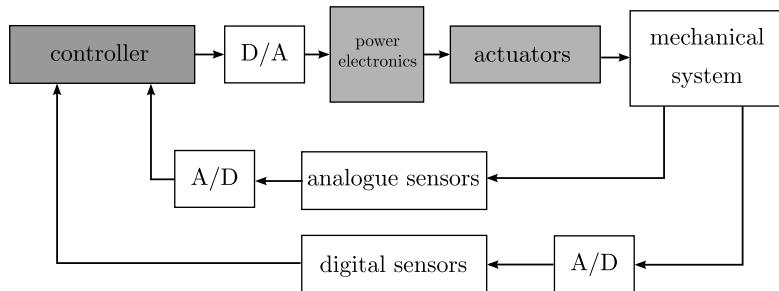


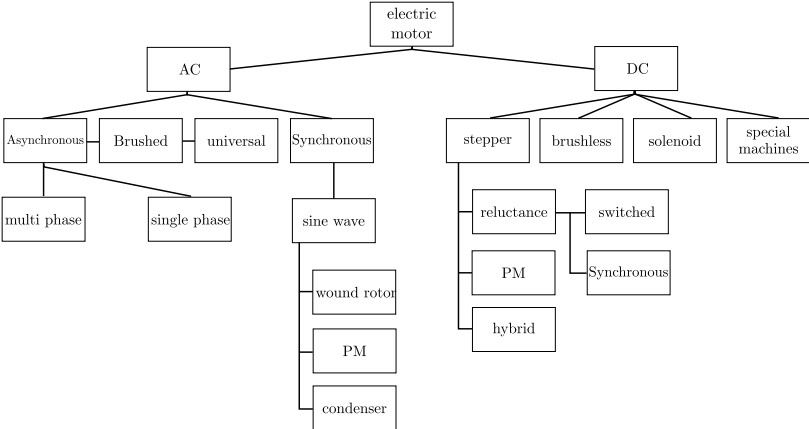
METE 3100U
Actuators and Power Electronics

Lecture 21
Final Examination Review

Mechatronics control loop



Electric motors



Brushed DC motors

Advantages:

- Linear speed-torque curve
- Medium speed operation 1k-5k rpm
- High starting torque
- Operation on DC voltage
- Life 2,000+ hours

Limitations:

- Brushes require maintenance
- Medium noise due to brushes
- Electrical noise
- High stall current
- Efficiency 60%-75%



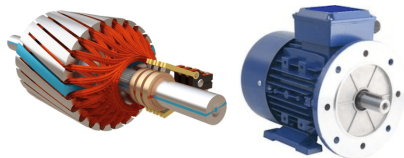
Induction motors

Advantages:

- Maintain speed over a range of torque
- Life 20,000+ hours
- Efficiency 60%-90%
- Suitable for speed control
- Quiet operation

Limitations:

- Fixed speed without control
- Low starting torque
- Not suitable for portable application
- High cost per watt



Synchronous motors

Advantages:

- Maintain speed over a range of torque
- Power varies linearly with voltage
- Runs at synchronous speed
- Suitable for speed control
- High efficiency

Limitations:

- Require AC and DC excitation
- Collector rings need maintenance
- Starting torque is zero
- More expensive than induction



Brushless DC motors

Advantages:

- Variable speed operation
- Medium speed operation 1k-5k rpm
- Efficiency 70%-95%
- High starting torque
- Life 20,000+ hours

Limitations:

- non-linear speed-torque curve
- Requires control to operate
- High stall current



Stepper motors

Advantages:

- Needs no feedback
- Excellent low speed torque
- Excellent repeatability
- High starting torque
- Cannot be damaged by overload

Limitations:

- Low efficiency
- Torque drops rapidly with speed
- No feedback for missed step
- Low output power/size or weight



Servo motors

Advantages:

- Low cost
- Simple to control
- Easy integration with μ controllers
- No power unit required
- Active feedback control

Limitations:

