IIT ROORKEE

NPTEL ONLINE CERTIFICATION COURSE

# Charging Infrastructure

## Lecture-29

## Closed loop control of three-phase AC-DC converter-IV


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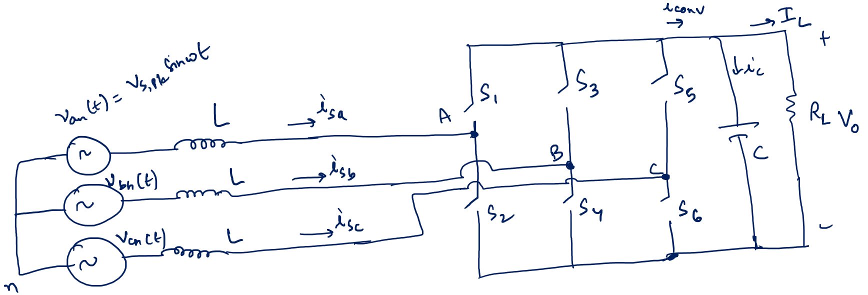
# Recap

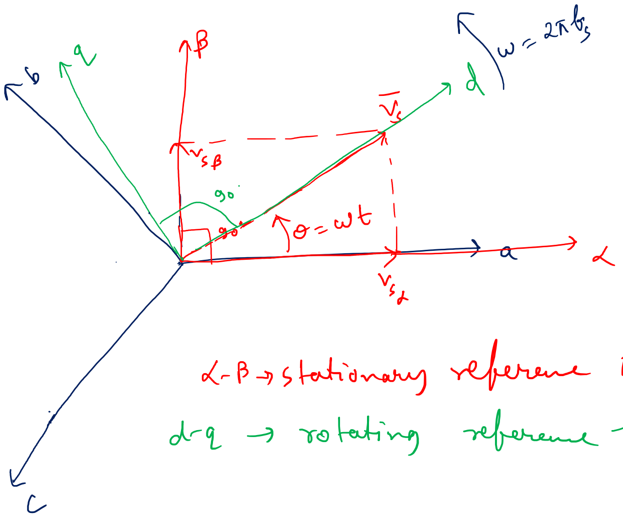
Control Objectives

① To regulate the output voltage to a desired value. $(> \sqrt{2}\, V_{L-L})$




② The current drawn should have unity power factor (upf) operation

# Recap




$\alpha$-$\beta$ → stationary reference frame

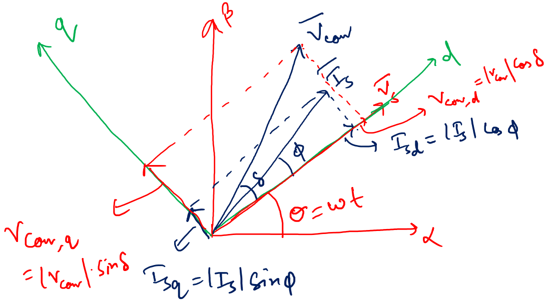
d-q → rotating reference frame

$i_{sa} + i_{sb} + i_{sc} = 0$

3ph → 2-phase → d-q
$\alpha$-$\beta$

