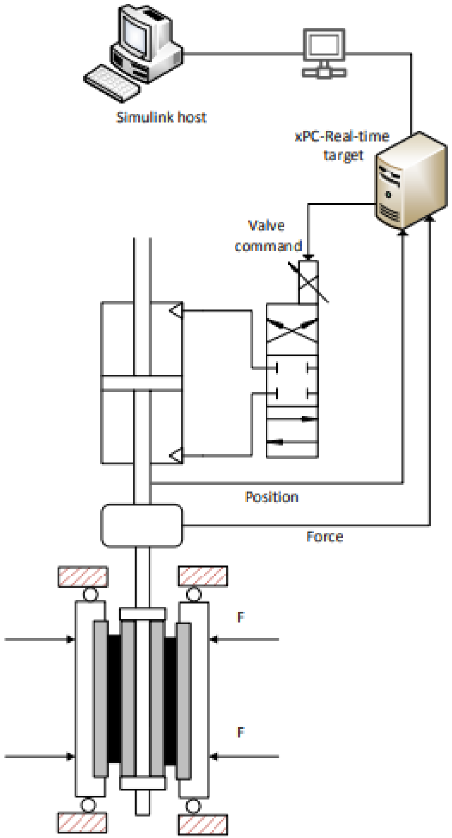
Including hard-to-model systems

- *For example rubber is surprisingly difficult to model*

Testing controller against a model of a system

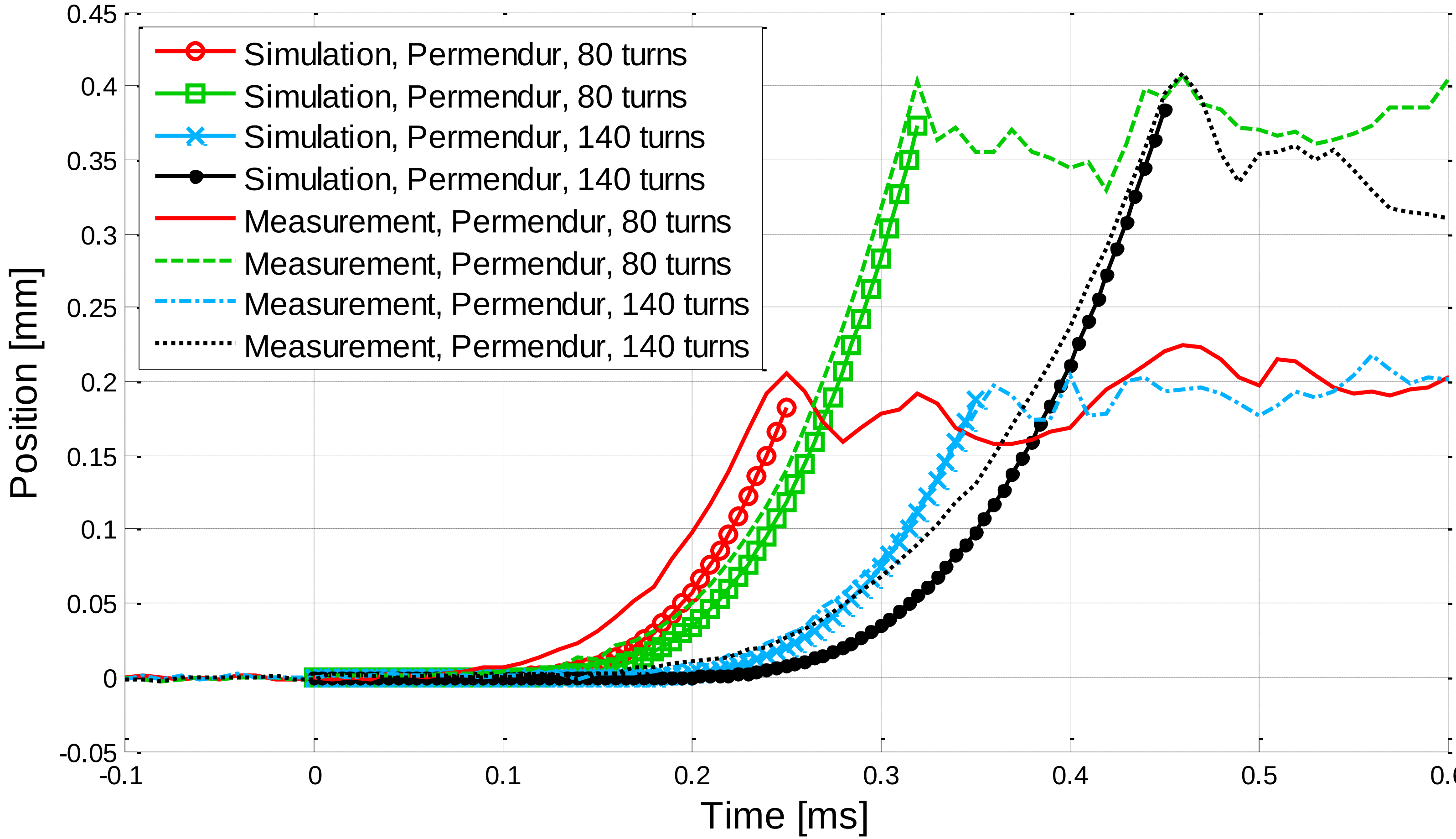
- *Motor controller controls simulated motor etc.*

