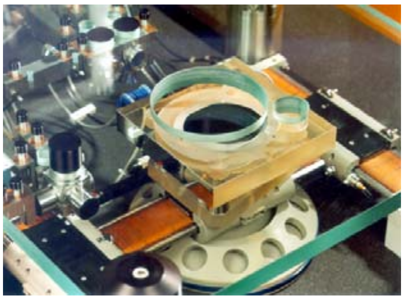
Mechatronic system design

Mechatronic system design wb2414-2013/2014
Course part 6



Power electronics

Prof.ir. R.H.Munnig Schmidt
Mechatronic System Design

Contents

- Power electronics, what's so special about it?
- Passive (power) electronic filters
  - Why so many inductors?
- Current or voltage source amplifier output
  - Actuator determined spec.
- Linear, dissipative power amplifiers
- Dynamic impact of power amplifiers
  - Stability and frequency dependent characteristics
- Switched mode power conversion
  - 4 quadrant power delivery
  - PWM Amplifiers
  - 3-phase amplifiers

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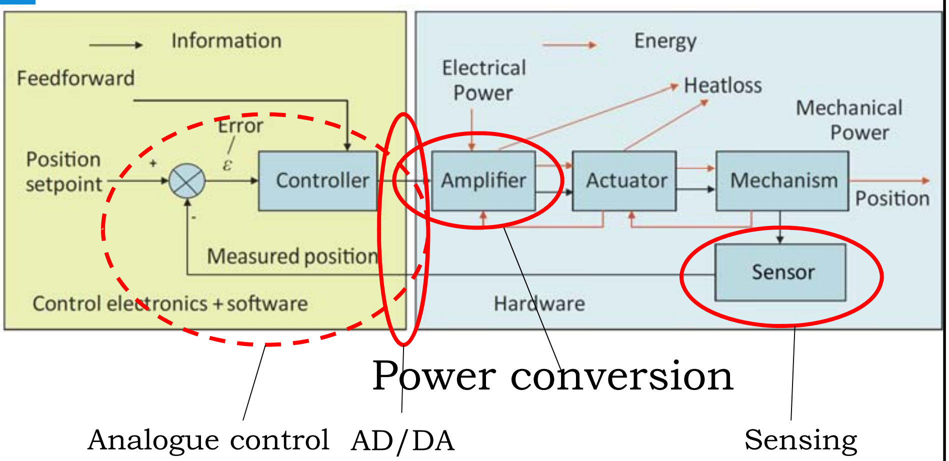
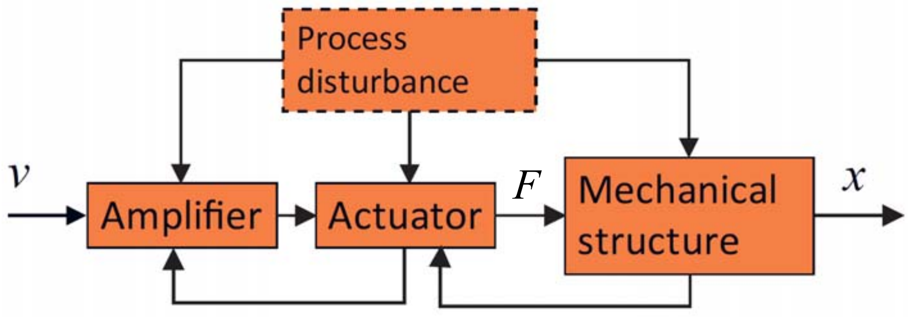
Electronics in mechatronics



The amplifier and actuator have to deliver a real force *F*, at best equal to the control force



The task of the power amplifier is that of a controller!

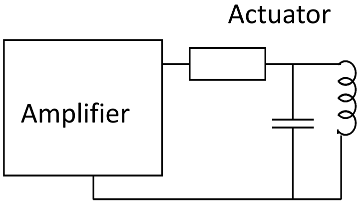
- Controlling the characteristics of an electromagnetic actuator/motor by controlling the actuator-input signal: the voltage and current.
- Distinguishing items:
  - Power capability (Voltage × Current)
  - Dynamic properties like stability and control bandwidth
  - Low or high output impedance (voltage or current source output)
  - Efficiency (Power dissipation)
  - Linearity, full range proportional output value (freedom of distortion)

Power Capability is directly visible

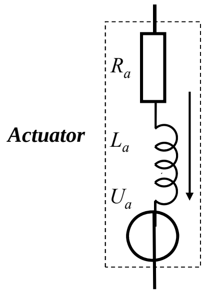
- High voltage and current levels limit small size (solid-state) integration
  - Discrete Components
  - Switching relays
  - Thermal Control
- Risk of interference by strong magnetic and electric fields (EMC)

Dynamic Properties in two directions

- Amplifiers are part of the position feedback loop
  - Delay for instance from latency in a digitally controlled amplifier, will reduce stability .
  - Also the bandwidth, how quickly can the current follow a setpoint change (HF behaviour), is related to a negative impact on the phase.
- The dynamic load from the actuator(L,R,C) will impact stability of the amplifier

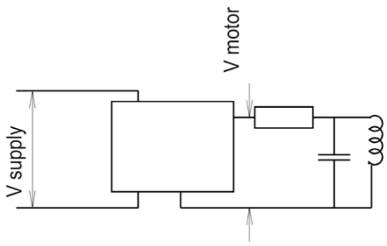


Low or high output impedance of an Amplifier



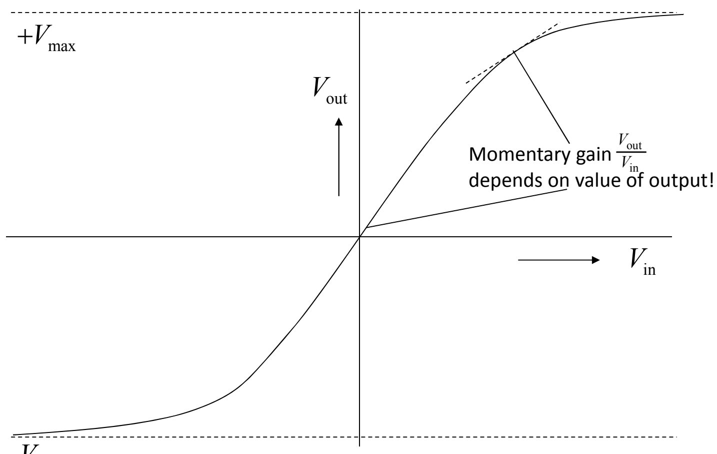
- Low impedance (voltage source output):
  - When damping is necessary
    - Loudspeakers
    - Feedforward (no feedback)
- High impedance (current source output)
  - When the current/force has to be independent of the movement (Lorentz actuators).
  - When the current/force has to be independent of the self inductance (servo systems)

Efficiency



- An amplifier converts a supply voltage/ current into a motor voltage/current.
- A difference of voltage means power loss unless….
- A difference in current requires energy buffering in capacitors or batteries.
- Switched mode/PWM amplifiers reduce dissipation but have other special properties that have to be known.

Linearity, distortion



Clipping example

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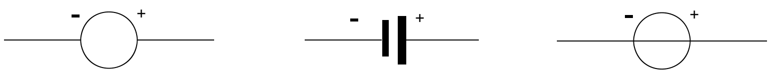
  - 3-phase amplifiers

First a few definitions while keeping “real”electronics to the bare minimum

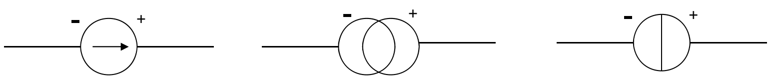
- Voltage and current source
- Ohm’s law
- Resistors
- Capacitors
- Inductors

Ideal voltage and current sources

- An **ideal voltage source** is a circuit element where the voltage across it is independent of the load (current). It has a zero source impedance.
  It can be replaced by a short circuit when the influence of another electric source in the circuit is to be determined.