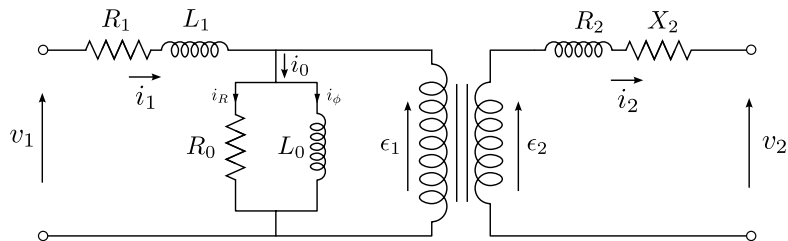
- Limited range of motion
- Moderate precision
- No feedback available



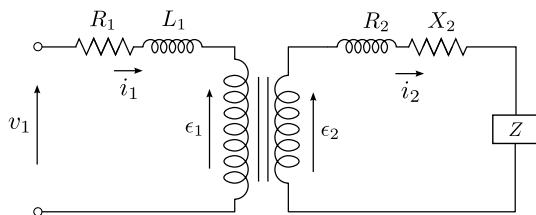
Part 1

Power Electronics

Transformers

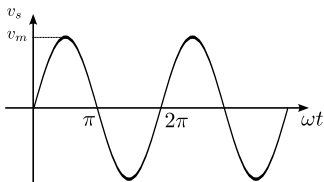
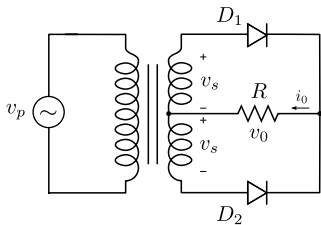


If the transformer is loaded, then $i_1 \gg i_0$:



Single phase full wave rectifiers

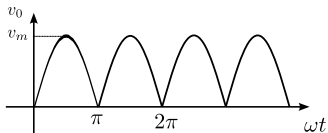
Centre-tapper transformer rectifier: An additional wire is connected across the middle of the secondary winding of a transformer



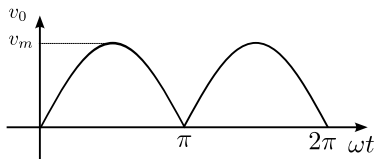
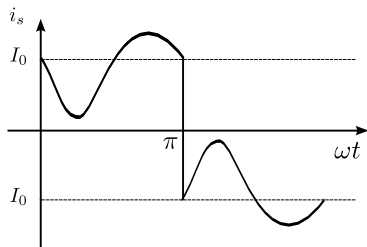
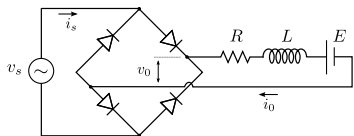
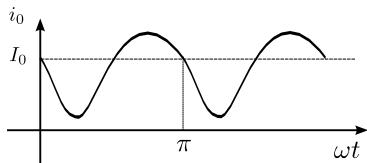
The root mean square (rms) voltage is

$$V_0 = \sqrt{\frac{2}{T} \int_0^{\frac{T}{2}} [v_s \sin(\omega t)]^2 d\omega t}$$

$$V_0 = \frac{V_m}{\sqrt{2}} = 0.707 v_s$$



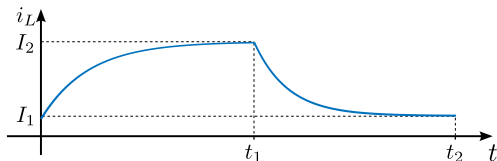
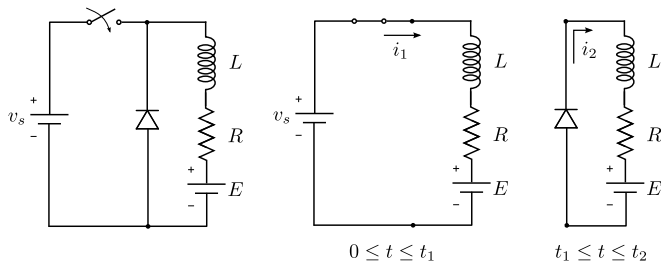
Bridge rectifiers



