Lecture 16 (24th Feb 2022)

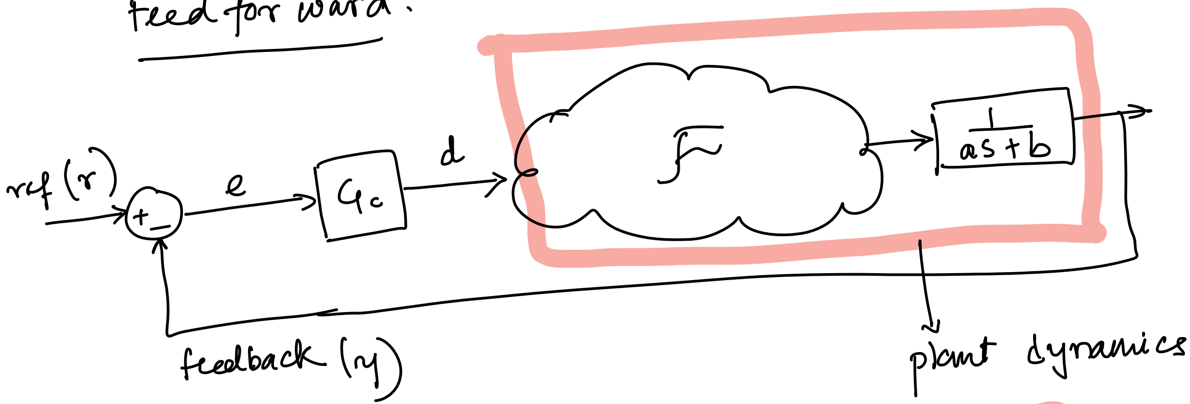
HW4 due today (now) - mail if you need extension

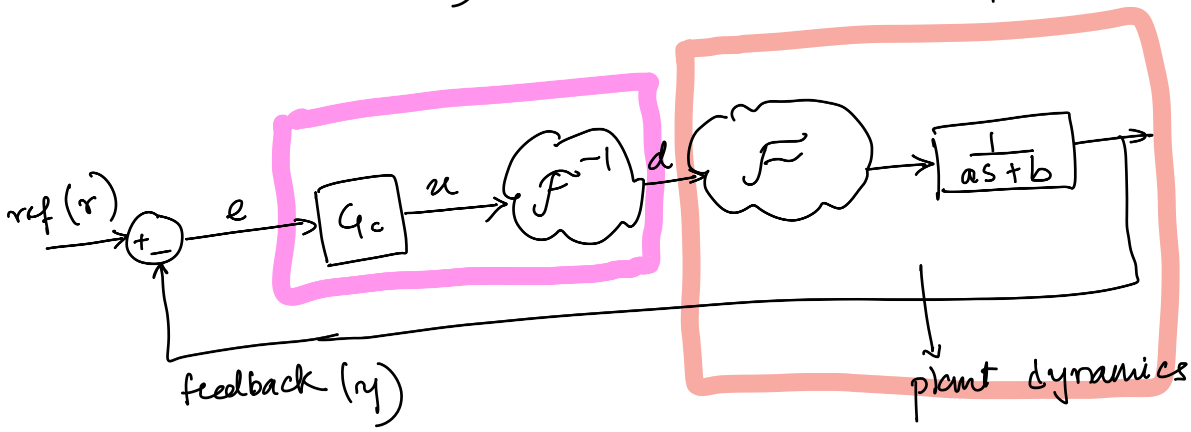
HW5 is out. due next thursday

Today's agenda

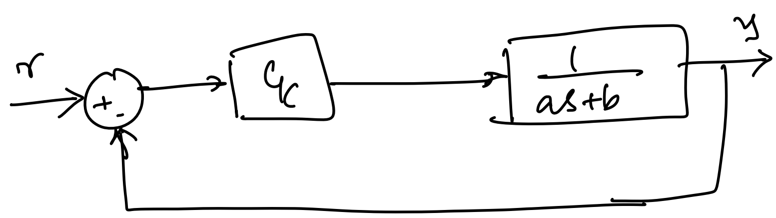
- feedforward
- Clear up some machine notation
- simulation of BLDC motor & current control
  - → verification of steps.

Feed forward.