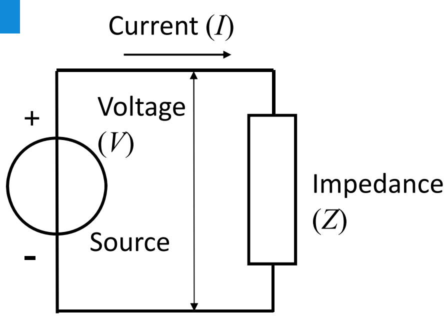


- An **ideal current source** is a circuit element where the current through it is independent of the load (voltage). It has an infinite source impedance.
  It can be replaced by an open circuit when the influence of another electric source in the circuit is to be determined.



- Both do not exist in reality but only in physical models of circuits. In reality one can only approximate its behaviour.

Ohm's law, the definition of impedance



$$V = IR \qquad I = \frac{V}{R}$$

Power in Watt (W):

$$P = IV = I^2R = \frac{V^2}{R}$$

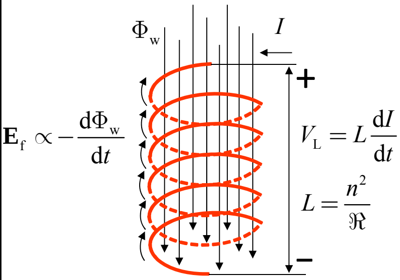
Dynamic impedance *Z(f)*

$$V(f) = I(f)Z(f) \qquad I(f) = \frac{V(f)}{Z(f)}$$

Practical resistors

- Resistor size is determined by the power dissipation
- (Wirewound) resistors have parasitic self inductance and capacitance
- Range from mΩ to GΩ

First dynamic impedance, the coil or Inductor (symbol L from Lenz).



Inductor L with n windings

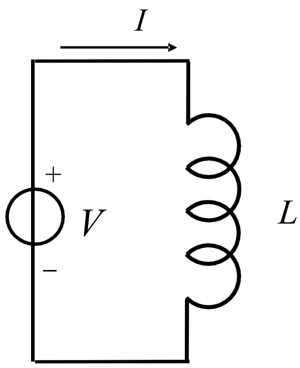
Self-inductance of windings is related to induced magnetic field

$$L = \frac{\Phi_{w,t}}{I} = n \cdot \frac{\Phi_w}{I} = n\frac{nI}{I\Re} = \frac{n^2}{\Re}$$

Induced voltage by a changing magnetic field (Faraday)

$$V_L = \mathcal{F}_e = n\frac{d\Phi_w}{dt} = \frac{d\Phi_{w,t}}{dt} = L\frac{dI}{dt}$$

First dynamic impedance, the coil or Inductor (symbol L from Lenz).



- For AC the voltage leads the current with 90°

Fourier transform:

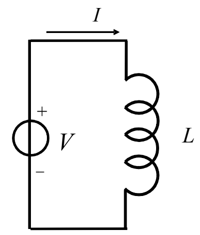
$$\mathcal{F}\left\{\frac{d}{dt}\right\} = j\omega$$

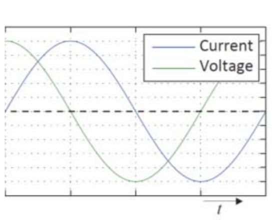
$$V(t) = n\frac{d\Phi_w}{dt} = L\frac{dI}{dt}$$

$$\mathcal{F}\{V(t)\} = V(\omega) = j\omega L I$$

$$Z_c(\omega) = \frac{V}{I}(\omega) = j\omega L$$

Power and energy in an inductor.





- The current as function of the voltage equals:

$$V(\omega) = j\omega L I(\omega) \;\;\Rightarrow\;\; I(\omega) = \frac{V(\omega)}{j\omega L}$$

$$V(\omega) = V_{\mathrm{p}} \cos\omega t \;\;\Rightarrow\;\; I(\omega) = \frac{V(\omega)}{j\omega L} = I_{\mathrm{p}} \sin\omega t \quad \left(I_{\mathrm{p}} = \frac{V_{\mathrm{p}}}{\omega L} \right)$$

- The power equals:

$$P = I_{\mathrm{p}} \sin\omega t \cdot V_{\mathrm{p}} \cos\omega t = 0.5 I_{\mathrm{p}} V_{\mathrm{p}} \sin(2\omega t) = \text{ average } 0$$

- And the momentary energy equals

$$E_{\mathrm{L}} = \int_{t_0}^{t_1} P_{\mathrm{L}}(t)\mathrm{d}t = \int_{t_0}^{t_1} I(t) L \frac{\mathrm{d}I}{\mathrm{d}t}\mathrm{d}t = L\int_0^{I_1} I(t)\mathrm{d}I = \frac{1}{2} L I_1^2$$

$$(\text{compare}: E_{\text{spring}} = 0.5kF^2)$$

Practical Inductors

- Inductor size is determined by the selfinductance and the current.
- Inductors have parasitic capacitance, resistance and eddy current losses
- Range from µH to several mH

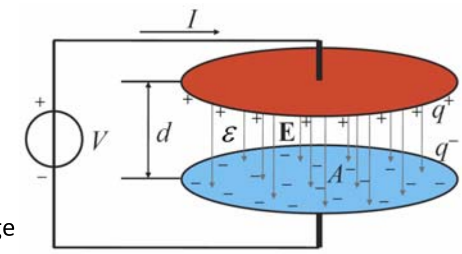
Second dynamic impedance, the Capacitor

A capacitor is storing electrical energy in charge on two separated plates with distance D and surface A

- The capacitance is: $C \approx \dfrac{\varepsilon A}{d}$
- In vacuum the permittivity ε_0 is:

$$\varepsilon_0 = \frac{1}{c^2 \mu_0} \approx 8.85 \cdot 10^{-12}$$

- The charge is: $q = CV$
- With AC the current leads the voltage

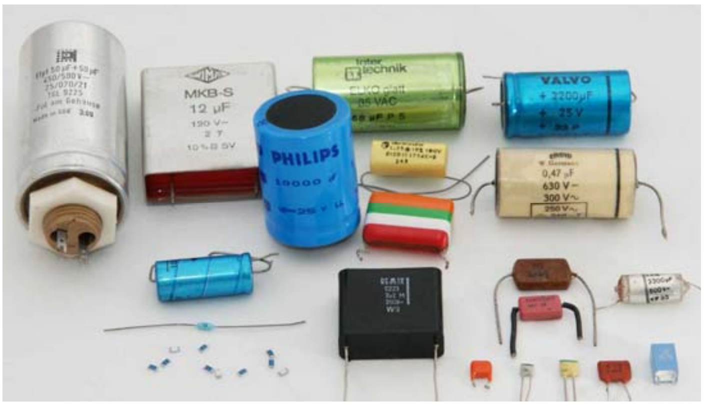


$$I(t) = \frac{dQ}{dt} = C\frac{dV}{dt} \;; \qquad \mathcal{F}\{I(t)\} = I(\omega) = j\omega CV \;; \quad Z(\omega) = \frac{V}{I} = \frac{1}{j\omega C} \;;$$

$$P = V_p \sin\omega t \cdot I_p \cos\omega t = 0.5 V_p I_p \sin(2\omega t) = \text{ average } 0; \;\; E = 0.5CV^2 \;\; (\text{compare: } E_{kin} = 0.5mv^2)$$

Practical Capacitors

- Capacitor size is determined by the Capacitance and current.
- Capacitors have parasitic self inductance and resistance
- Range from 1pF (ceramic) to ~ > 1 F (electrolytic super caps)

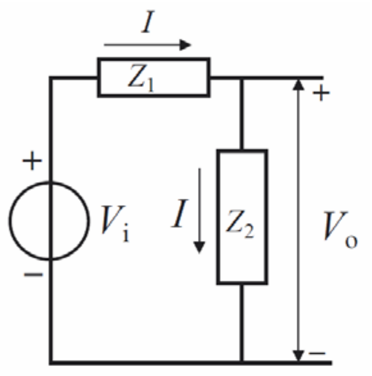


So do you recognise these elements?