DC/DC step-down converters

Switch is closed from $0 \leq t \leq t_1$: Current i_1 rises

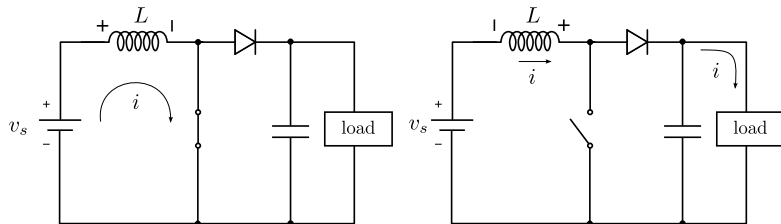
Switch is opened ($t = t_2$): Current i_2 decays



DC/DC step-up converters

Switch is closed: Energy is stored in the inductor

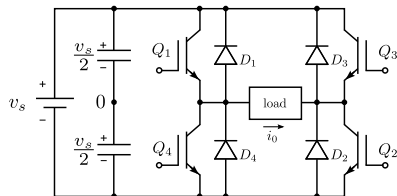
Switch is opened: Sudden drop in current causes the inductor to produce a back *emf* in the opposite polarity to the voltage across it.



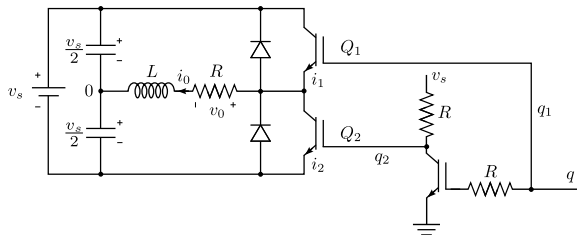
The voltage across the load becomes $v_s + v_L$

DC to AC converters (inverters)

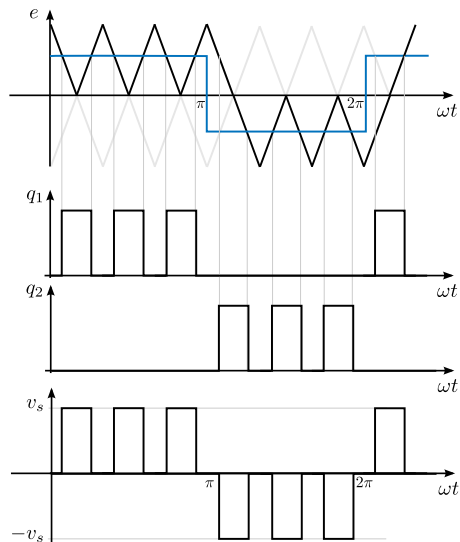
Inverters using full-bridges



Inverters using H-bridges



Multiple pulse width modulation

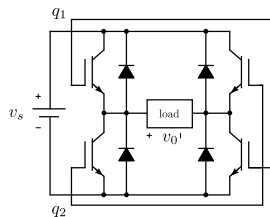


q_1 : Signal fed to Q_1 and Q_3

q_2 : Signal fed to Q_2 and Q_4

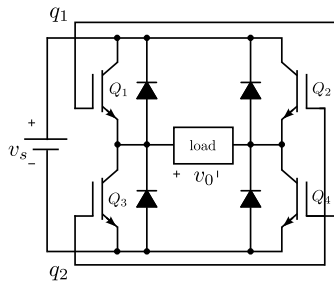
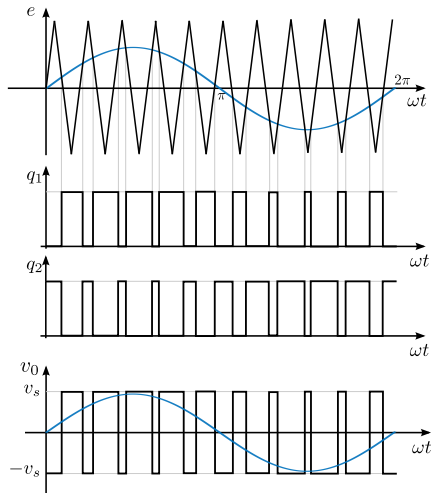
The instantaneous voltage is