$v_{sq} = 0$

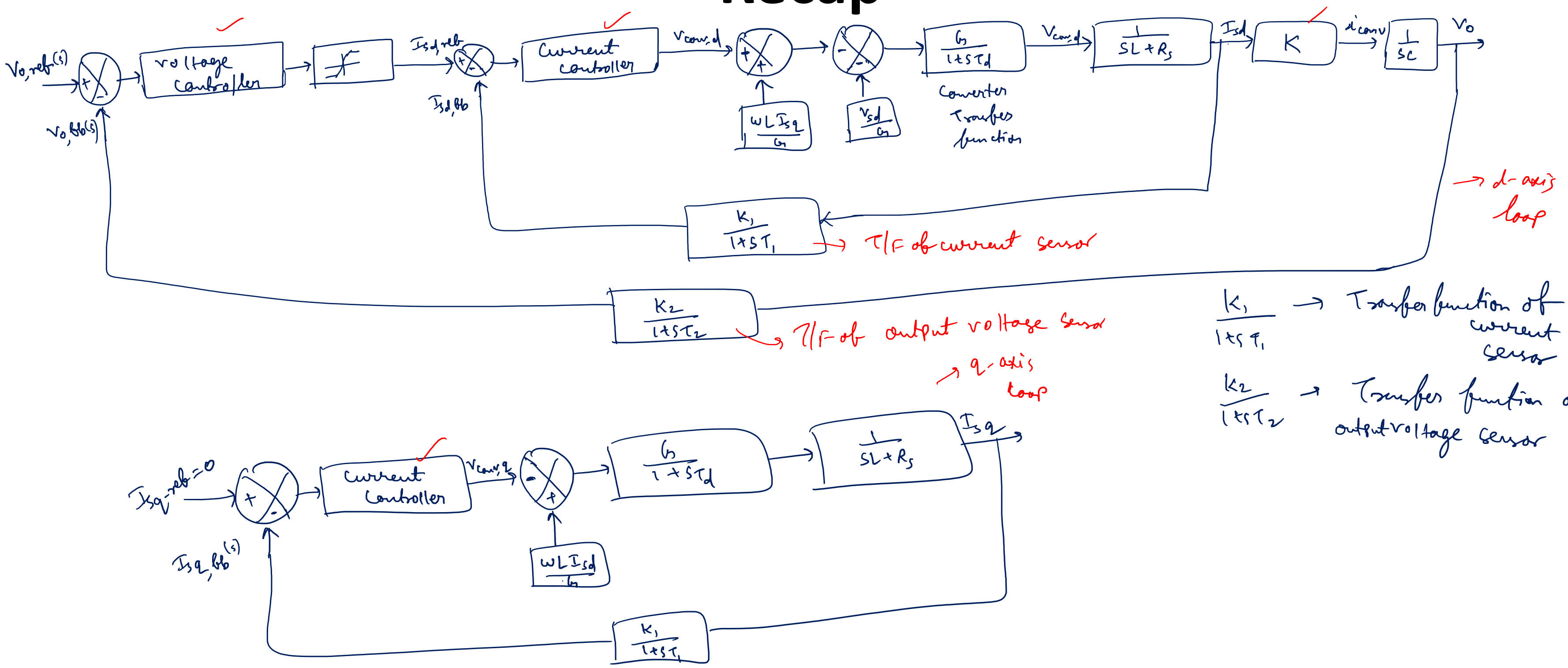
→ d-axis is aligned along the $\bar{V}_s$




d-axis model, $L\frac{d}{dt}I_{sd} + R_s I_{sd} = -V_{conv,d} + \underbrace{\omega L I_{sq}}_{\text{cross-coupling}} + V_{sd}$

q-axis model, $L\frac{d}{dt}I_{sq} + R_s I_{sq} = -V_{conv,q} - \omega L I_{sd}$ → cross-coupling

# Recap

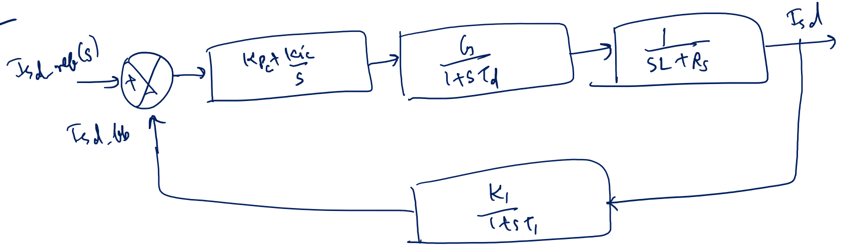



$\frac{K_1}{1+sT_1}$ → Transfer function of current sensor

$\frac{K_2}{1+sT_2}$ → Transfer function of output voltage sensor

Source: Siva Prasad, J.S., Bhavsar, T., Ghosh, R. *et al.* Vector control of three-phase AC/DC front-end converter. *Sadhana* **33**, 591–613 (2008)