$\Downarrow$



$$G_c = K_p + \frac{K_i}{s}$$

$l = \frac{\omega_g}{s} \longrightarrow$

1. perfect dc tracking
2. 90° PM
3. ω_g = bandwidth

$$l = G_c\left(\frac{1}{as+b}\right) \qquad G_c = l\cdot(as+b)$$

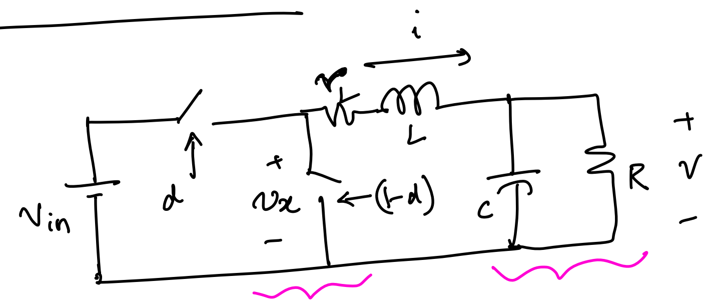
$$= \frac{\omega_g}{s}(as+b)$$

$$G_c = \omega_g a + \frac{\omega_g b}{s}$$

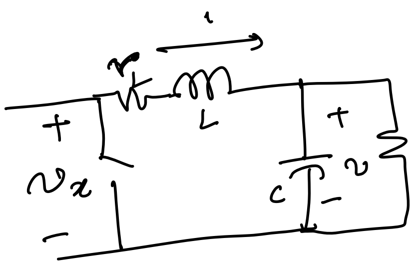
$$K_p + \frac{K_i}{s} = \omega_g a + \frac{\omega_g b}{s}$$

$$\boxed{\begin{aligned} \therefore\quad K_p &= \omega_g a \\ K_i &= \omega_g b \end{aligned}}$$

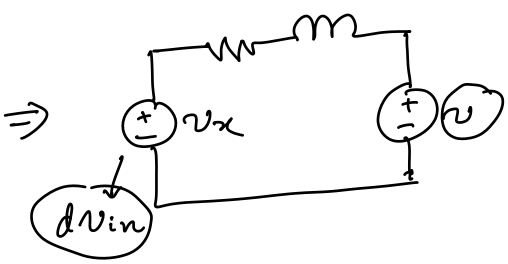
Buck converter



- objective: control current through inductor. (L, r_L)