$$v_0 = v_s(q_1 - q_2)$$



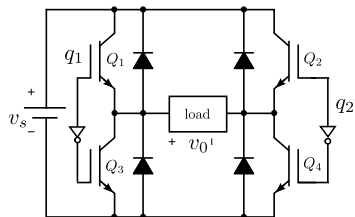
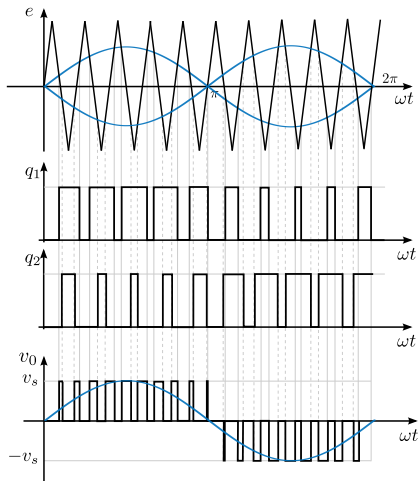
Bipolar sinusoidal pulse width modulation

The upper and lower switches in the same leg work in a complementary manner.



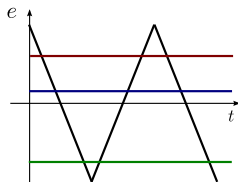
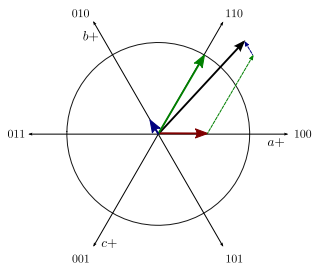
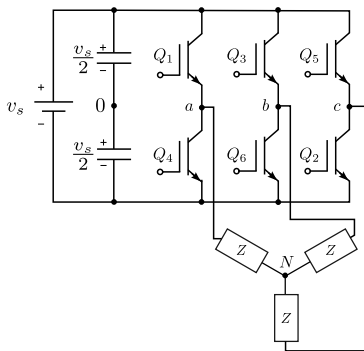
Unipolar sinusoidal pulse width modulation

Two modulated waves 180° out of phase are compared to the carrier signal.



3-phase inverters

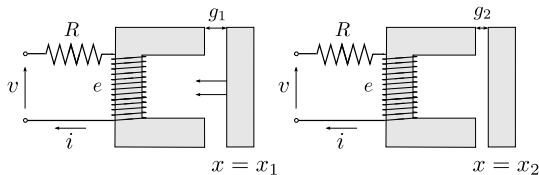
The 3 arms are delayed by 120° to generate a three-phase AC supply.



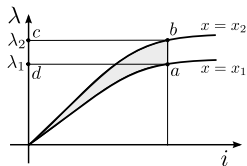
Part 2

Actuators

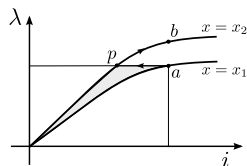
Electromechanical energy conversion



$$W_f = \left(\int H_c dB \right) V_c + \left(\frac{B^2}{2} \frac{1}{\mu_0} \right) V_g$$

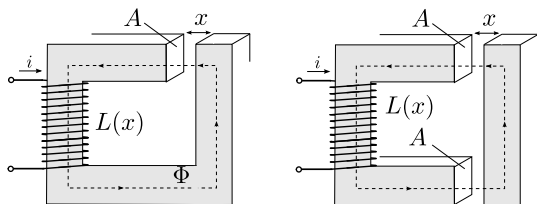


$$f_m = \left. \frac{\partial W_f(\lambda, x)}{\partial x} \right|_{\lambda=cte}$$



$$f_m = \left. \frac{\partial W'_f(i, x)}{\partial x} \right|_{i=cte}$$

Electromechanical energy conversion



The force between both sides of the air gap is

$$f_m = \frac{B^2}{2\mu} A$$

A is the area of the gap. Thus, the force per unit area of air gap

$$F_m = \frac{B^2}{2\mu}$$

is called the magnetic pressure (N/m^2).