Current loop




Closed-loop T/F

$$\frac{I_{sd}(s)}{I_{sd\_ref}(s)} = \frac{\dfrac{G K_{pc}}{L(1+sT_d)s}}{1 + \dfrac{G K_{pc} K_1}{L(1+sT_d)(1+sT_1)s}}$$

$$\frac{I_{sd}(s)}{I_{sd\_ref}(s)} = \frac{G K_{pc}(1+sT_1)}{s(1+sT_d)(1+sT_1)L + G K_{pc} K_1} \longrightarrow (1)$$

$$(1+sT_d)(1+sT_1) = 1 + s^2 T_d T_1 + s(T_d + T_1)$$

$T_d = \frac{T_{sw}}{2}$ ; $T_1$ is the bandwidth of current sensor

$\Rightarrow$ $T_d$ & $T_1$ are small value

$\Rightarrow T_d \cdot T_1 \approx$ very small $\approx 0$

Current controller

$$K_{pc} + \frac{K_{ic}}{s} \Rightarrow \frac{K_{pc}\left(s + \frac{K_{ic}}{K_{pc}}\right)}{s}$$

$$\Rightarrow \frac{1}{sL+R_s} = \frac{1/L}{s + R_s/L} = \frac{1/L}{s + 1/T_s}$$

where $T_s = L/R_s$

$$\Rightarrow \boxed{\frac{K_{pc}}{K_{ic}} = T_s} \longrightarrow (A)$$

Source: Siva Prasad, J.S., Bhavsar, T., Ghosh, R. *et al.* Vector control of three-phase AC/DC front-end converter. *Sadhana* **33**, 591–613 (2008)

$\Rightarrow (1+sT_d)(1+sT_1) = 1 + s(T_d + T_1)$ (approximated value)

$$T_d + T_1 = T_\sigma$$

$\Rightarrow (1+sT_d)(1+sT_1) = 1 + sT_\sigma$

from eq. (1)

$$\frac{I_{sd}(s)}{I_{sd\text{-}ref}(s)} = \frac{G K_{pc}(1+sT_1)}{s(1+sT_\sigma)L + G K_{pc} K_1}$$

$$= \frac{G K_{pc}(1+sT_1)}{sL + s^2 T_\sigma L + G K_{pc} K_1}$$

$$\frac{I_{sd}(s)}{I_{sd\text{-}ref}(s)} = \frac{G K_{pc}(1+sT_1)}{T_\sigma L\left[s^2 + \frac{s}{T_\sigma} + \frac{G K_{pc} K_1}{T_\sigma L}\right]} \longrightarrow (2)$$

we can compare with standard second order closed loop T/F (CLTF)

$\Rightarrow (s^2 + 2\xi\omega_n s + \omega_n^2)$ denominator of 2nd order CLTF

$$\Rightarrow 2\xi\omega_n = \frac{1}{T_\sigma} \quad ; \quad \omega_n^2 = \frac{G K_{pc} K_1}{T_\sigma L}$$

Source: Siva Prasad, J.S., Bhavsar, T., Ghosh, R. *et al.* Vector control of three-phase AC/DC front-end converter. *Sadhana* **33**, 591–613 (2008)

$\zeta_q = 0.707$

$\Rightarrow \quad 2 \cdot \frac{1}{\sqrt{2}} \omega_n = \frac{1}{T_\sigma}$

$\omega_n^2 = \frac{1}{2T_\sigma^2} \quad ; \quad \omega_n^2 = \frac{G K_{pc} K_1}{T_\sigma L}$

$\Rightarrow \quad \boxed{K_{pc} = \frac{L}{2 G K_1 T_\sigma}} \longrightarrow (B)$

from (A) & (B) we can calulate the current contoller Parameters

from eq. (2)