$\Rightarrow$



$$\langle v_x \rangle = V_{in} \cdot d + 0 \cdot (1-d)$$

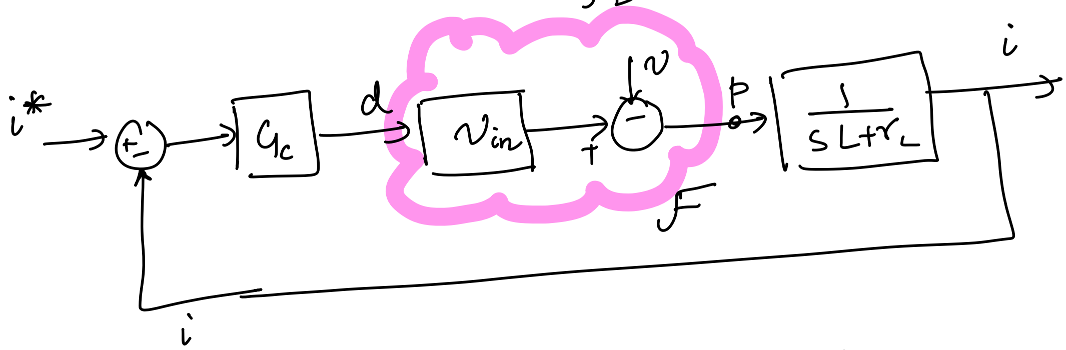
$$= dV_{in}.$$

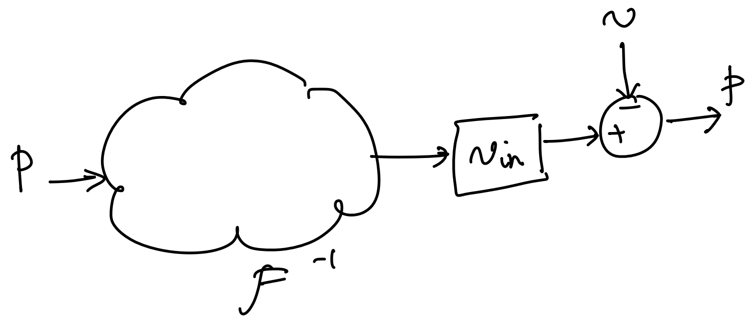
$$L\frac{di}{dt} + i r_L = v_x - v$$

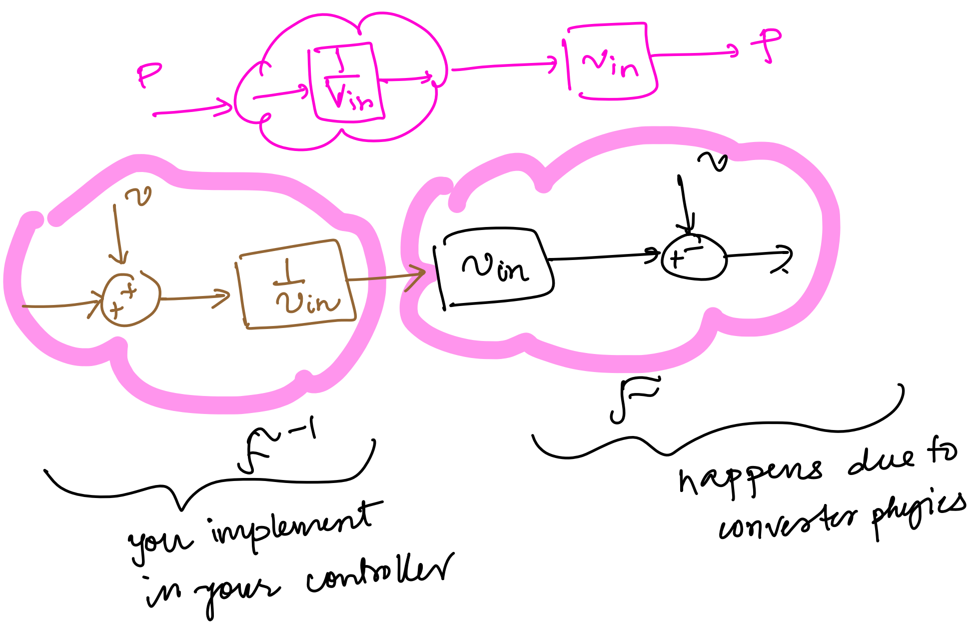
$$sL\, i(s) + r_L\, i(s) = v_x(s) - v(s)$$

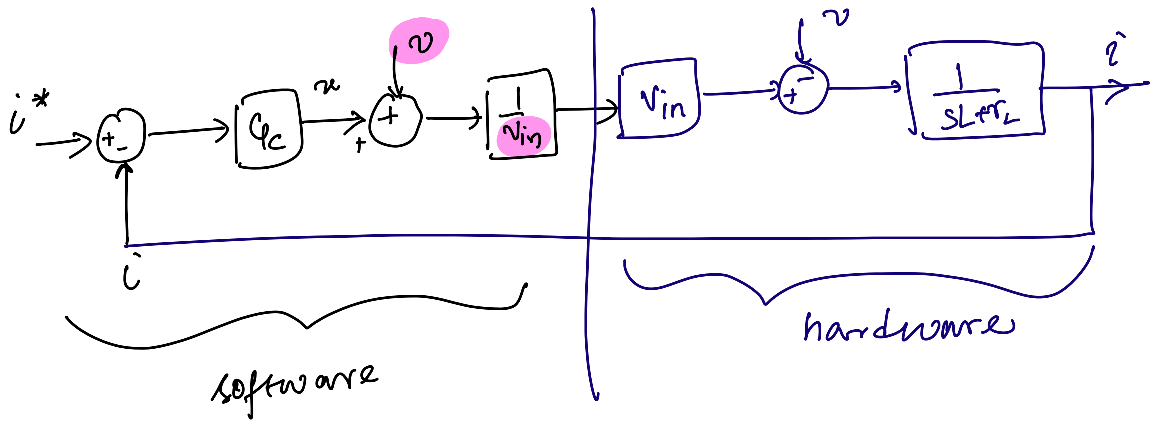
$$= d\, v_{in}(s) - v(s)$$

$$i(s) = \frac{d\, v_{in}(s) - v(s)}{sL + r_L}$$









disadvantage

: needs more sensors → $$

$$\boxed{\therefore \quad k_p = \omega_g a \qquad k_i = \omega_g b}$$

$$\left.\begin{aligned} k_p &= \omega_g L \\ k_i &= \omega_g r_L \end{aligned}\right\}$$ How do you determine r_L?

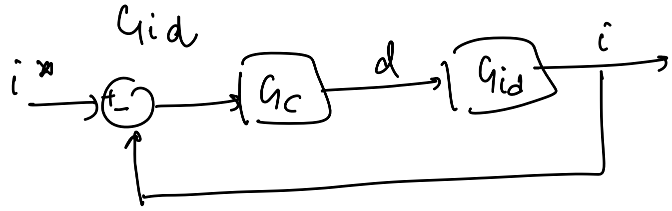
advantage

: control design becomes simpler

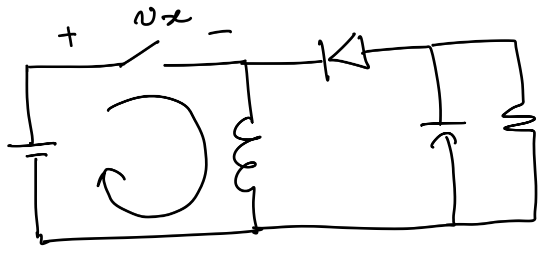
Conventional control:

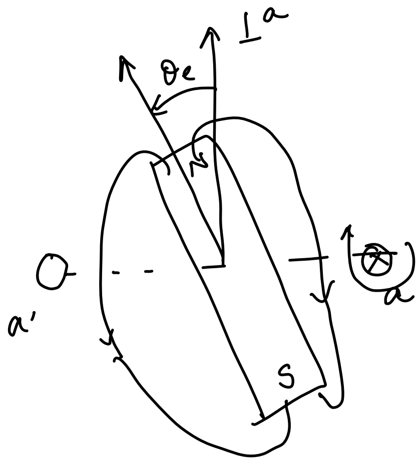
Lecture 1–5:

You derive <u>small signal model</u>



buck-boost

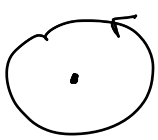


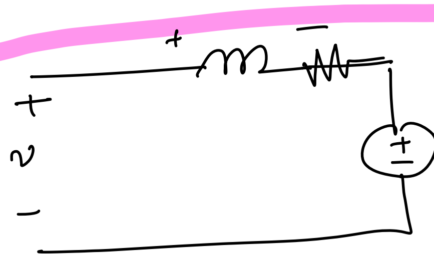


flux linkages
$$\begin{cases} \lambda_a = -\lambda_{pk}\cos\theta_e + Li_a \\ \lambda_b = -\lambda_{pk}\cos\left(\theta_e - \frac{2\pi}{3}\right) + Li_b \\ \lambda_c = -\lambda_{pk}\cos\left(\theta_e - \frac{4\pi}{3}\right) + Li_c \end{cases}$$

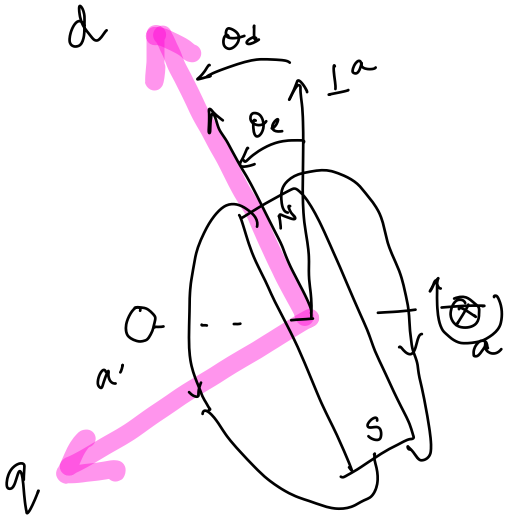
$$\text{back emf} = -\frac{\partial\lambda}{\partial t}$$

$$e_a = \text{back emf}_a = -\lambda_{pk}\,\omega_e \sin\theta_e - L\frac{di}{dt}$$