Rotating machines

The field energy is

$$W_f = L_s \int_0^{i_s} i_s di_s + L_r \int_0^{i_r} i_r di_r + L_m \int_0^{i_s} di_s \int_0^{i_r} di_r$$

$$W_f = \frac{1}{2} L_s i_s^2 + \frac{1}{2} L_r i_r^2 + L_m i_s i_r$$

Recall that

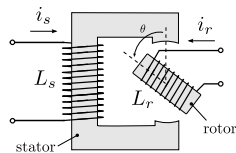
$$L(\theta) = \frac{N^2}{\mathcal{R}(\theta)}$$

Thus, the torque developed in the actuator is

$$T(\theta, i) = \left. \frac{\partial W_f'(i, \theta)}{\partial \theta} \right|_{i=\text{cte}}$$

and it can be calculated as

$$T(\theta, i) = \frac{1}{2} i_s^2 \frac{dL_s}{d\theta} + \frac{1}{2} i_r^2 \frac{dL_r}{d\theta} + i_s i_r \frac{dL_m}{d\theta}$$



Bipolar stepper motor

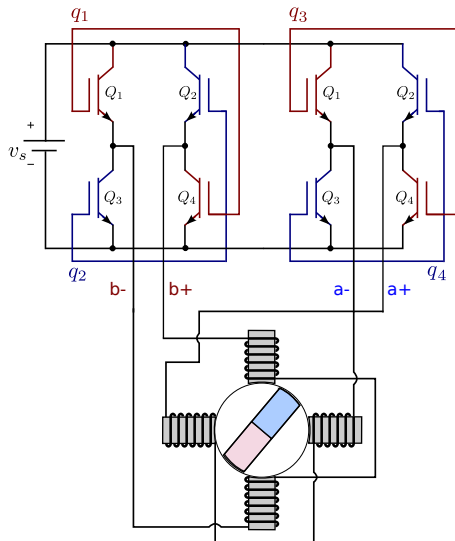
2 H-bridges can be used to power the motor

Voltage in Phase B

q_1	q_2	phase B
0	0	
0	1	
1	0	
1	1	not used

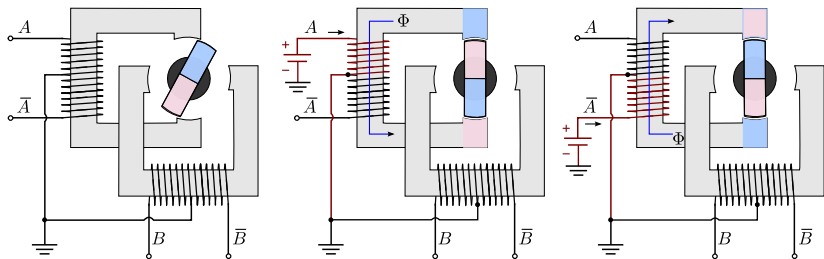
Voltage in phase A

q_3	q_4	phase A
0	0	
0	1	
1	0	
1	1	not used



Unipolar stepper motor

The unipolar motor operates with one winding with a center tap per phase.
A different winding section is switched on for each direction of Φ .



Full-step commutation sequence:

→ Counter-clockwise: $A \rightarrow B \rightarrow \bar{A} \rightarrow \bar{B}$

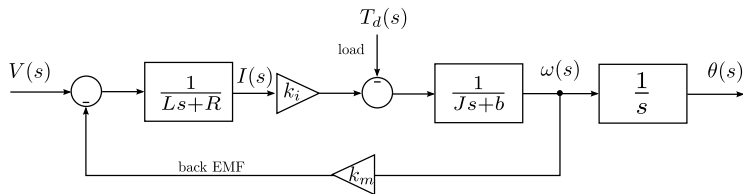
→ Clockwise: $A \rightarrow \bar{B} \rightarrow \bar{A} \rightarrow B$

What happens if A and \bar{A} are activated at the same time?