HIL simulation



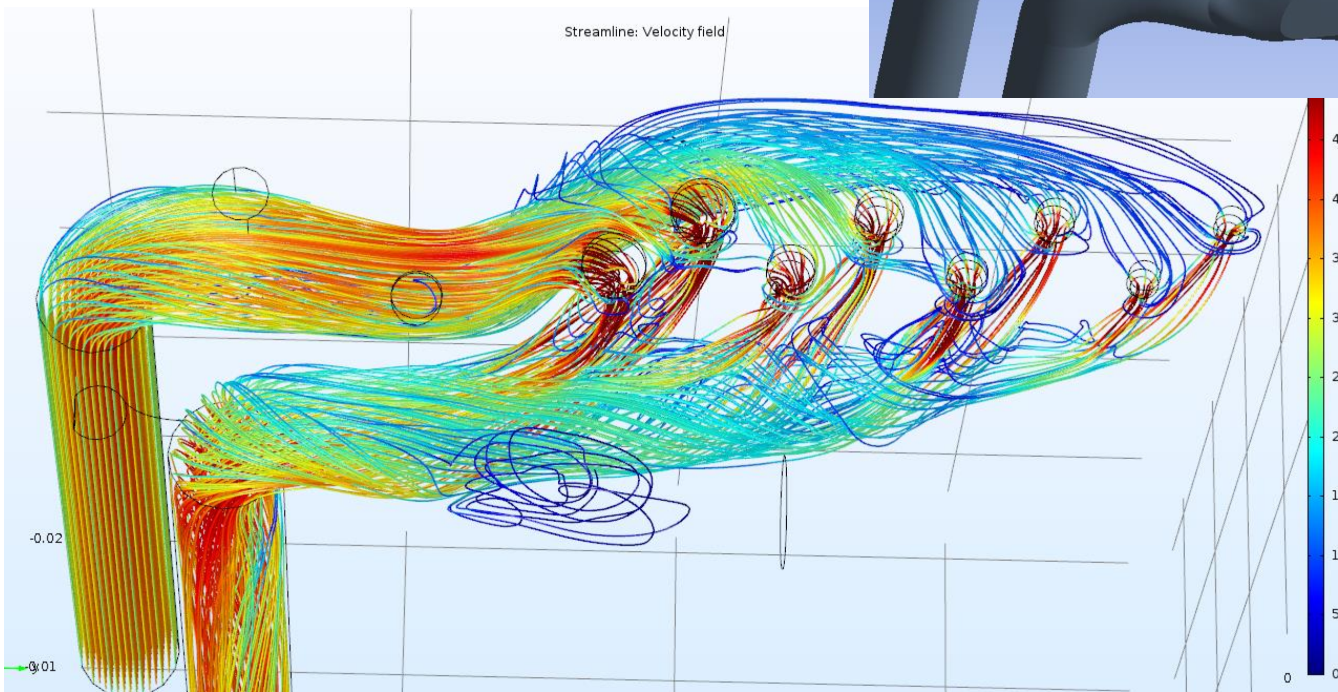
Saarikoski, T. and Pietola, M., 2014, June. HIL Simulation of Elastomer Supported Machine Bed Dynamics. In *Fluid Power Systems Technology* (Vol. 45820, p. V001T02A011). American Society of Mechanical Engineers.