These parts are used to make filters for the output of switching-mode amplifiers

- Voltage dividers or attenuators
- 1st order low-pass filters
- 2nd order low-pass filters

A voltage divider



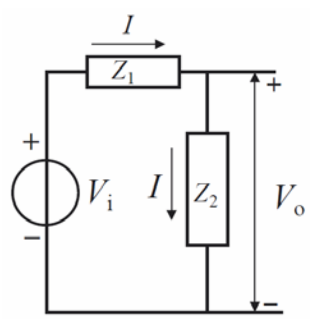
a: Voltage divider

$$I = \frac{V_i}{Z_1 + Z_2}$$

$$V_o = I \cdot Z_2 = \frac{V_i Z_2}{Z_1 + Z_2}$$

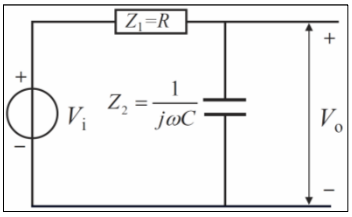
Discussion:

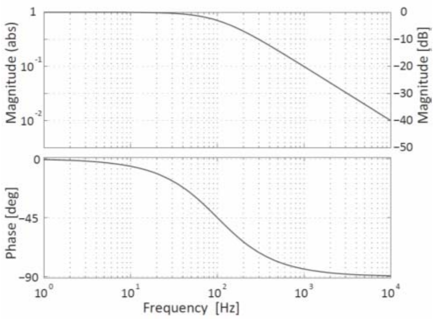
- Design a first-order low pass filter for 1000Hz
  - Use voltage divider
  - Choose best suitable components
  - Determine frequency response
  - Determine component values



a: Voltage divider

1^{st} order low-pass with capacitor





$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

$$Z_1 = R \,,\, Z_2 = \frac{1}{j\omega C} \text{ and } \tau = RC$$

$$\frac{V_o}{V_i}(\omega) = G_f(\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} =$$

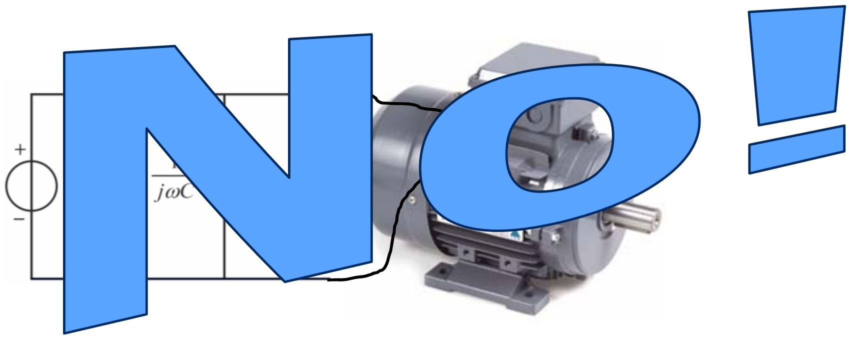
$$= \frac{1}{j\omega RC + 1} = \frac{1}{j\omega\tau + 1}$$

Corner frequency :

$$\omega_0 = 2\pi f_0 = \frac{1}{\tau} = \frac{1}{RC}$$

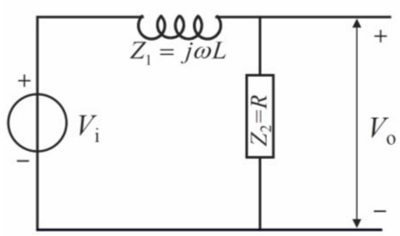
Questione prosciutto!

- Will this work with power transfer from input to output?

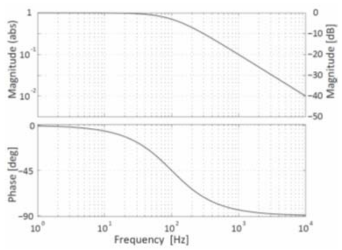


- So what must be avoided?

1st order low-pass with inductor without series resistor



Z_2 represents the power in the load.



$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

$$Z_1 = j\omega L \text{ , } Z_2 = R \text{ and } \tau = \frac{L}{R}$$

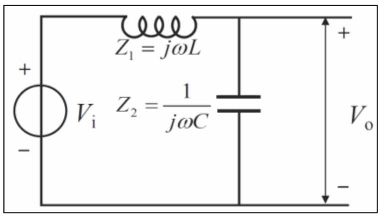
$$\frac{V_o}{V_i}(\omega) = G_f(\omega) = \frac{R}{R + j\omega L} =$$

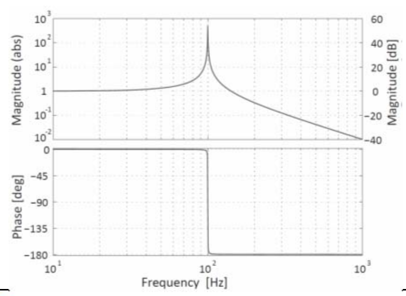
$$= \frac{1}{j\omega \frac{L}{R} + 1} = \frac{1}{j\omega\tau + 1}$$

Corner frequency :

$$\omega_0 = 2\pi f_0 = \frac{1}{\tau} = \frac{R}{L}$$

A second order passive low pass filter without series resistor





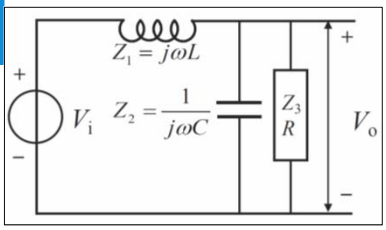
$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

$$Z_1 = j\omega L \text{ , } Z_2 = \frac{1}{j\omega C} \text{ , } \omega_0 = \frac{1}{\sqrt{LC}}$$

$$\frac{V_o}{V_i}(\omega) = G_f(\omega) = \frac{\frac{1}{j\omega C}}{j\omega L + \frac{1}{j\omega C}} =$$

$$= \frac{1}{(j\omega)^2 LC + 1} = \frac{1}{-\frac{\omega^2}{\omega_0^2} + 1}$$

A second order low pass filter with parallel damping



$$\frac{V_o}{V_i} = \frac{Z_2 \parallel Z_3}{Z_1 + Z_2 \parallel Z_3} = \frac{1}{\frac{Z_1}{Z_2 \parallel Z_3} + 1} = \frac{1}{Z_1\left(\frac{1}{Z_2} + \frac{1}{Z_3}\right) + 1}$$

$$Z_1 = j\omega L\ ,\ Z_2 = \frac{1}{j\omega C}\ ,\ Z_3 = R$$

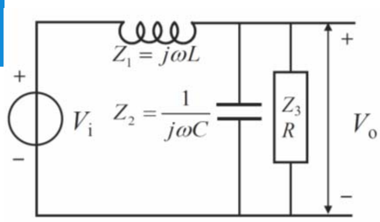
$$\omega_0 = \frac{1}{\sqrt{LC}}\ ,\ \varsigma = \frac{1}{2R}\sqrt{\frac{L}{C}} \Rightarrow Q = \frac{1}{2\varsigma} = R\sqrt{\frac{C}{L}}$$

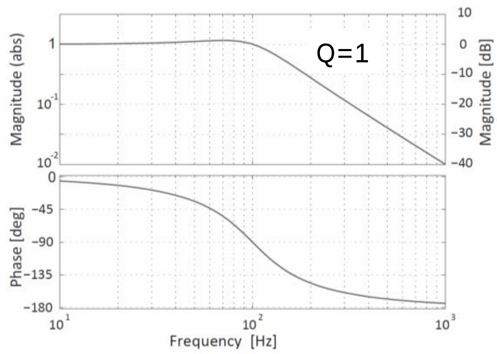
Z_3 represents the power in the load.

$$\frac{V_o}{V_i}(\omega) = G_f(\omega) = \frac{1}{j\omega L\left(j\omega C + \frac{1}{R}\right) + 1} =$$

$$= \frac{1}{(j\omega)^2 LC + j\omega \frac{L}{R} + 1} = \frac{1}{-\frac{\omega^2}{\omega_0^2} + \frac{2\varsigma j\omega}{\omega_0} + 1} = \frac{1}{-\frac{\omega^2}{\omega_0^2} + \frac{j\omega}{\omega_0 Q} + 1}$$

