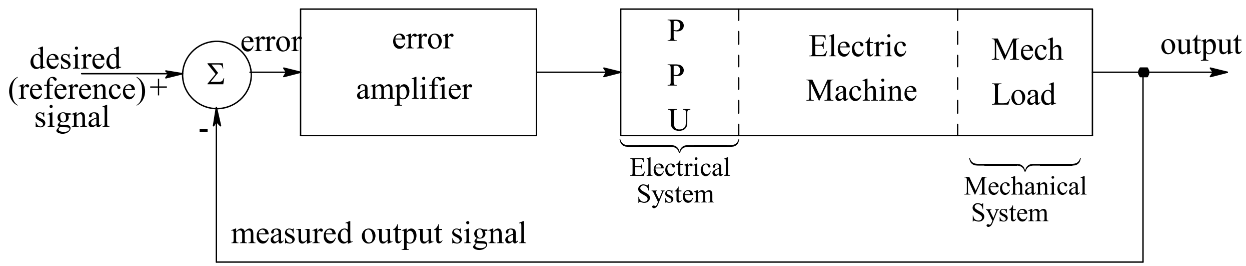
Chapter 13

DESIGNING FEEDBACK CONTROLLERS FOR MOTOR DRIVES

Feedback Control Objectives



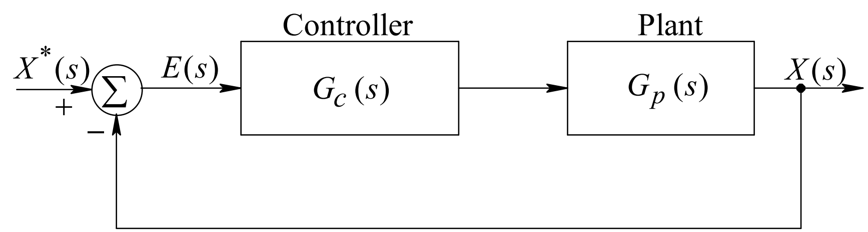
- ❑ Feedback control
  - ◆ makes system insensitive to disturbances and parameter variation