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)} = \frac{(1+sT_1)}{K_1 (2T_\sigma^2 s^2 + 2T_\sigma s + 1)}$$

neglected due to slower outer voltage loop

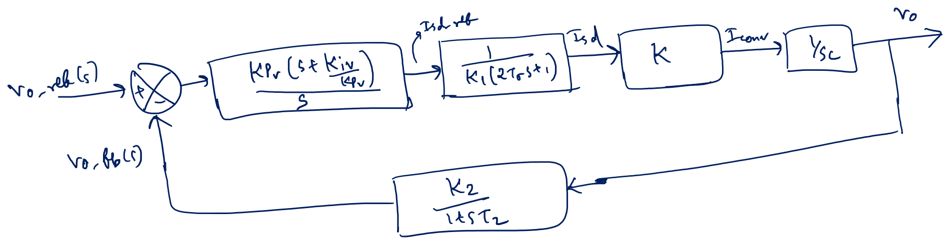
(putting (B) in eq. (2))

Since our outer voltage loop is a slower loop, thus the dynamics due to zero (at $s = 1/T_1$) & due to $s^2$ terms in denominator can be neglected

$$\left.\frac{I_{sd}(s)}{I_{sd,ref}(s)}\right|_{CLTF} = \frac{1}{K_1 (2T_\sigma s + 1)} \longrightarrow (3)$$

Source: Siva Prasad, J.S., Bhavsar, T., Ghosh, R. *et al.* Vector control of three-phase AC/DC front-end converter. *Sadhana* **33**, 591–613 (2008)

voltage loop




Open loop Transfer function (OLTF)

$$\left.\frac{V_o(s)}{v_{o,ref}(s)}\right|_{OLTF} = \frac{K_{Pv}\cdot K\cdot K_2\left(s+\frac{K_{iv}}{K_{Pv}}\right)}{s^2 C K_1\,(1+2T_\sigma s)(1+sT_2)} \longrightarrow (4)$$

$$(1+2T_\sigma s)(1+sT_2) = 1+2T_\sigma T_2\cdot s^2 + (2T_\sigma+T_2)s$$

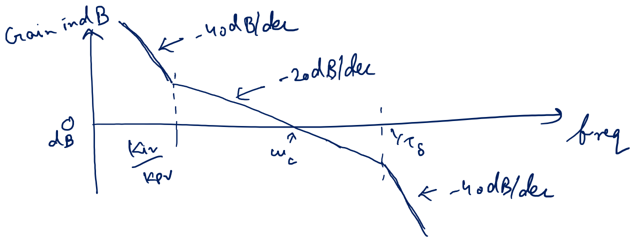
$T_\sigma$ & $T_2$ are small quantities $\Rightarrow$ $T_\sigma\cdot T_2 \simeq 0$ (very small)

$$\Rightarrow (1+2T_\sigma s)(1+sT_2) = 1+(2T_\sigma+T_2)s \qquad (2T_\sigma+T_2 = T_\delta)$$

$$= 1+T_\delta s$$

Source: Siva Prasad, J.S., Bhavsar, T., Ghosh, R. *et al.* Vector control of three-phase AC/DC front-end converter. *Sadhana* **33**, 591–613 (2008)

$$\left.\frac{v_o(s)}{v_{o,ref}(s)}\right|_{OLTF} = \frac{K_{pv}\cdot K\cdot k_2\left(s+\frac{K_{iv}}{K_{pv}}\right)}{s^2\cdot C\cdot K_1\,(1+sT_\delta)}$$

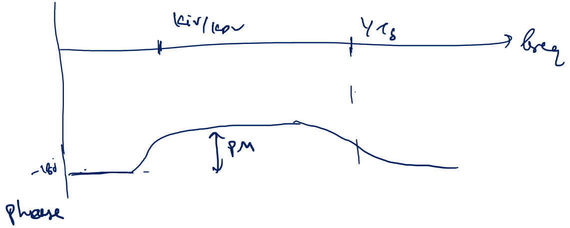



$$\omega_c = \sqrt{\frac{K_{iv}}{K_{pv}\cdot T_\delta}} = \frac{1}{a T_\delta}$$

⇒ If we cross the 0 dB line with a slope of −20dB/dec, then high PM can be achieved ⇒ stable CL operation

$$\Rightarrow \quad a^2 T_\delta = \frac{K_{pv}}{K_{iv}}$$

$$\Rightarrow \quad \boxed{\frac{K_{pv}}{K_{iv}} = a^2 T_\delta} \rightarrow \text{C}$$




$$\left|\frac{v_o(s)}{V_{o,ref}(s)}\right|_{\omega=\omega_c} = 1$$

$$\Rightarrow \quad \boxed{K_{pv} = \frac{C K_1}{k_2 K a T_\delta}} \rightarrow \text{D}$$