A second order low pass filter with parallel damping



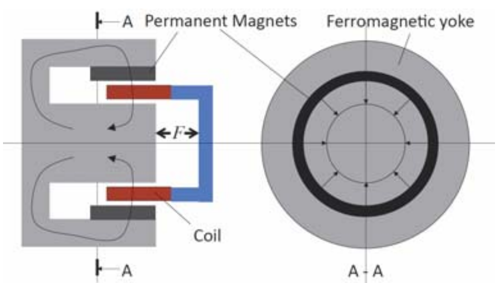


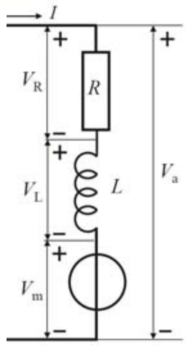
$$G_f(\omega) = \frac{1}{-\frac{\omega^2}{\omega_0^2} + \frac{j\omega}{\omega_0 Q} + 1}$$

Contents

Group discussion

- Discuss difference of voltage and current control to drive an actuator in mechatronic systems

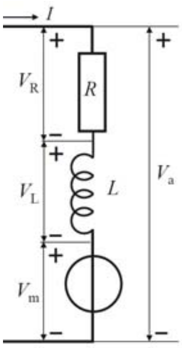




A current source output will cancel effects of the self inductance and motion EMF

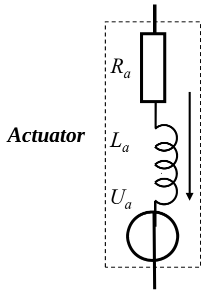
With a voltage source the current is:

$$I = \frac{V_\mathrm{R}}{R} = \frac{V_\mathrm{a} - V_\mathrm{m} - V_\mathrm{L}}{R} = \frac{V_\mathrm{a} - V_\mathrm{m} - L\dfrac{\mathrm{d}I}{\mathrm{d}t}}{R}$$



With a Lorentz actuator a current source will create a direct conversion from the setpoint (control force) to actuator force.

Low or high output impedance of an Amplifier



- Low impedance (voltage source output):
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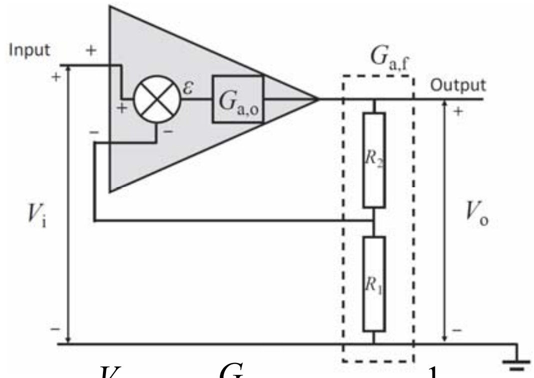
Linear power amplifiers

- A linear power amplifier is nothing else than a powerful version of a small signal amplifier.
- It is often designed like an operational amplifier with high-power output stage
- So it starts with the basic Op-amp.

The analogue (operational) amplifier is an integrated feedback-controlled system!

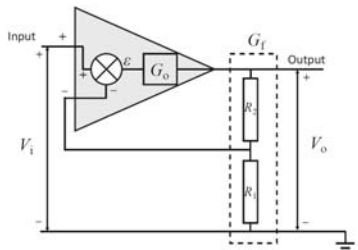


Complementary sensitivity:

$$\frac{V_o}{V_i} = \frac{G_{a,o}}{1+G_{a,o}G_{a,f}} = \frac{1}{\frac{1}{G_{a,o}}+G_{a,f}} = \xrightarrow{G_{a,o}=\infty} = \frac{1}{G_{a,f}}$$

Main guidelines of determining the behaviour of an ideal Op-Amp circuit

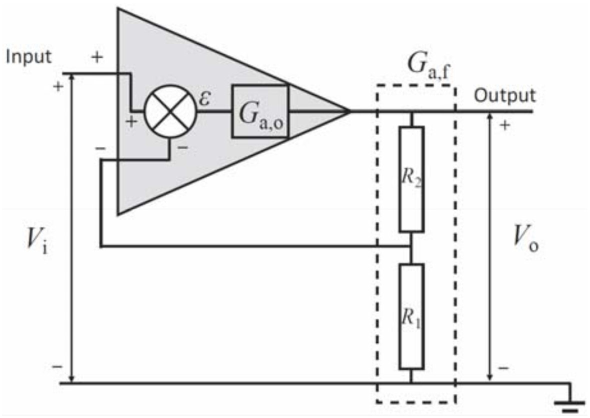
1. Input currents in the Op-amp are zero
2. With negative feedback the output will do whatever it can to keep the negative input voltage equal to the positive input voltage.



Modelling:

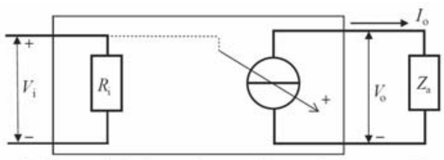
1. Verify that there is Negative Feedback
2. Calculate the voltage on the positive input.
3. Calculate the voltage at the output by applying rule 1 and 2, which means that it generates the same voltage over the feedback path at the negative input as was calculated in step 2.

What source is the output of this amplifier?

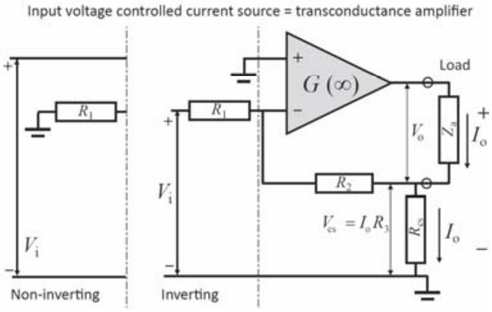


Voltage or Current source? What is controlled?

Transconductance amplifier has a current source output

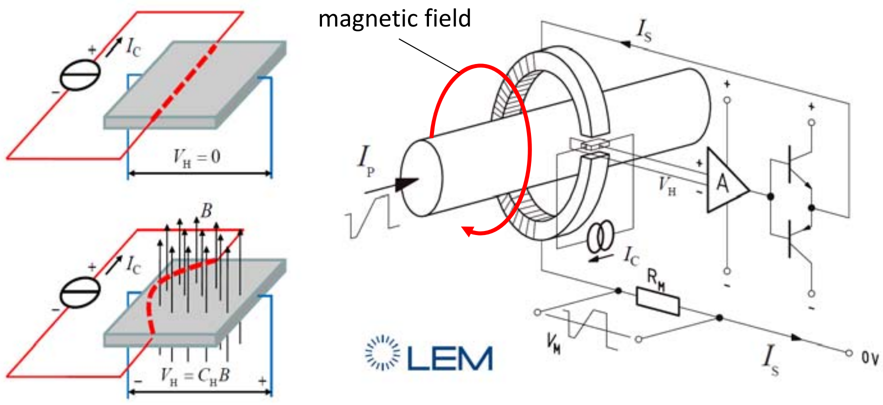


Input voltage controlled current source = transconductance amplifier



- Converts an input setpoint voltage into an output current by measuring the current through the load and controlling the output of the amplifier to keep the current proportional to the setpoint.
- Used for driving electromagnetic actuators
- R_{cs} measures current but there is a better way without voltage drop.

Lossless current sensing for high current levels and improved efficiency



Hall sensor for magnetic field

Active compensation of magnetic field generated by current I_p

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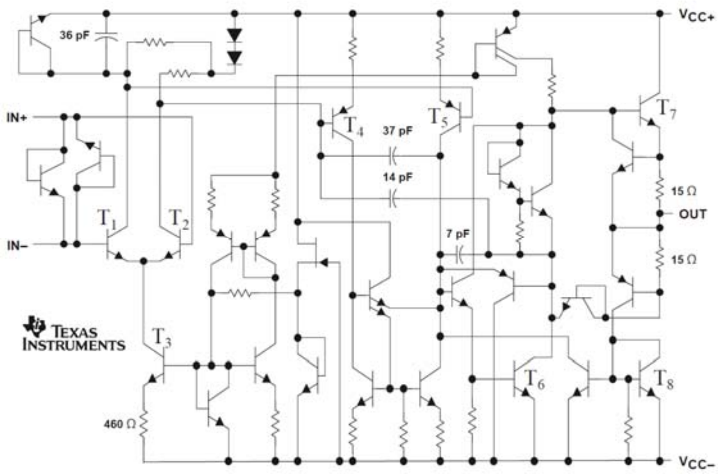
  - PWM Amplifiers
  - 3-phase amplifiers