○ Control Objectives

_ Zero steady-state error

_ Good dynamic response

- fast
- small overshoot



Definitions

- Open loop

  $$G_{OL}(s) = G_c(s)G_p(s)$$

- Closed loop

  $$G_{CL}(s) = G_{OL}(s)/(1 + G_{OL}(s))$$

- Crossover frequency

  $$f_c, \omega_c$$

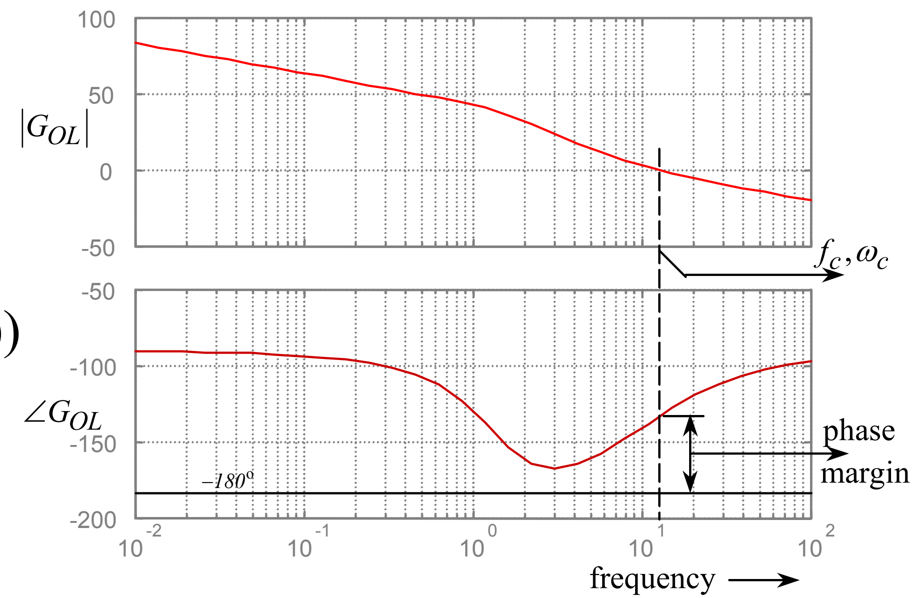
- Gain Margin
- Phase Margin

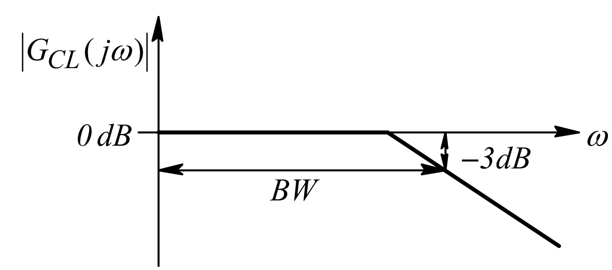
  $> 45^o$ for no oscillations

  60^o preferable

- Closed loop bandwidth □ f_c

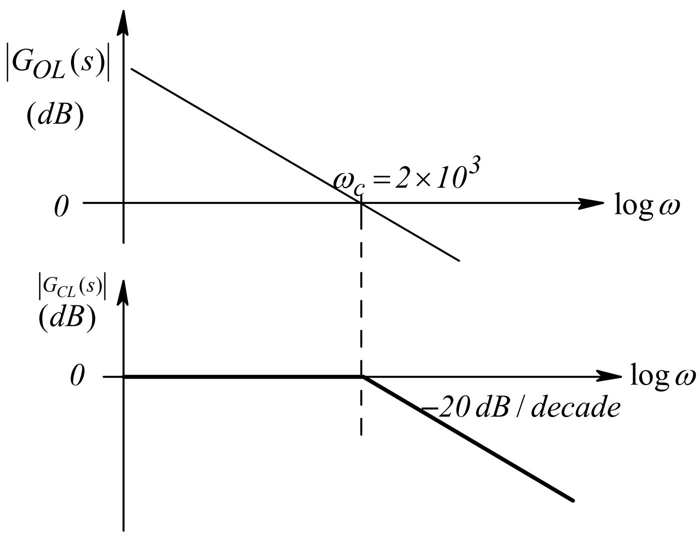
  desired high for fast response

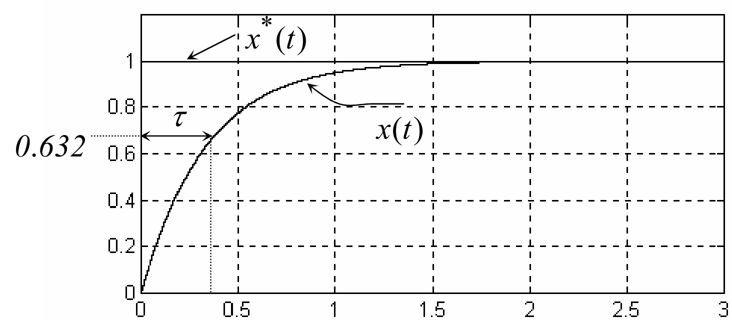




Example

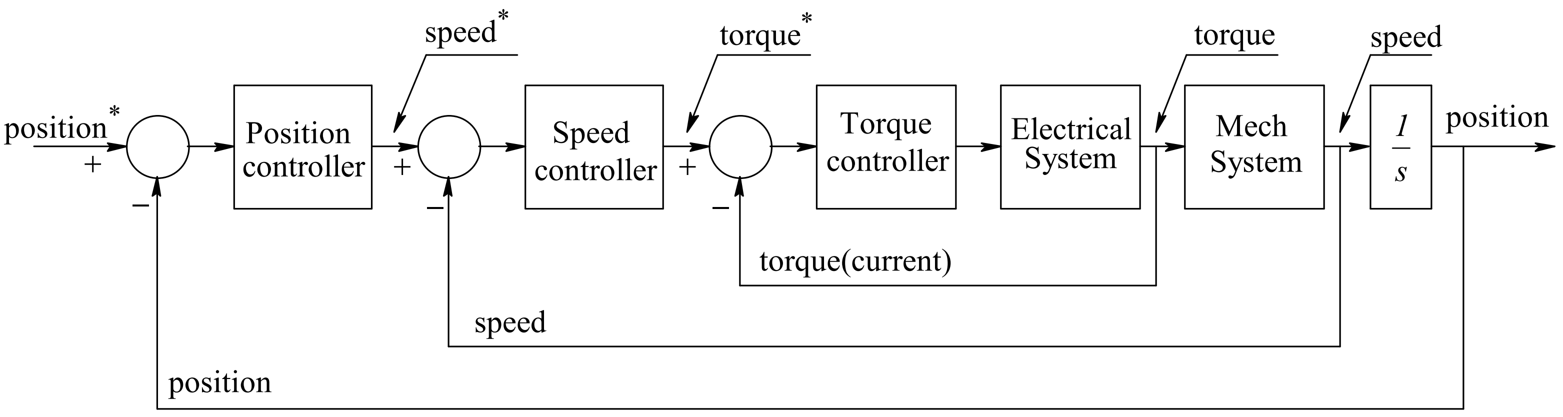
$$G_{OL}(s) = K_{OL}/s \quad ; K_{OL} = 2\times 10^3$$