DC motors

$$V(s) = (R + Ls)I(s) + \omega(s)k_m \rightarrow I(s) = \frac{V(s) - \omega(s)k_m}{Ls + R}$$

$$T(s) = (Js + b)\omega(s) + T_d(s) \rightarrow \omega(s) = \frac{I(s)k_i - T_d(s)}{Js + b}$$

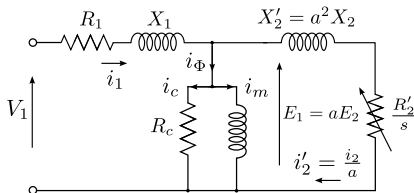
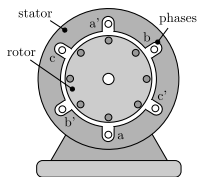


If the motor is driven at a constant voltage $V(t) = V$, the steady state speed and torque satisfy

$$\omega = \frac{k_i V - RT_d}{k_i k_m + Rb},$$

$$T = \frac{k_i (Vb + k_m T_d)}{k_m k_i + Rb}$$

Induction motors



$$s = \frac{n_s - n}{n_s}$$

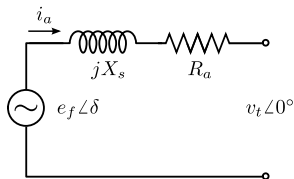
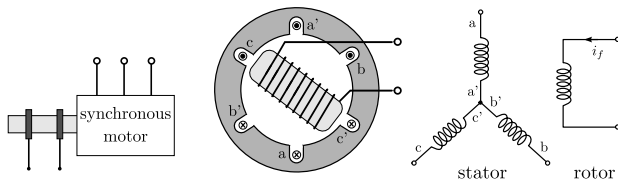
The electrical frequency in the winding is

$$f_1 = \frac{p}{120} (n_s - n) = \frac{p}{120} s n_s = s f$$

The torque is

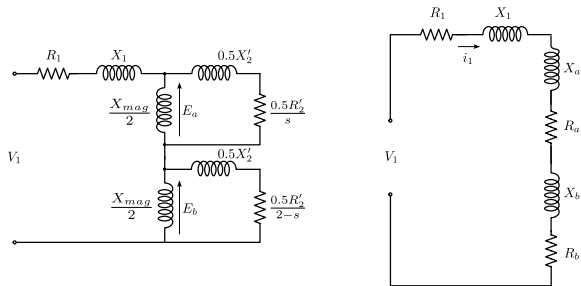
$$T = \frac{1}{\omega} \left[i_2'^2 \frac{R_2}{s} (1 - s) \right] = \frac{1}{\omega_s} \left[i_2'^2 \frac{R_2}{s} \right]$$

Synchronous motors



$$P = \frac{|v_t||e_f|}{|Z_s|} \cos(\theta - \delta) - \frac{|v_t|^2}{|Z_s|} \cos \theta$$

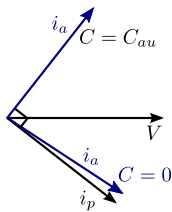
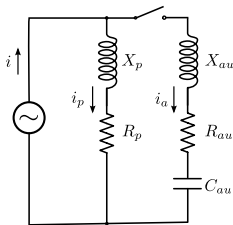
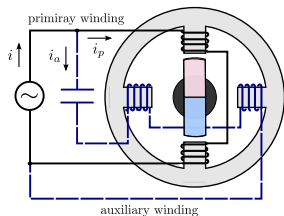
Single phase induction motors



$$Z_a = R_a + jX_a = \frac{j0.5X_{mag} \left(j0.5X_2' + 0.5\frac{R_2'}{s} \right)}{\left(0.5\frac{R_2'}{s} \right) + j0.5(X_{mag} + X_2')} \quad (1)$$

$$T = T_a - T_b = \frac{i_1^2}{\omega_{syn}} (R_a - R_b) \quad (2)$$

Starting of single phase motors



- An auxiliary winding is displaced 90° from the primary winding
- The capacitor is connected in series to shift the current
- C_{au} is chosen such that i_a and i_p are 90° out of phase

Research opportunities

Students interested in part/full time research in mechatronics with applications to biomedical robotics:



www.biomechatronics.ca

- Summer research internships
- Capstone design projects
- MSc/PhD positions

The End