Ideal and real properties of regular (non-power) operational amplifiers

Parameter	Ideal Op Amp	OPA27	Unit
DC Open loop Gain (G_0)	∞	120 (=10^6)	dB
Input impedance (Z_{in})	∞	$6 \cdot 10^6$	Ω
Output impedance (Z_{out})	0	70	Ω
Input offset voltage (V_{os})	0	< 25	μV
Temp. coëff of V_{os} (γ)	0	0,6	μV/°C
Input bias current (I_b)	0	40	nA
Input offset current (I_{os})	0	10	nA
Gain bandwidth product	∞	$5 \cdot 10^6$	Hz.
Common mode rejection ratio (CMRR)	∞	120 (=10^6)	dB

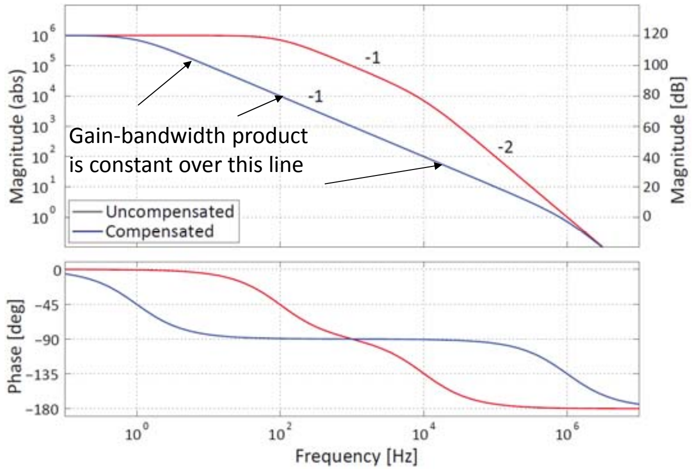
Dynamic limitations of standard Op-Amp



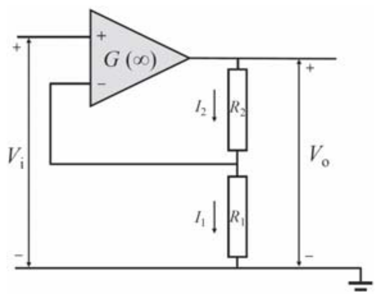
Many capacitors!

And with a power amplifier they are large!

Often a dominant pole is applied @ ~1 Hz to compensate several poles



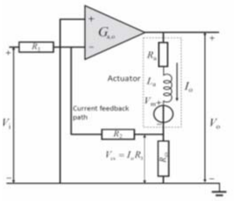
Discussion!



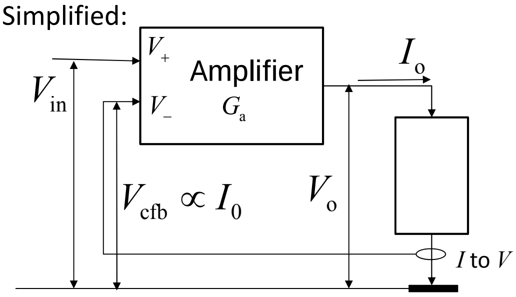
What is the bandwidth of this amplifier?

- Gain BW product = 10^6
- R_1=100
- R_2=10.000

What is the impact of the dominant pole on the current source output impedance?



Simplified:



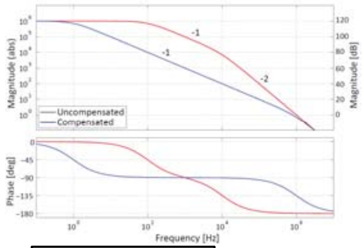
- The higher the loop-gain, the better the current is controlled, so the higher is the output impedance.
- Cut the loop just before the minus input

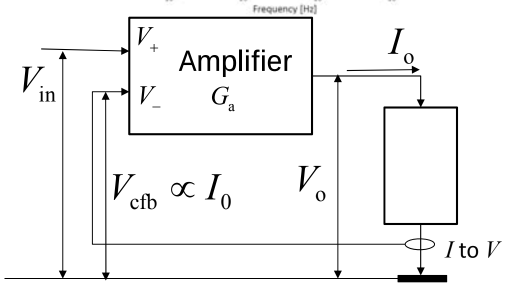
$$G_l = \frac{V_{cfb}}{V_-} \propto G_a$$

$$\Delta V_o = G_a \Delta V_{cfb} \propto G_a \Delta I_o$$

$$\frac{\Delta V_o}{\Delta I_o} = Z_o \propto G_l$$

What is the impact of the dominant pole on the current source output impedance?



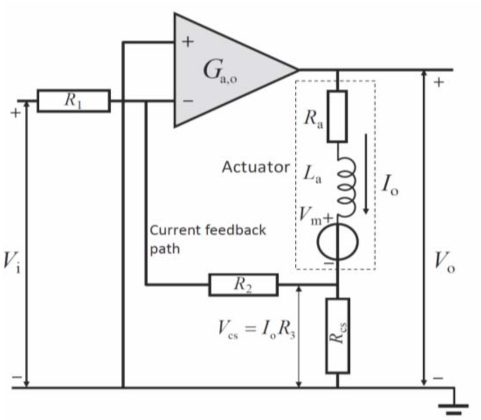


- The higher the loop-gain, the better the current is controlled, so the higher is the output impedance.

$$Z_o \propto G_l$$

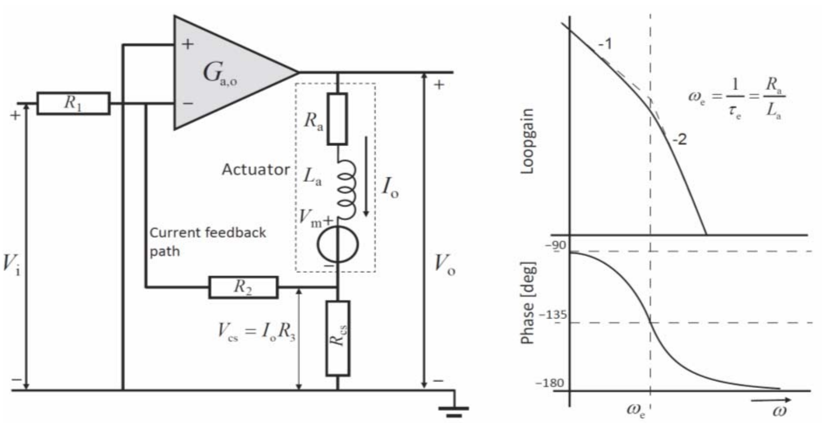
- The loopgain and output impedance is inverse proportional to the frequency
- So what is the character of the output impedance?

The actuator inductance creates an additional pole (R/L)

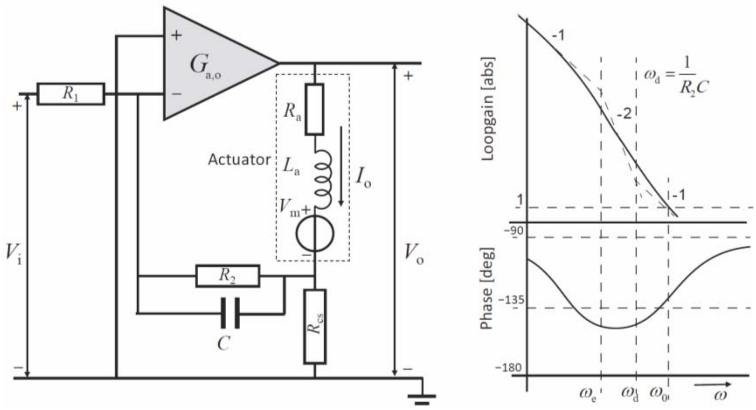


This creates stability issues and a potential resonance

The actuator inductance creates an additional pole (R/L)



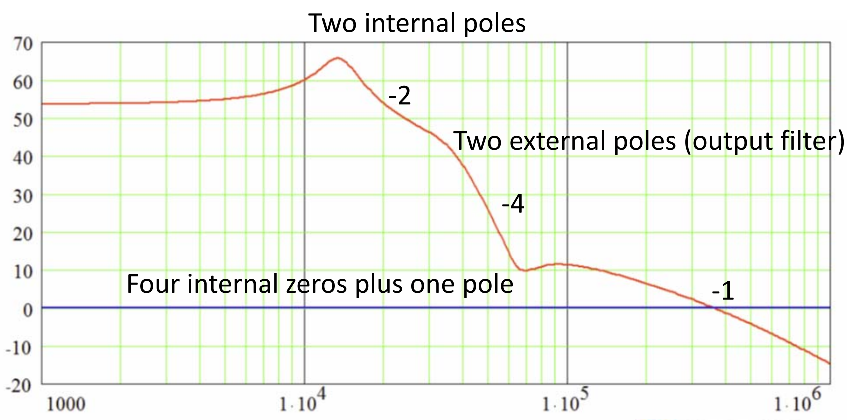
Phase compensation can help the stability



But that changes the closed loop response, which can be OK for rejection of resonances.