closed loop step response

Cascaded Control



- Torque loop : fastest
- Speed loop : slower
- Position loop : slowest

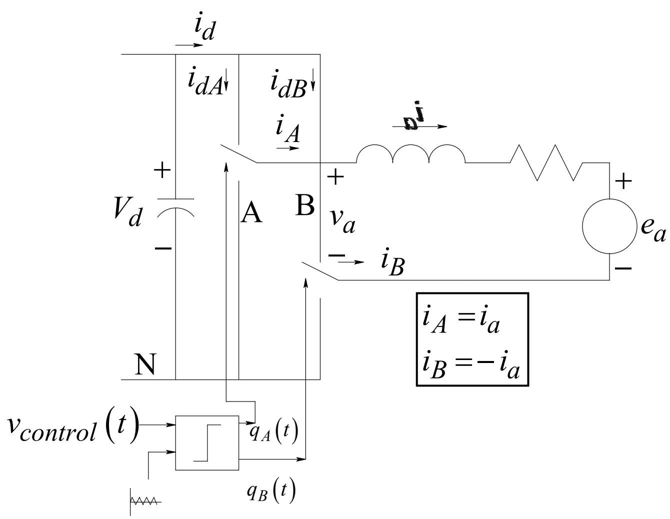
Steps in Designing the Controller

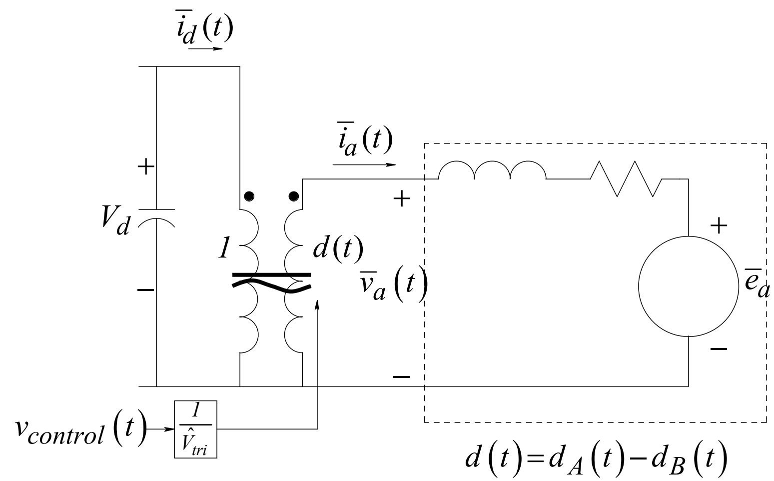
- ❑ Assume system is linear about the steady state operating point ➞ design controller using Linear Control Theory
- ❑ Simulate design under large signal conditions and “tweak” controller as necessary

System representation for small signal analysis

- ○ Assume
  - _ Steady state system operating point = 0
  - _ Highest bandwidth at least an order of magnitude lower than switching frequency neglect switching frequency components