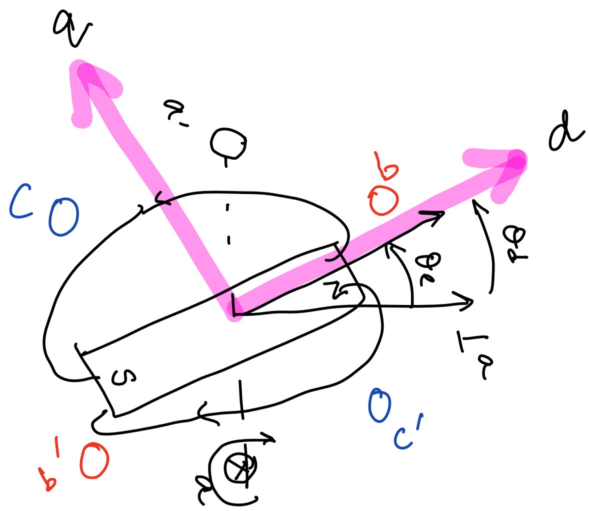


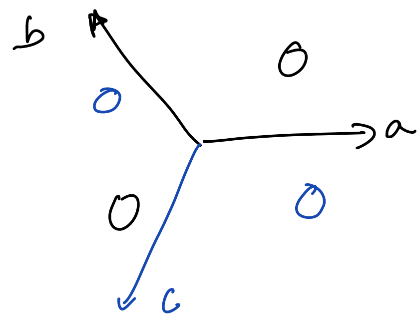


$$\mathcal{E}_a = \lambda_{pk}\,\omega_e \sin\theta_e$$

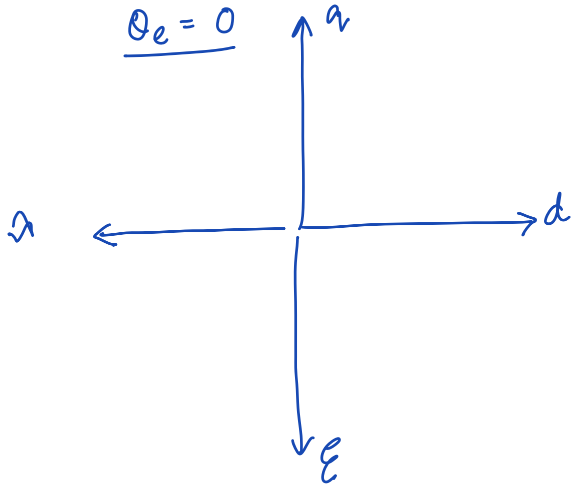


$$\boxed{\tau = -\lambda_{pk}\,\frac{3}{2}\,\frac{P}{2}\,i_q}$$

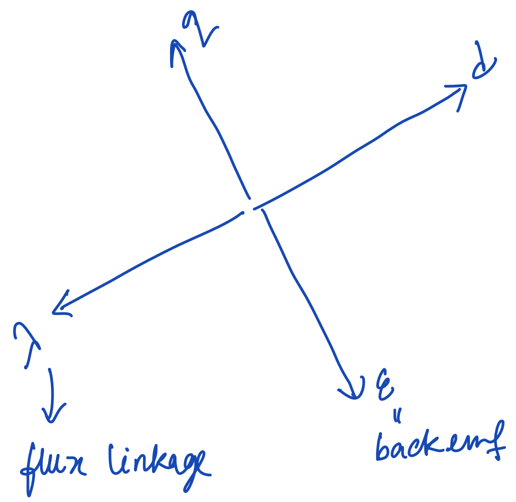




$\underline{\theta_e = 0}$



$\theta_e = 45^\circ = \theta_d$



$$J\frac{d\omega}{dt} + B\omega = T_e - T_m$$

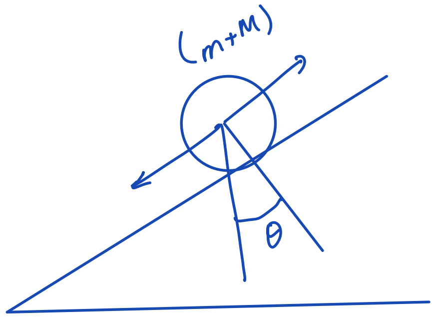
$$T_e = \frac{1}{\omega_m}\frac{3}{2}\left(\cancel{e_d}\, i_d + e_q i_q\right), \quad e_d = 0, \quad e_q = -\lambda_{pk}\cdot\omega_e$$

$$= -\frac{3}{2}\lambda_{pk}\frac{\omega_e i_q}{\omega_m}$$

$$= -\frac{3}{2}\lambda_{pk}\cdot\frac{P}{2} i_q .$$

5:35

Mechanical torque:-

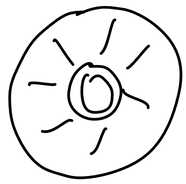


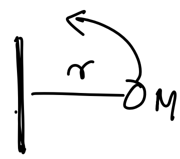
$$T_m = \omega_m \beta + (m+M) g r \sin\theta_g + \omega_m^3 \beta_{drag}$$

$$J\frac{d\omega_m}{dt} + B\omega_m = T_e - T_m \longrightarrow ?$$

$$T_e \rightarrow \left(-\frac{3}{2}\lambda_{pk}\frac{P}{2}\cdot i_q\right)$$

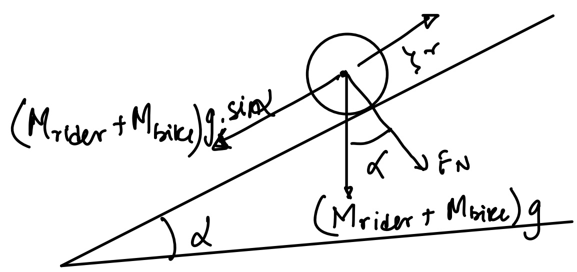
$B\omega_m \rightarrow$ shaft friction





$$J = M\cdot r^2$$

$J \rightarrow$ moment of inertia $= (M_{rider} + M_{bike})\cdot r^2$



$$T_m = \underbrace{\left[(M_{rider} + M_{bike})\cdot g.r.\sin\alpha\right]}_{\text{because of slope}} + \overset{\text{friction}}{f_{road}}\cdot\omega_m + \beta_{drag}\,\omega_m^2$$