Conclusion: One has to "shape" the feedback loop inside the amplifier towards the application!

Extreme example of loopshaping @ voltage source audio amplifier



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Main drawback of a linear non-switching power output stage is dissipation of energy

Issue 1: High supply voltage is needed with an inductive load:

$$V_a = V_R + V_m + V_L = IR + V_m + L\frac{dI}{dt}$$

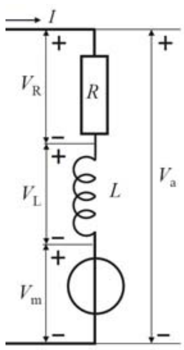
$$\text{Jerk} = \frac{d^3x}{dt^3} \propto \frac{dI}{dt}$$

$$V_{max} = IR + V_m + L\frac{dI}{dt}_{max}$$

$$I \propto \ddot{x}$$

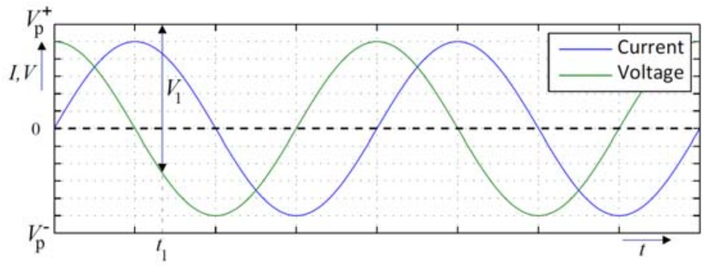
$V \propto \dddot{x}$ = "Jerk"

$\ddddot{x}$ = "Snap"



Issue 2: Current and voltage are not in phase.

- In case of pure inductor:



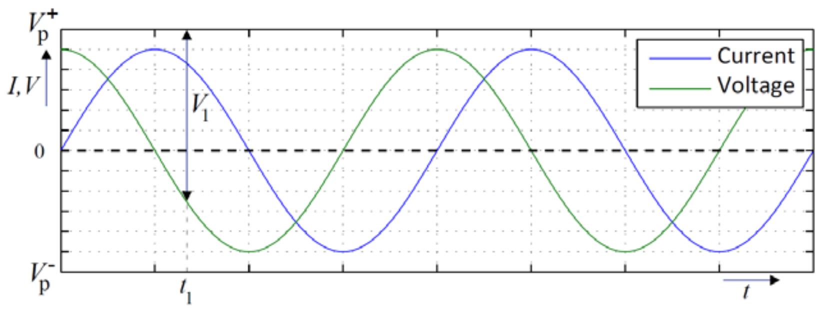
$$V = L\frac{dI}{dt}$$

$$I = \hat{I}\sin\omega t$$

$$V = L\frac{d(\hat{I}\sin\omega t)}{dt} = L\hat{I}\frac{d(\sin\omega t)}{dt} = \hat{V}\cos\omega t \quad \hat{V} = L\hat{I}\omega$$

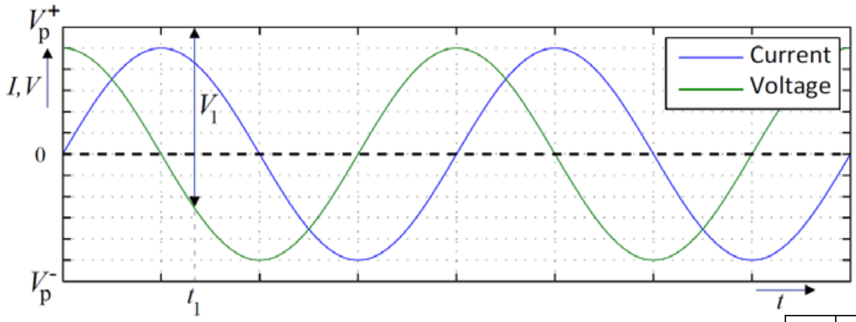
Discussion:

What happens at t_1

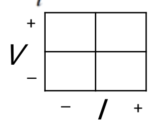


Negative current with positive voltage.

f.i. @ t_1 $P_{\text{loss}} = I_o V_1 = I_o (V_p - V_o)$

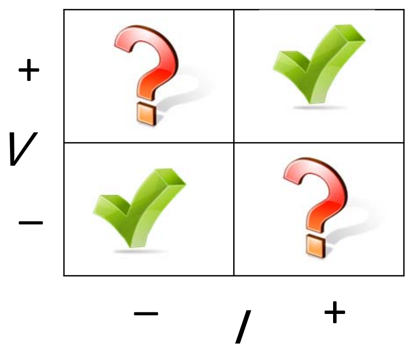


4 quadrant operation:
any combination of *+/- V* and *I*



4 Quadrant power delivery

4 quadrant operation:
Any combination of $+/-V$ and I



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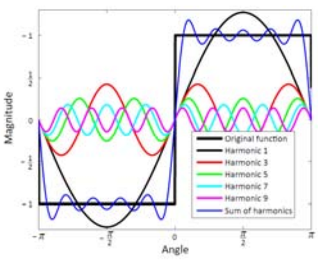
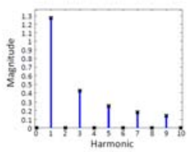
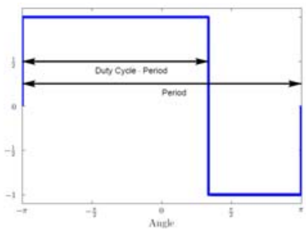
PWM or switched mode power conversion

- A switch does not dissipate energy
- Switches can only create squarewave signals (on/off) when switching fast.
- Low pass filtering gives the average value (Fourier) depending on duty cycle.



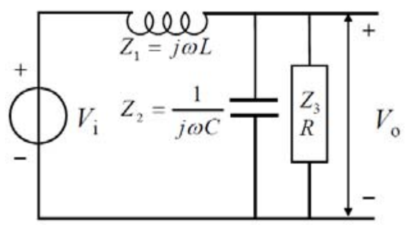
$$a_0 = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(\theta)\, d\theta \;=\; 2D-1$$

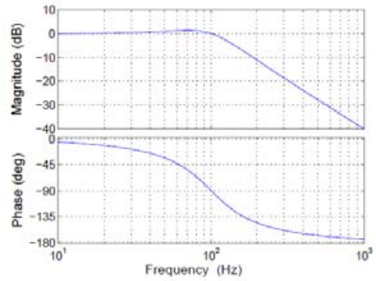




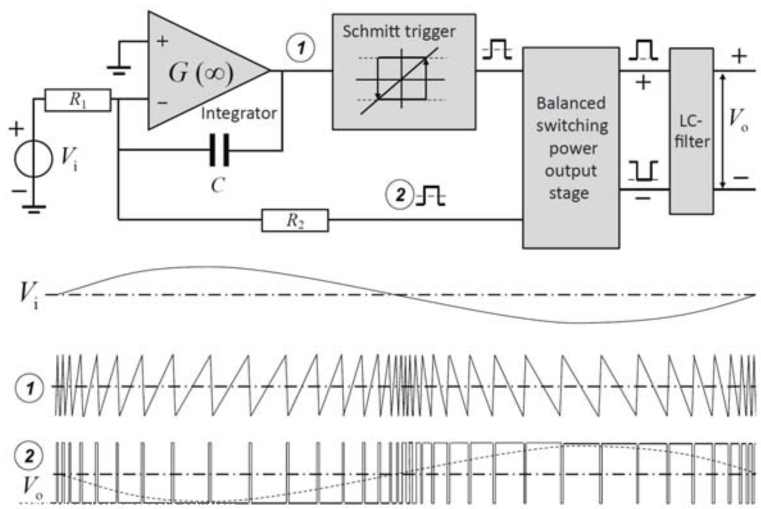
PWM or switched mode power conversion

- A switch does not dissipate energy
- Switches can only create squarewave signals (on/off) when switching fast.
- Low pass filtering gives the average value (Fourier).
- L-C filtering is non-dissipative