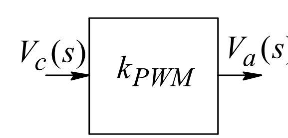
Averaged Representation of the PPU





$$\overline{v}_a(t) = k_{PWM} v_c(t)$$

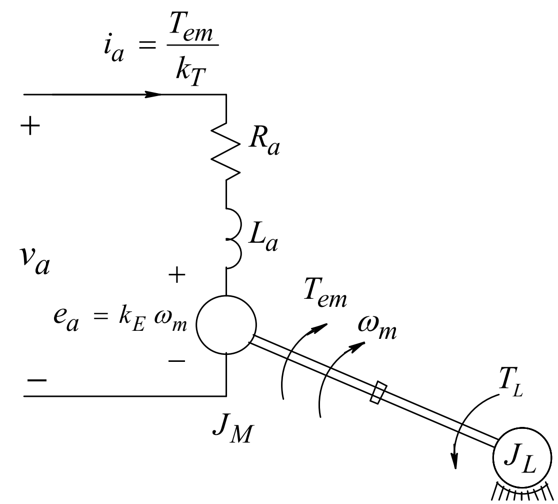
$$V_a(s) = k_{PWM} V_c(s)$$



Modeling of DC Machines and Mechanical Load Combinations

$$\overline{v}_a(t) = e_a(t) + R_a \overline{i}_a(t) + L_a \frac{d\,\overline{i}_a(t)}{dt}$$

$$e_a(t) = k_E\,\omega_m(t)$$

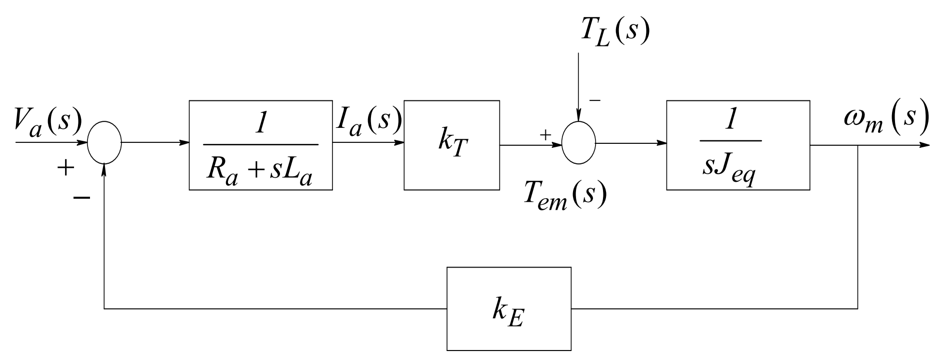


$$V_a(s) = E_a(s) + (R_a + s\,L_a)\,I_a(s)$$

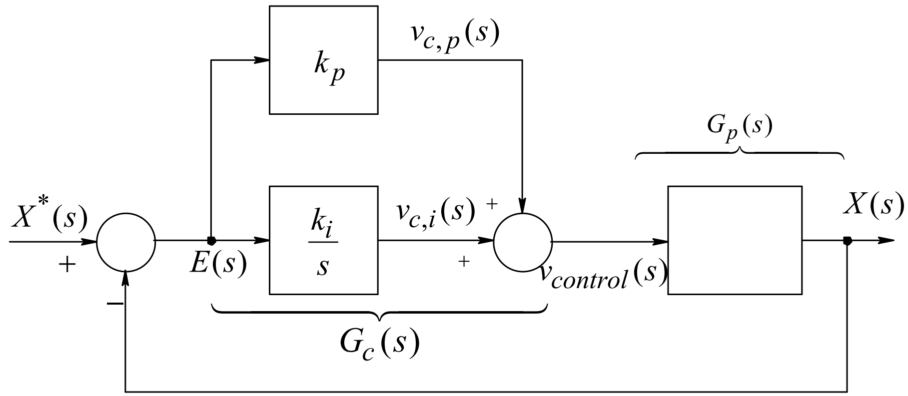
$$\Rightarrow I_a(s) = \frac{V_a(s) - E_a(s)}{(R_a + s\,L_a)} \quad ; \; E_a(s) = k_E\,\omega_m(s)$$

$$T_{em}(s) = k_T I_a(s)$$

$$\omega_m(s) = \frac{T_{em}(s)}{sJ_{eq}}$$



PI Controller



$$\frac{v_c(s)}{E(s)} = k_p + \frac{k_i}{s} = \frac{k_i}{s}\left(1 + \frac{s}{k_i / k_p}\right)$$