ω_m = mechanical speed of bike

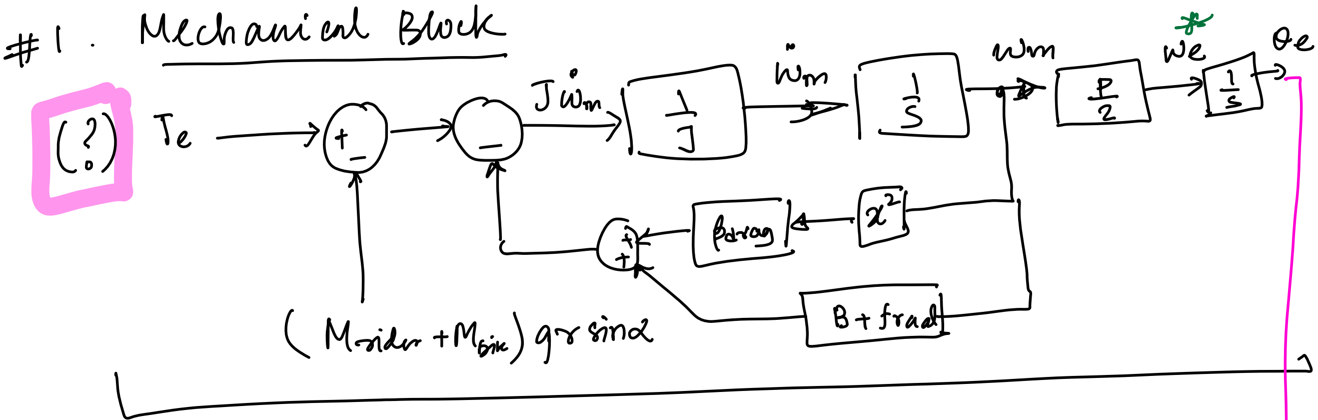
$$\theta_e = \frac{P}{2}\theta_m$$

$$\frac{P}{2}\omega_m = \omega_e$$

$$J\dot{\omega}_m + B\omega_m = T_e - \left\{\left[(M_{rider} + M_{bike})\cdot g.r.\sin\alpha\right] + f_{road}\cdot\omega_m + \beta_{drag}\,\omega_m^2\right\}$$

$$\underbrace{\underbrace{J\dot{\omega}_m + (B + f_{road})\,\omega_m + \beta_{drag}\,\omega_m^2} + \underbrace{[(M_{rider} + M_{bike})\,g r \sin\alpha]}}_{} = T_e$$

#1. Mechanical Block



#2. ABC to DQ

θ_e

a, b, c $\underbrace{\quad}_{ac}$

$$\frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}$$

d, q $\underbrace{\quad}_{dc}$

#3 DQ to ABC

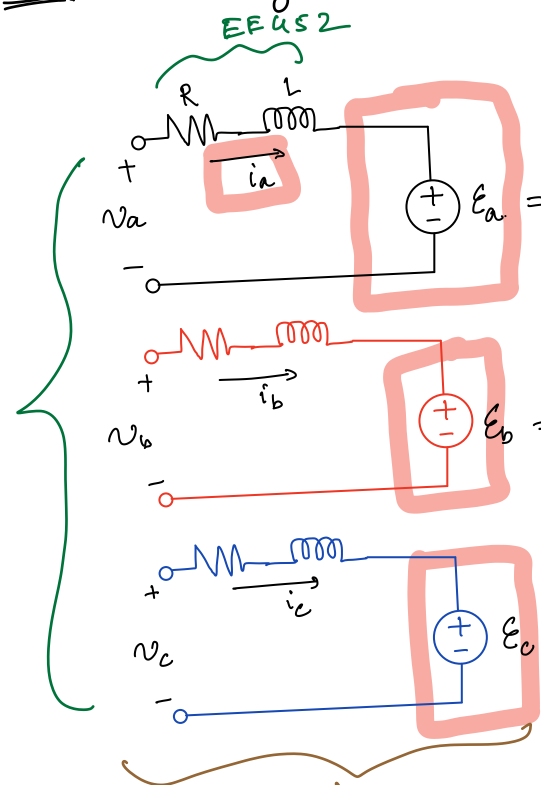
θ_e

d, q $\underbrace{\quad}_{dc}$

$$\begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{4\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}$$