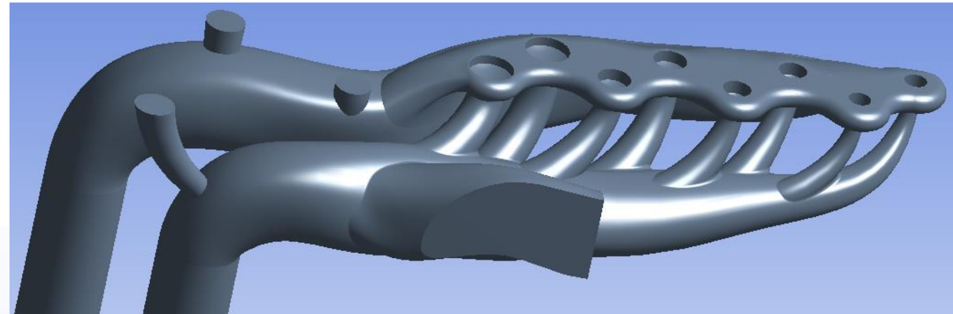
Model verification with experiments



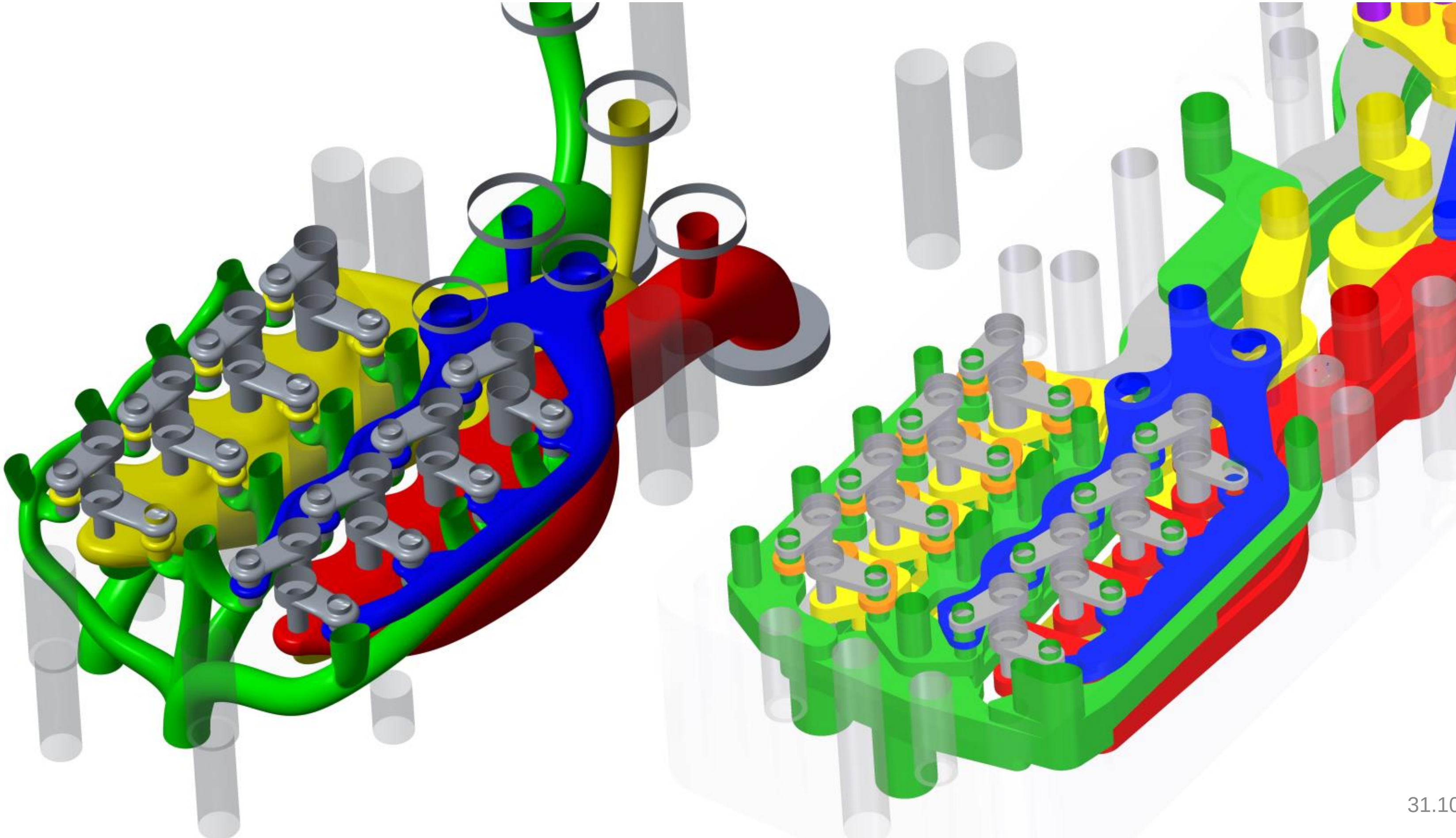
Computational Fluid Dynamics

Ansys Fluent





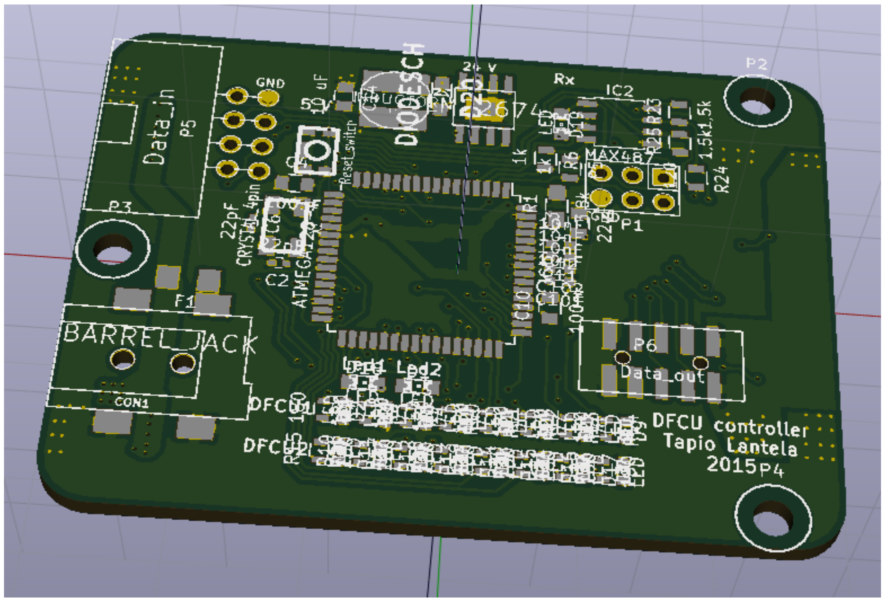
Improvement with CFD and 3D printing

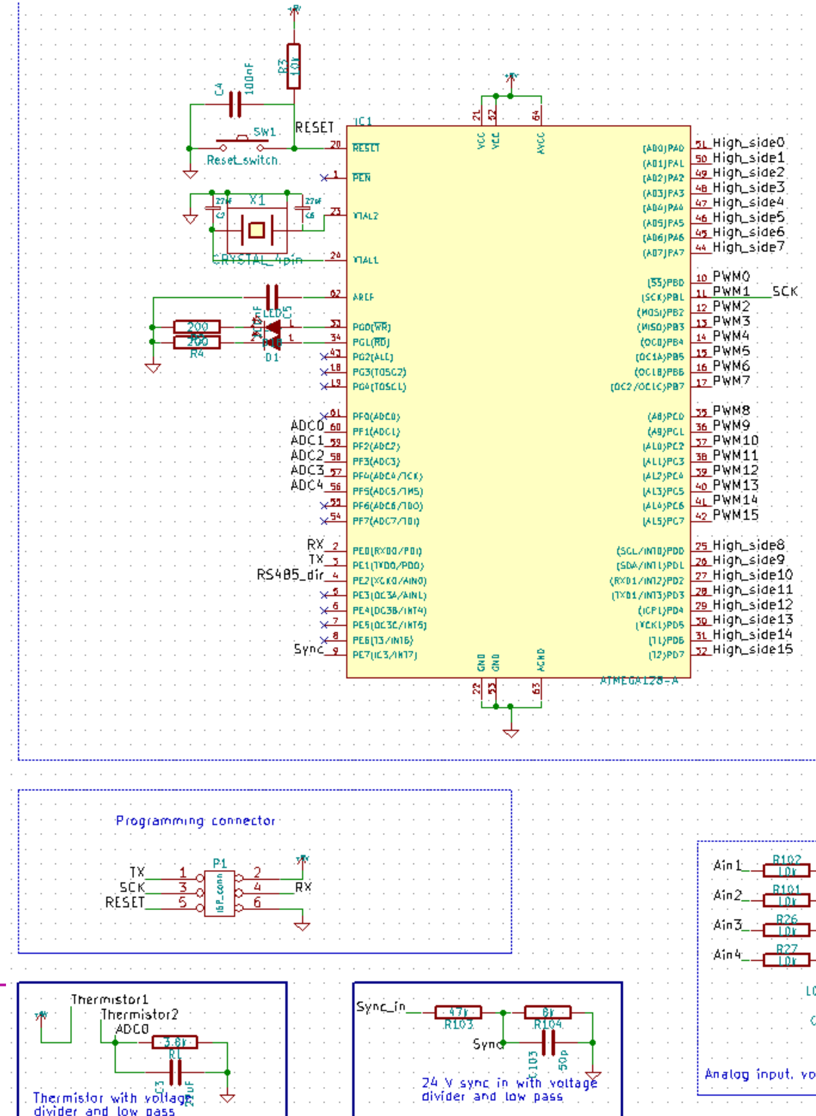


Resulting 16-valve manifold

Modeling electronics

KiCAD



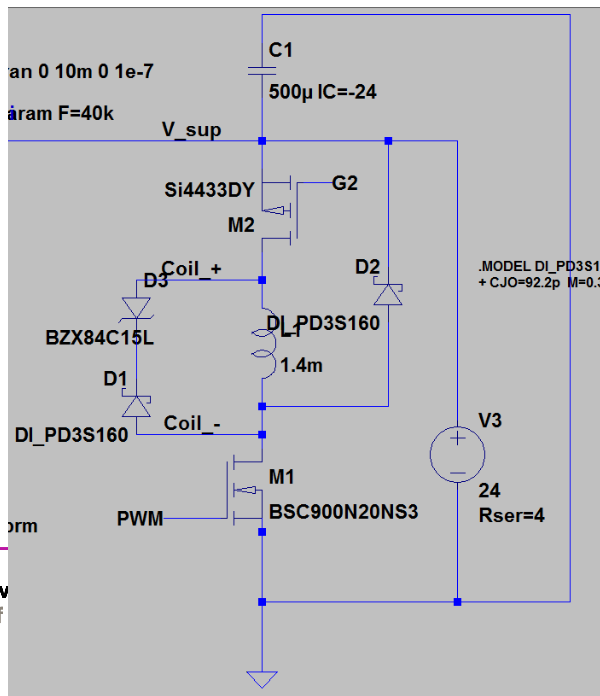


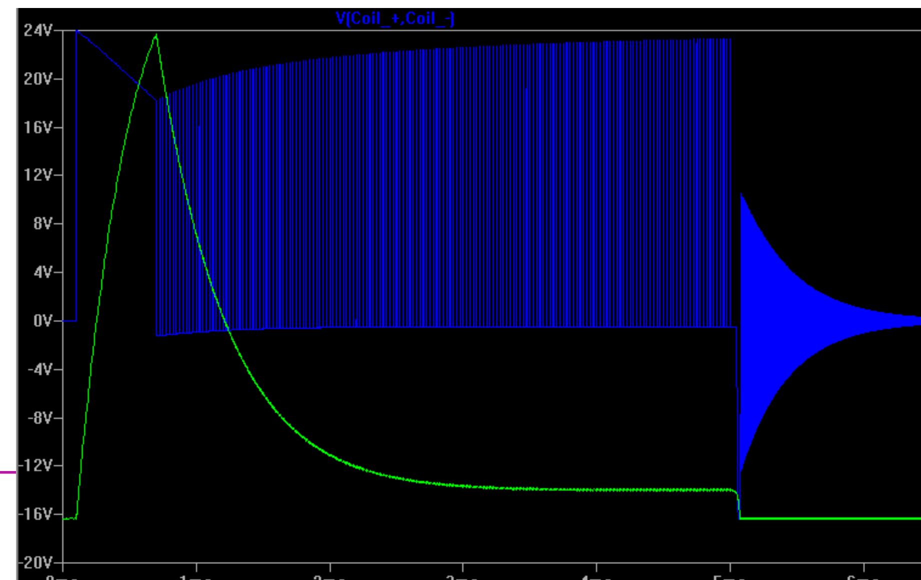
Electric circuit simulation

SPICE = Simulation Program with Integrated Circuit Emphasis