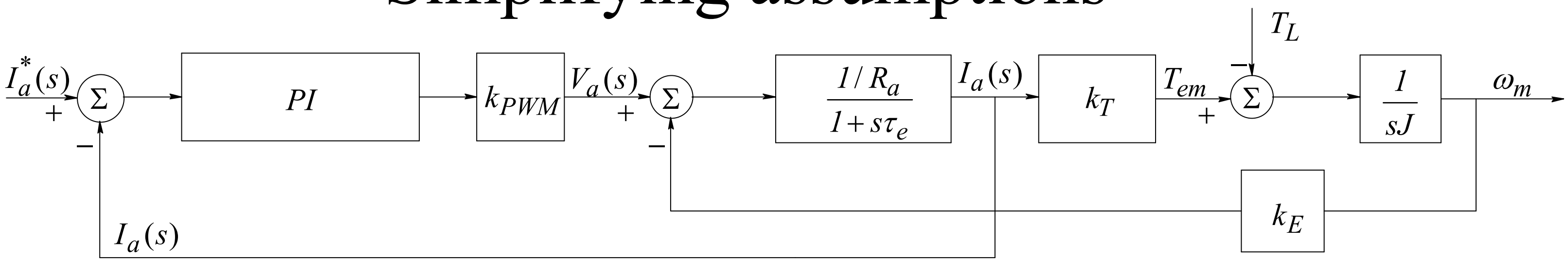
- Proportional-Integral (PI) Controller
  - In the torque and speed loops, proportional control without integral control input leads to steady-state error

Controller Design

- Procedure
  - Design torque loop (fastest) first
  - Design speed loop assuming torque loop to be ideal
  - Design position loop (slowest) assuming speed loop to be ideal