a, b, c $\underbrace{\quad}_{abc}$

#4 voltage source model of machine

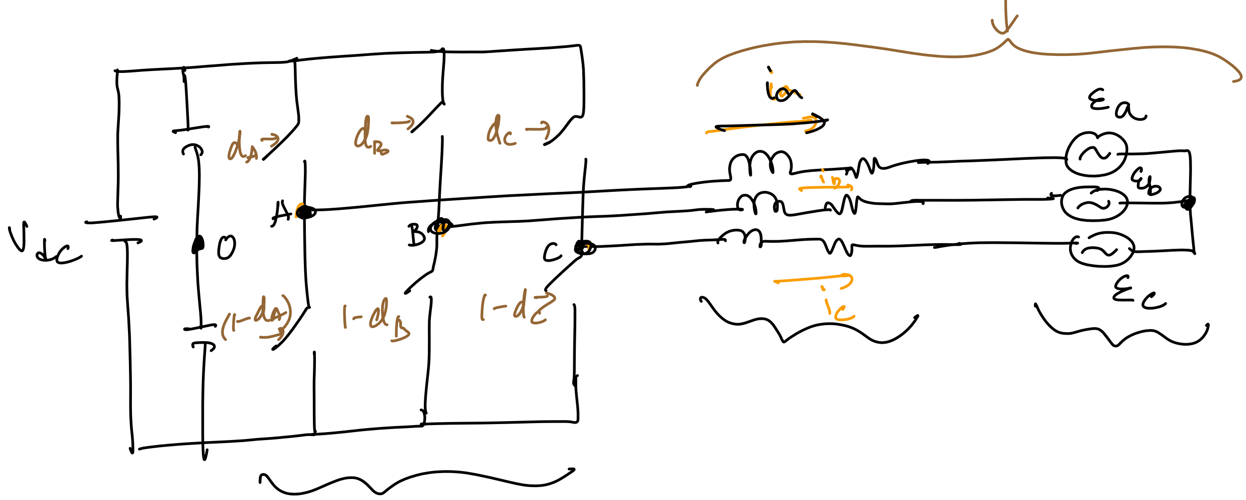


$$\mathcal{E}_a = \lambda_{pk}\,\omega_e^{*}\,\sin(\theta_e)$$

$$\mathcal{E}_b = \lambda_{pk}\,\omega_e^{*}\,\sin\left(\theta_e - \frac{2\pi}{3}\right)$$

$$\mathcal{E}_c = \underbrace{\lambda_{pk}}_{\text{back emf constant EE452}}\,\omega_e^{*}\,\sin\left(\theta_e - \frac{4\pi}{3}\right)$$

#5 Three phase voltage source inverter



#6 Modulation indices generation.

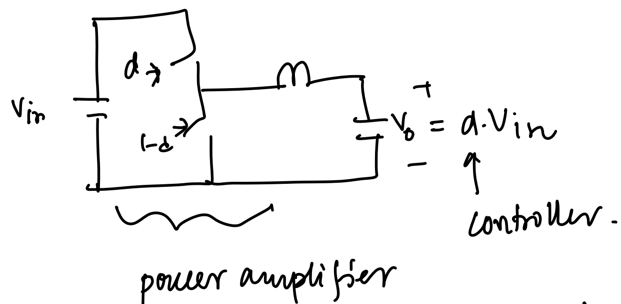
$$\langle v_{AO}\rangle_{T_s} = \boxed{\frac{m V_{dc}}{2}} \sin\omega t = m_a \cdot \frac{V_{dc}}{2}$$

$$\langle v_{BO}\rangle_{T_s} = \frac{m V_{dc}}{2} \sin\left(\omega t - \frac{2\pi}{3}\right) = m_b \cdot \frac{V_{DC}}{2}$$

$$\langle v_{CO}\rangle_{T_s} = \frac{m V_{dc}}{2} \sin\left(\omega t - \frac{4\pi}{3}\right) = m_c \cdot \frac{V_{DC}}{2}$$

$$-1 < m_a, m_b, m_c < 1$$

* Buck converter



It amplifies the controller output by Vin

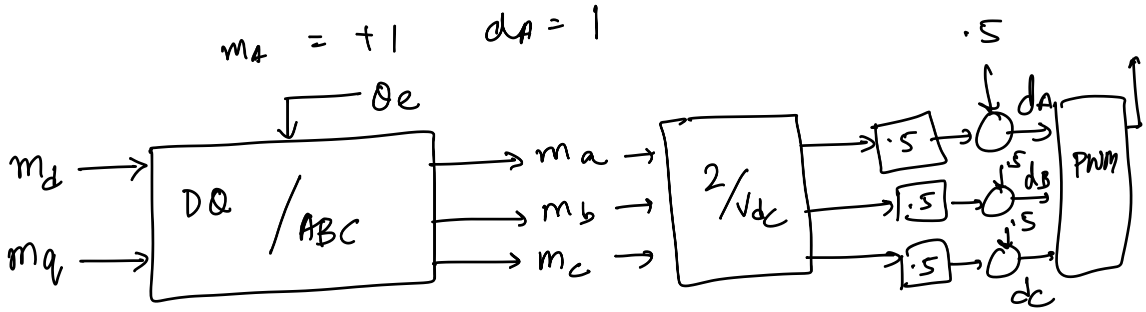
Similarly three phase inverter is like a power amplifier