⇒ $a = 2$

⇒ $PM \approx 37°$

$$\phi_{\omega_c} = \tan^{-1}\left(\omega_c \frac{K_{pv}}{K_{iv}}\right) - \tan^{-1}(\omega_c T_\delta)$$

from C & D voltage controller parameter can be obtained

$$\Rightarrow \phi_{\omega_c} = \tan^{-1}\left(\frac{1}{aT_\delta}\cdot a^2 T_\delta\right) - \tan^{-1}\left(\frac{1}{aT_\delta} T_\delta\right)$$

$$\Rightarrow \phi_{\omega_c} = \tan^{-1}(a) - \tan^{-1}(1/a)$$

$$\Rightarrow PM = 180 + \phi_{\omega_c}$$

$$\Rightarrow a = 2 \Rightarrow PM = 36.86°$$

Source: Siva Prasad, J.S., Bhavsar, T., Ghosh, R. *et al.* Vector control of three-phase AC/DC front-end converter. *Sadhana* **33**, 591–613 (2008)

To obtain 'K'.

$$\text{3-Ph Power} = \frac{3\, V_{s,pk} \cdot I_{s,pk}}{2} \longrightarrow (1)$$

$$\text{2-Ph power} = V_{sd} I_{sd} + V_{sq} \cdot I_{sq}$$

$$V_{sq} = 0 \;\&\; I_{sq} = 0$$

$$V_{sd} = \tfrac{3}{2} V_{s,pk}, \quad I_{sd} = \tfrac{3}{2} I_{s,pk}$$

$$\Rightarrow \text{2-Ph power} = \tfrac{9}{4} V_{s,pk} \cdot I_{s,pk} \longrightarrow (2)$$

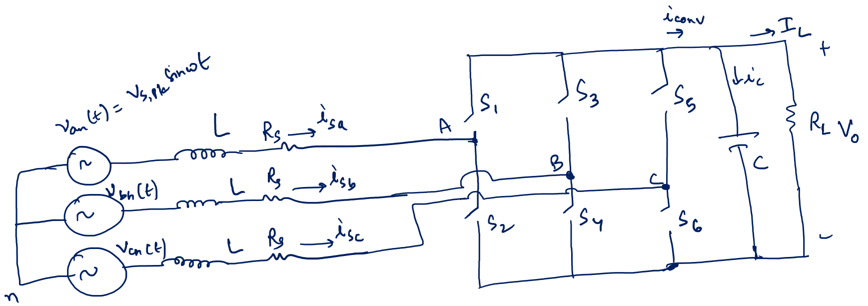
from (1) & (2)

$$\text{3-Ph Power} = \tfrac{2}{3}\left(\text{2-Ph Power}\right) = I_{conv} \cdot V_0$$

$$\Rightarrow \quad \tfrac{2}{3}\left(V_{sd} \cdot I_{sd}\right) = I_{con} \cdot V_0$$

$$\Rightarrow \quad I_{con} = \underbrace{\frac{2}{3} \frac{V_{sd}}{V_0}}_{'K'} \cdot I_{sd}$$