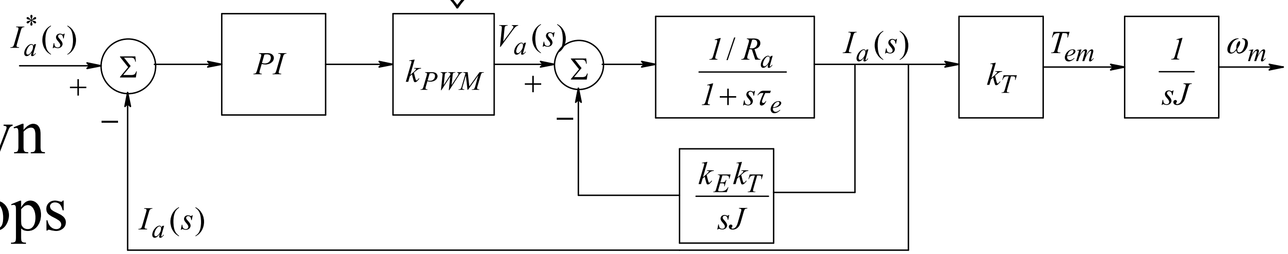
Design of the Torque (Current) Loop

Simplifying assumptions



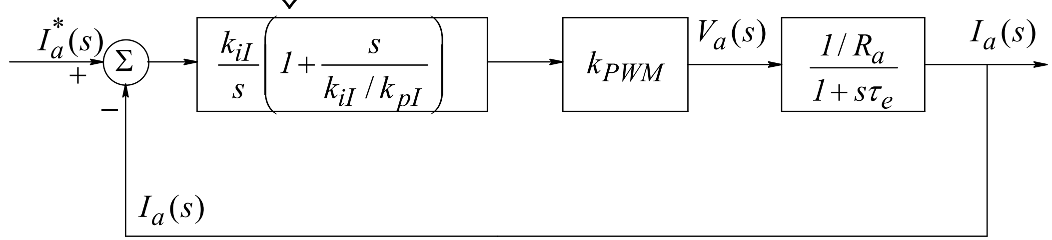
$\Downarrow$

- Interleaved loops redrawn as nested loops



$\Downarrow$

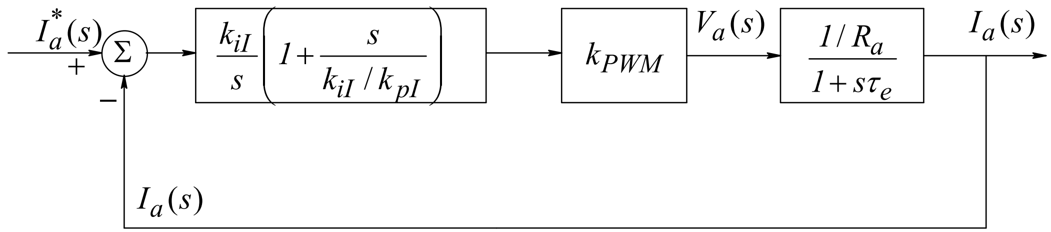
- Assuming J high enough, inner loop can be ignored



$$G_{I,OL}(s) = \underbrace{\frac{k_{iI}}{s}\left(1+\frac{s}{k_{iI}/k_p}\right)}_{PI\ controller} \underbrace{k_{PWM}}_{PPU} \frac{1/R_a}{\underbrace{1+s\tau_e}_{motor}}$$

Design of the Torque (Current) Loop

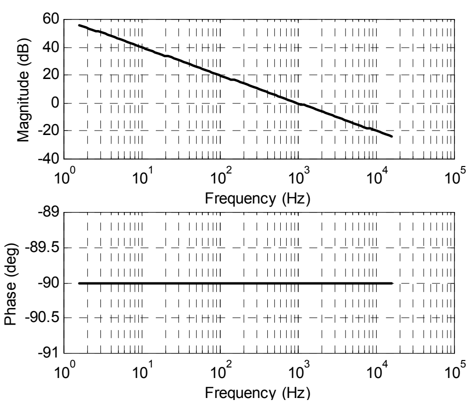
Selecting Parameters



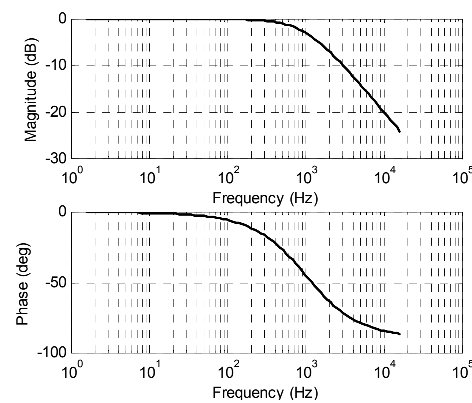
- Select zero of PI to cancel motor pole ; $\frac{k_{pI}}{k_{iI}}=\tau_e$

$$\Rightarrow G_{I,OL}=\frac{k_{I,OL}}{s}; \quad k_{i,OL}=\frac{k_{iI}\,k_{PWM}}{R_a}$$