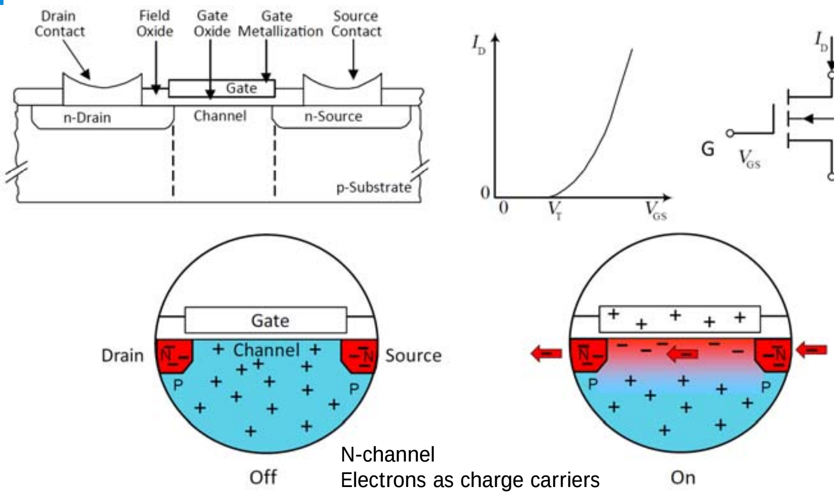




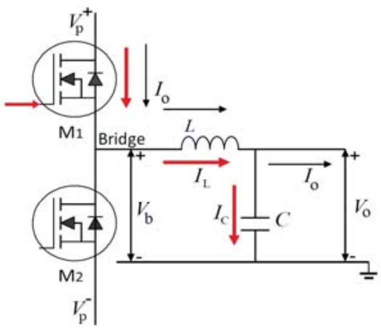
Pulse width (duty cycle) modulation



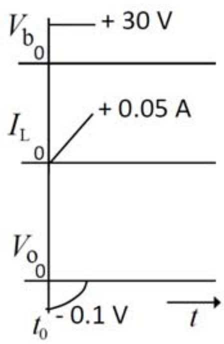
Power switches, the MOSFET



Switching cycle: step 1

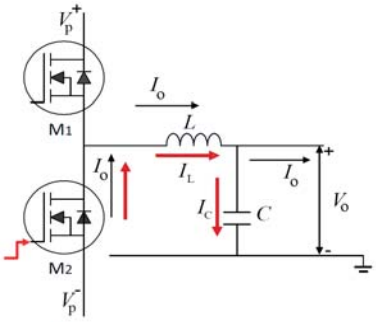


Step 1: M1 switched on.
Current I_L increases.
Voltage V_o becomes more positive.

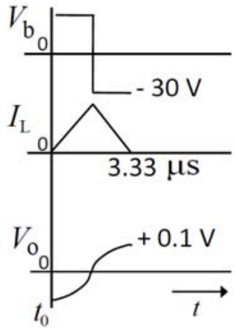


Step 1:

Switching cycle: step 2

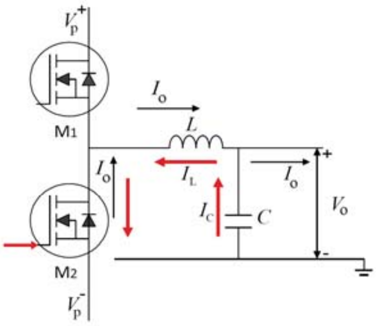


Step 2: M1 switched off, M2 switching on.
Current I_L keeps flowing through M2 and decreases.
Voltage V_o becomes more positive.

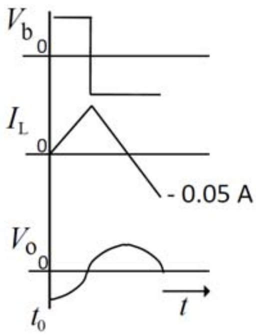


Step 2:

Switching cycle: step 3

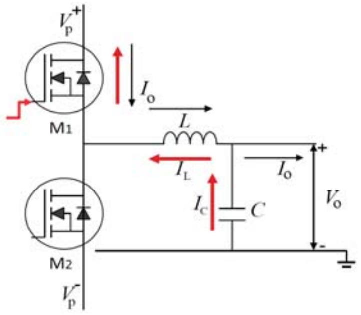


Step 3: M2 switched on.
Current I_L changes direction and increases.
Voltage V_o becomes more negative.

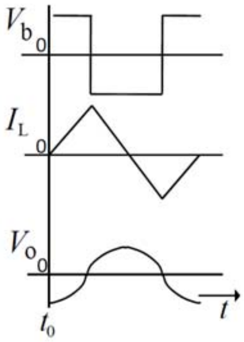


Step 3:

Switching cycle: step 4

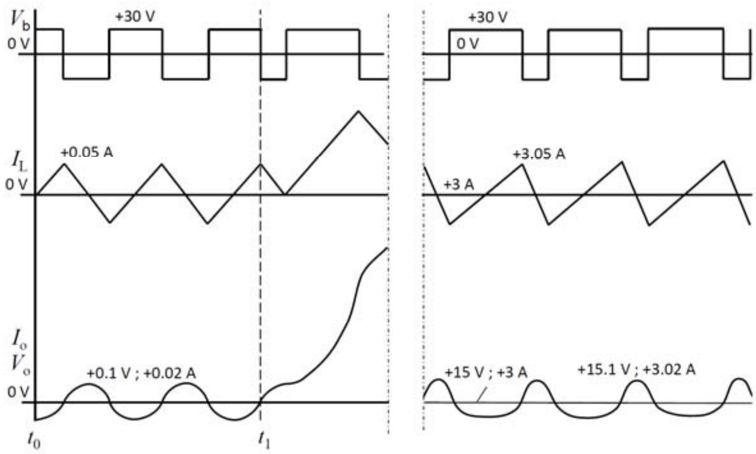


Step 4: M2 switched off, M1 switching on.
Current I_L keeps flowing through M1 and decreases.
Voltage V_O becomes more negative.



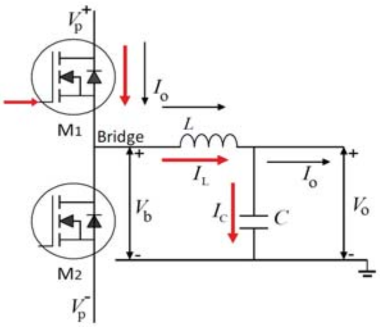
Step 4:

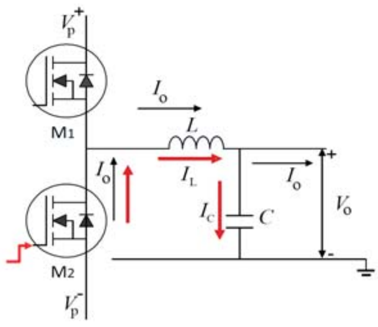
Change of duty cycle R_{load}=5 Ω



Transition from 50 % to 75 % duty cycle at t_1 After stabilisation

Charge pumping with unipolar output voltage



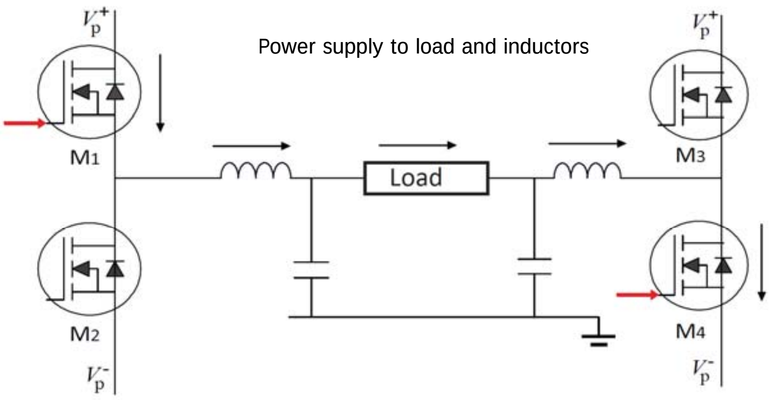


I_o flows from positive supply
Positive supply delivers power

and from negative supply
Negative supply receives power

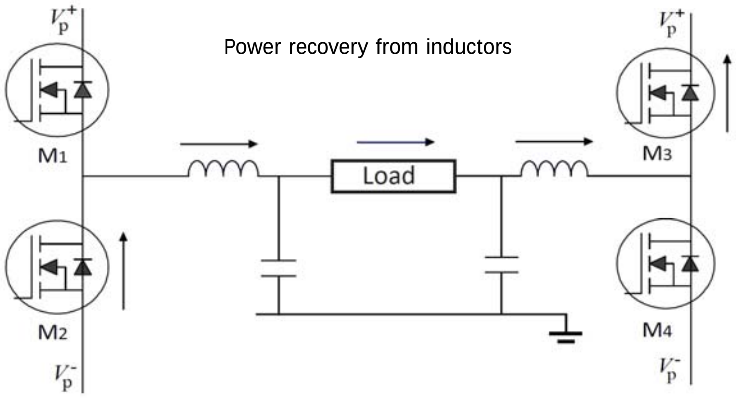
In a bridge configuration these currents are balanced

Power supply to load and inductors



Step 1: M1 and M3 switched on. The LF current flows from V_p^+ to V_p^-.

In a bridge configuration these currents are balanced



Step 2: M1 and M3 switched off. The LF current flows from V_p^- to V_p^+.

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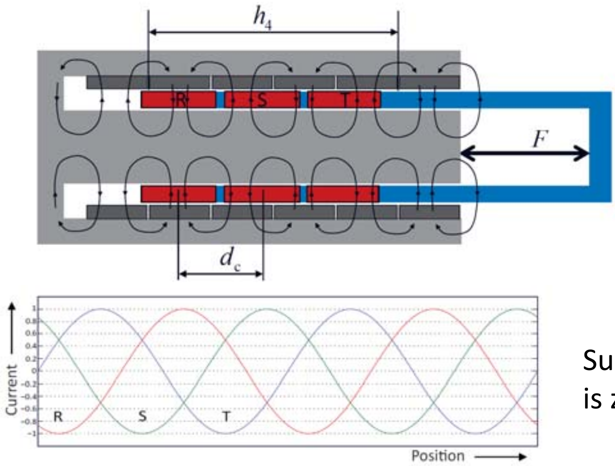
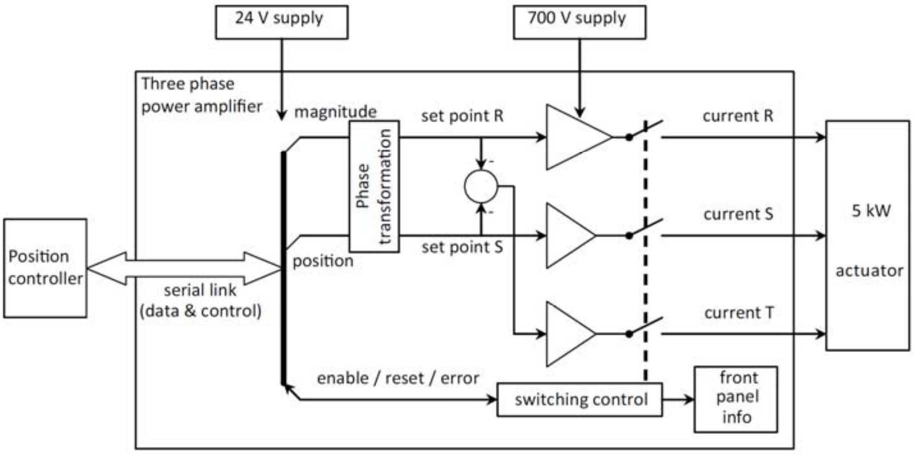
Three phase actuators need three currents



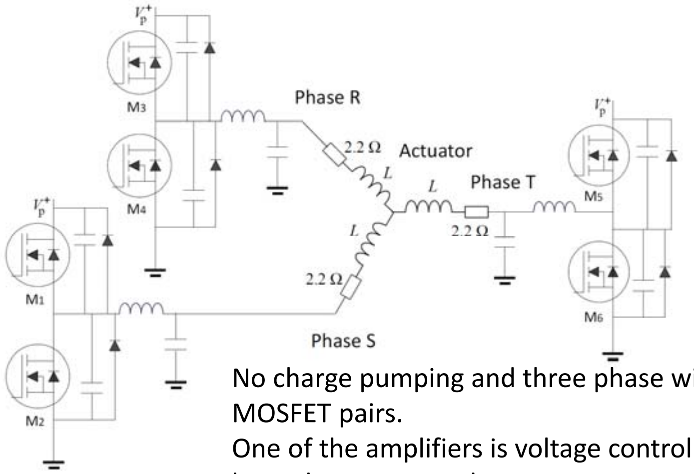
Sum of currents is zero!

Three phase amplifier concept



Question: What goes wrong when all three amplifiers have a current-source output

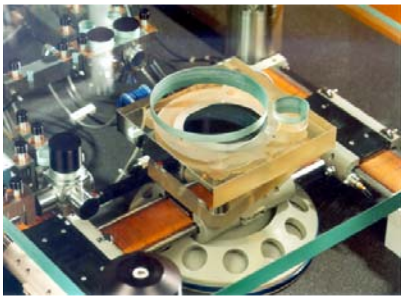
Three phase amplifier output stage.



No charge pumping and three phase with three MOSFET pairs.
One of the amplifiers is voltage controlled to keep the average voltage at zero.

Mechatronic system design

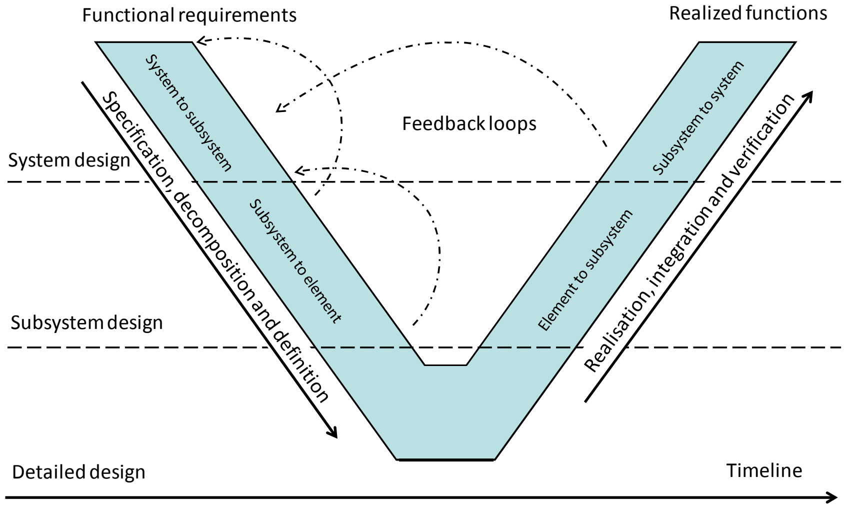
Mechatronic system design wb2414-2013/2014
Course part 7



How to connect?

Prof.ir. R.H.Munnig Schmidt
Mechatronic System Design

The V-model of Systems Engineering



Main items to keep in mind

- “Nesting”:
  - Lower parts are nested inside higher parts in the V model
  - Many nested control systems (amplifier, current, motion)
  - All influence eachother in two directions
- Mechanical dynamics determine the final performance
  - Bandwidth limited by eigenmodes
- Power Amplifier and actuator are one
  - Control force to real force
  - Optimal tuning in dynamics and electrical properties
- Motion Control is both the connecting lead as the polishing layer
  - Model based feedforward to almost perfection
  - All physical systems (plant=AD/DA, amplifier, actuator, mechanics, sensor) to be included in model
  - Feedback for robustness (to be minimised by feedforward)