$= \frac{V_{DC}}{2}$

$$\boxed{d_A = 0.5 + 0.5 \cdot m_A}$$

$m_A = -1 \quad d_A = 0$

$m_A = +1 \quad d_A = 1$

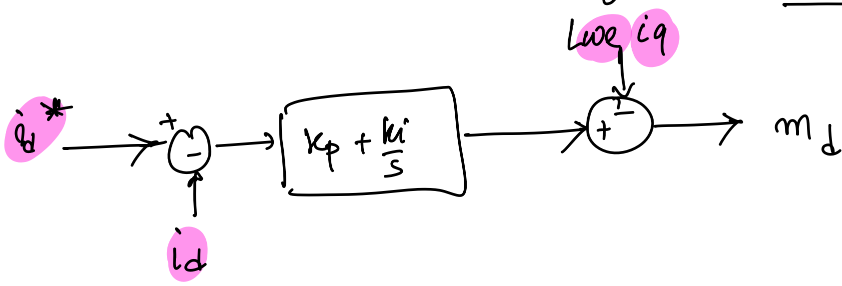


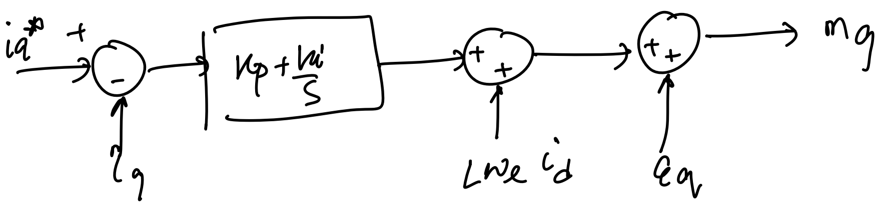
focus on A:-

$$\boxed{\frac{V_{dc}}{2}}\underbrace{m \sin\omega t}_{ma} = \underbrace{L\frac{di}{dt} + ir}_{} + \cancel{E_b}^{\,0}$$ by feedforward

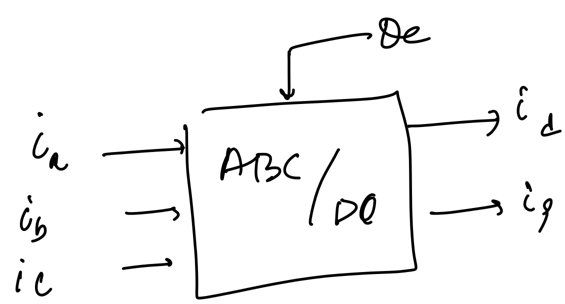
#7 Generation of m_d, m_q

controller outputs.





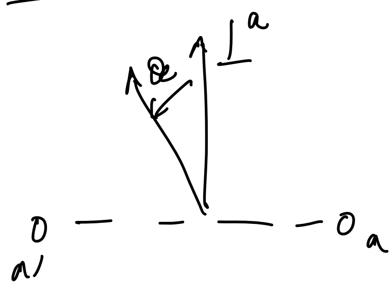
#8



#9 Link electrical side → mechanical side

$$T_e = \frac{3}{2}\lambda_{pk}\cdot\frac{P}{2}\cdot i_q.$$

Conclusion



if $\omega_e > 0$

θ_e is CCW

if $\omega_e < 0$

θ_e is CW.

$$P = \underline{\underline{\tau \cdot \omega_m}}$$

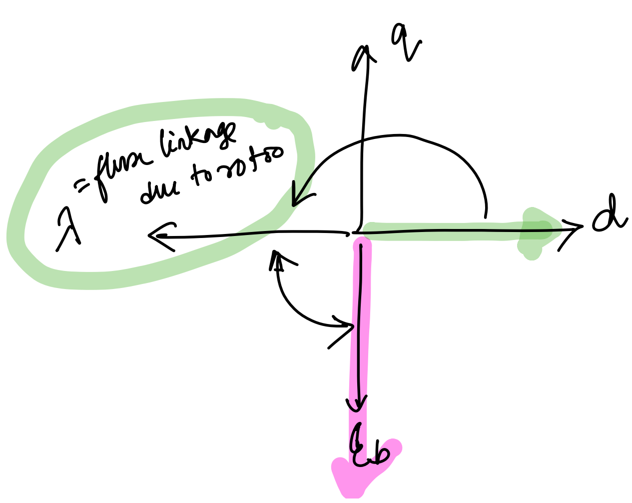
$$P = v_a i_a + v_b i_b + v_c i_c$$

$$= \frac{3}{2}(v_d i_d + v_q i_q)$$

$$\tau_e = \underbrace{-\frac{3}{2} \lambda_{pk} \frac{P}{2} i_q}$$

$$\underbrace{i_q^* < 0}$$

$$i_d^* = 0$$



flux weakening