- Choose k_{iI} to achieve desired cross-over frequency $k_{I,OL}=\omega_{CI}$

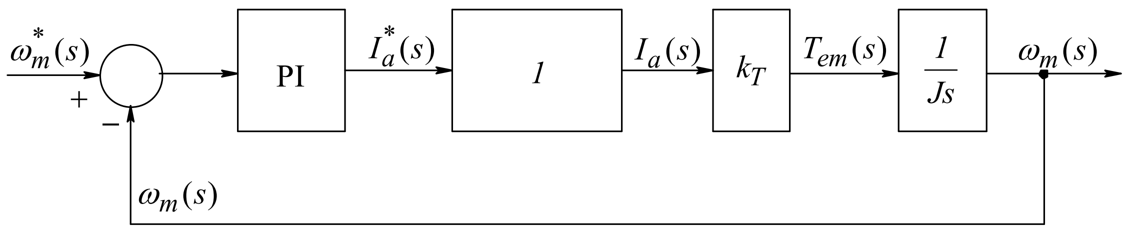


open loop



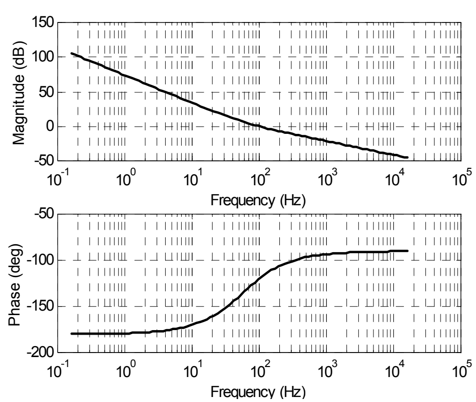
closed loop

Design of the Speed Loop

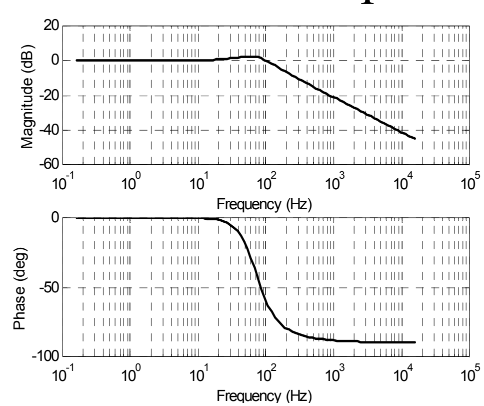


- Assume current loop to be ideal   represent by unity
- Choose crossover frequency $\omega_{C\omega}$ an order of magnitude lower than ω_{CI}
- Choose a reasonable phase margin $\phi_{PM,\omega}$

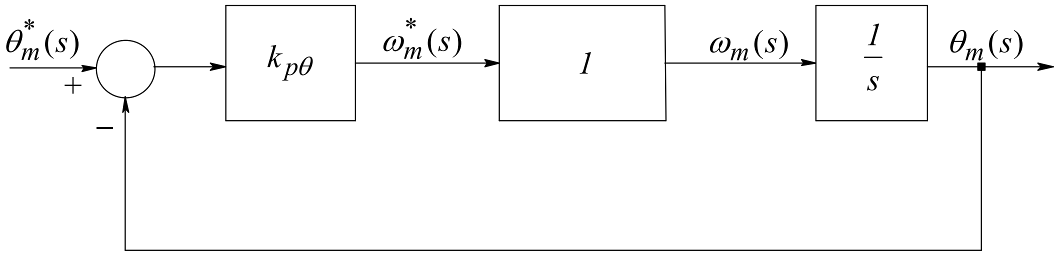
open loop



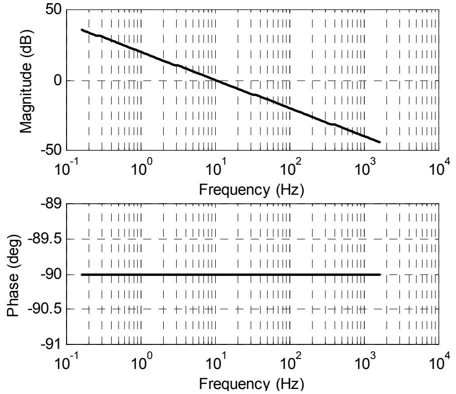
closed loop



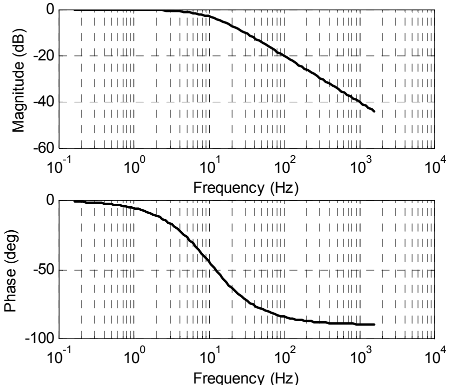
Design of the Position Loop



- Assume speed loop to be ideal
- Proportional gain ($k_{P\theta}$) alone is adequate due to presence of pure integrator $G_{\theta,OL} = \frac{k_{P\theta}}{s}$ $\Rightarrow k_{P\theta} = \omega_{CP}$



open loop



closed loop