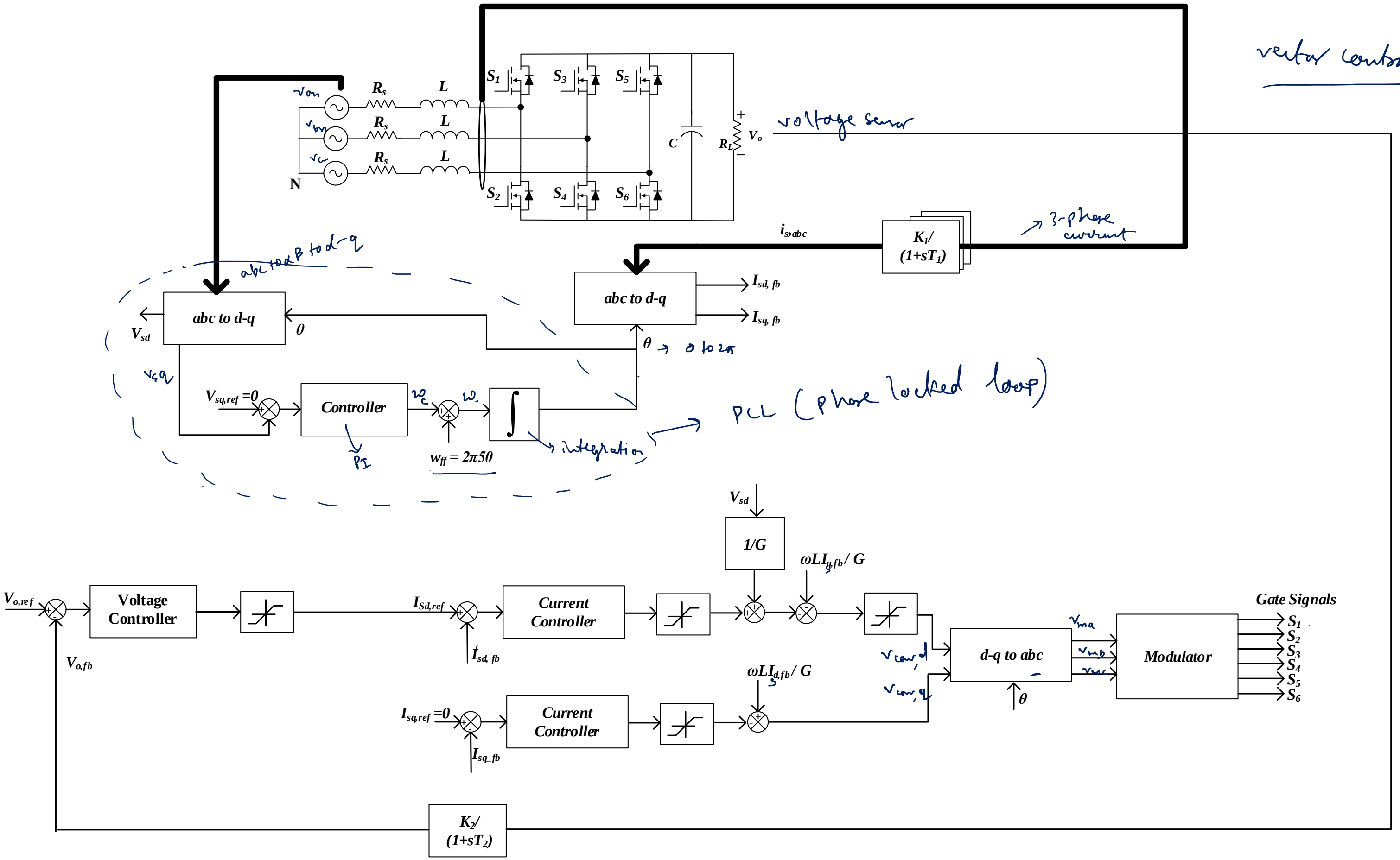
$$\Rightarrow \quad \boxed{K = \tfrac{2}{3} \frac{V_{sd}}{V_0}}$$

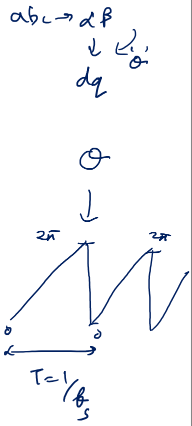



$$K_1 = \frac{\text{Max. voltage of Controller}}{\tfrac{3}{2} \times \text{Max. value of supply current}}$$

$$K_2 = \frac{\text{Max. voltage of Controller}}{\text{Output voltage}}$$

vector control approach



# Thank You