- *Analog electronic circuit simulation*

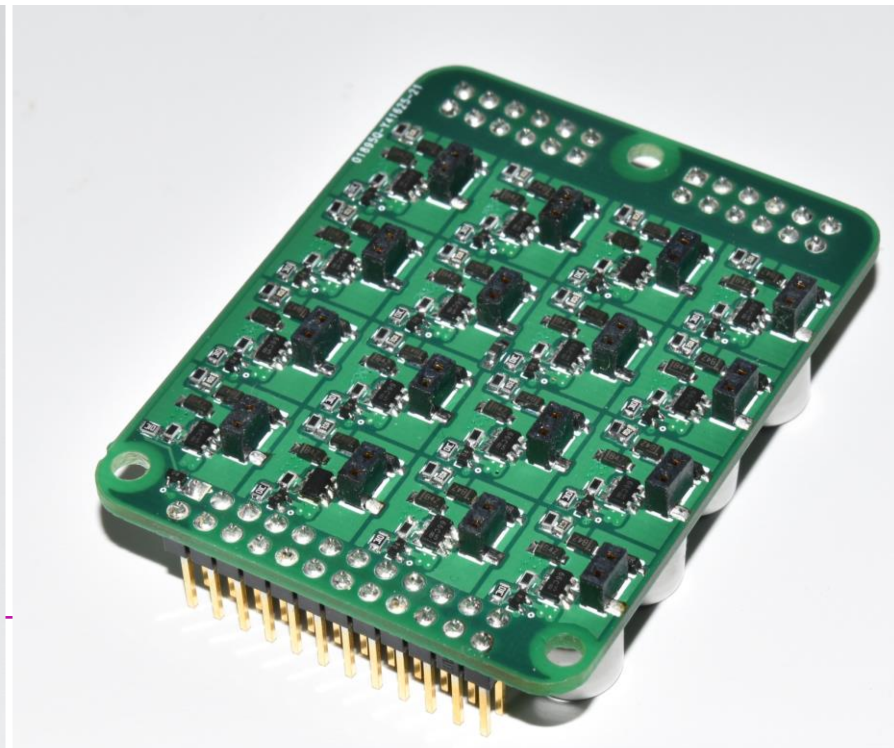
LTspice





Result

Microcontroller based 16-channel power electronics for a digital valve system.



Resulting prototype

Modeling involved

- *Manual sketching*
- *Lots of analytical equations*
- *CAD*
- *Finite element*
  - Magnetic fields
    - Genetic optimization
  - Mechanical stresses
- *Modeling of dynamics*
  - Simulink
- *Computational Fluid Dynamics*
- *Electrical circuit*
  - Topological, physical
  - Transient simulation

Modeling accuracy

Understand how your model and the program running it works

- *Or at least know its limits*
  - Is something relevant neglected?

Accuracy vs. computational cost

- *Time step, mesh refinement, turbulence model etc…*
- *2D vs 3D model, using symmetries*
- *Desktop pc vs. computing clusters*

Sanity check with simple simulation cases

Verification against experimental tests

Simulation tools available to you

General

- *Matlab – Simulink (via Aalto) (check also SimScape toolboxes)*
- *OpenModelica (open source)*

Electronic circuits

- *Design: KiCAD (open source)*
- *Simulation: LTspice (free) – one of many SPICE-based programs*

Finite element

- *Comsol Multiphysics, Abaqus (via Aalto)*
- *OpenFOAM (open source)*
- *Finite Element Method Magnetics (FEMM) (open source)*

CAD

- *Creo, NX, SolidWorks (via Aalto) – contain also FEM solvers*
- *SketchUp, FreeCAD (free)*

AUTOMATION & CONTROL INSTITUTE
INSTITUT FÜR AUTOMATISIERUNGS-
& REGELUNGSTECHNIK

Triple Pendulum on a Cart

Swing-up and Swing-down

Two-degrees-of-freedom design:

Constrained feedforward & optimal feedback control