DC-DC Control Techniques

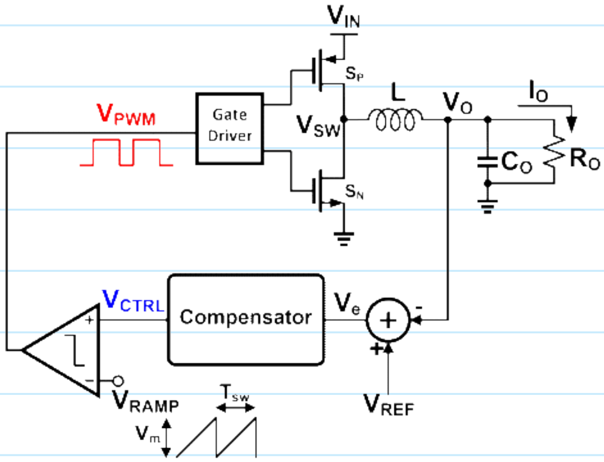
1. linear
   - voltage mode control (VMC)
   - current mode control (CMC)

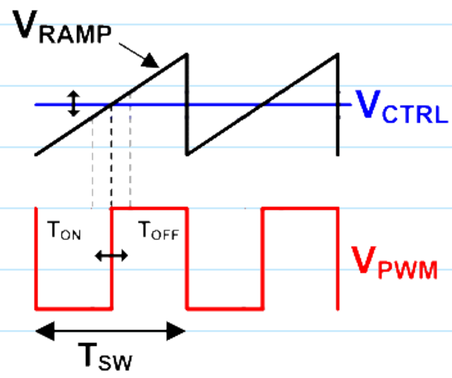
   PWM based

2. Non-linear
   - Hysteretic control or bang-bang control
   - constant ON or OFF time control (COT)

Voltage vs. Current Mode Control

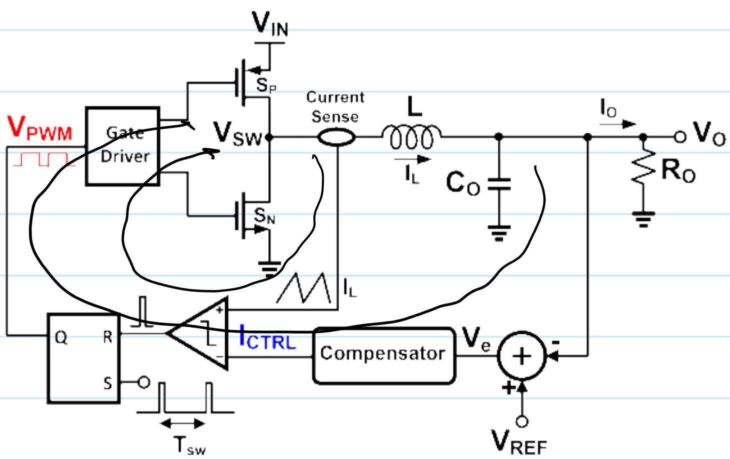
VOLTAGE MODE

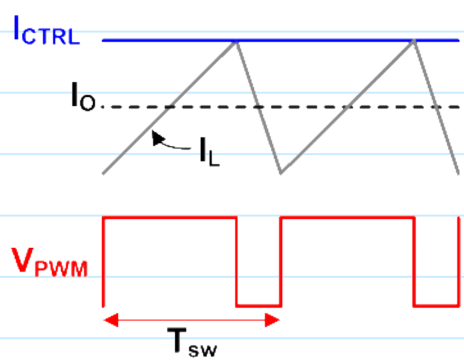




\# D is controlled by voltage

\# Uses ramp signal





\# D is controlled by current

\# does not use ramp signal for PWM

\# has built-in current limiting

Sampling Delay

$$f(t) \xleftrightarrow{L(s)} f(s)$$

$$f(t-T) \xleftrightarrow{L(s)} e^{-sT} f(s)$$

$$|e^{-sT}| = 1$$

$$\angle e^{-sT} = -\omega T$$

$\phi = -2\pi$ at $\omega = \frac{2\pi}{T_{sw}} = 2\pi F_{sw}$

Phase wraps to 0 if $\omega = N \cdot 2\pi F_{sw}$

$(N = 1, 2, 3 \cdots)$

$$T = T_{sw}$$

ϕ_{M_0} = PM w/o delay T_{sw}

ϕ_{Md} = PM with delay

$$\phi_{Md} = \phi_{M_0} - \omega T_{sw}$$

$$T_{sw} = \frac{1}{F_{sw}}$$

$$\phi_{Md} = \phi_{M_0} - \frac{2\pi f}{F_{sw}}$$

assume $f = \frac{1}{10} F_{sw}$

$$= \phi_{M_0} - \frac{180}{5} = \phi_{M_0} - 36°$$

delay in PWM (trailing edge)

$$T_d = (1-D) T_{sw}$$

Sampling Delay

using Taylor series with 1st order approximation

$$e^{-sT} = 1 - sT \quad -① \Rightarrow \text{R.H.P. Zero}$$

$$\text{or } \frac{1}{1+sT} \quad -② \Rightarrow \text{L.H.P. Pole}$$

magnitude $\neq 1$

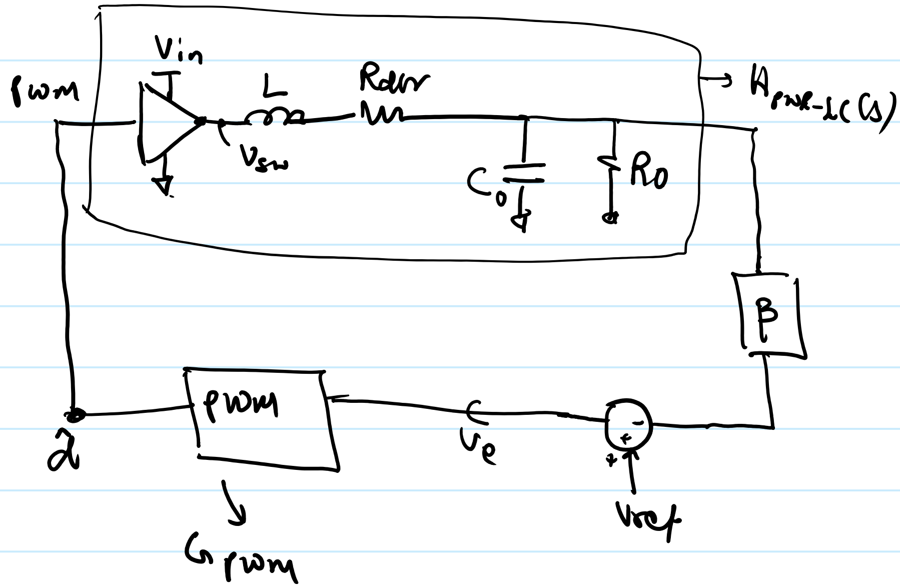
$$e^{-sT} = e^{-sT/2} \times e^{-sT/2}$$

$$= \frac{\frac{2}{T} - s}{\frac{2}{T} + s} \quad -③ \Rightarrow \text{R.H.P. Zero \& L.H.P. Pole}$$

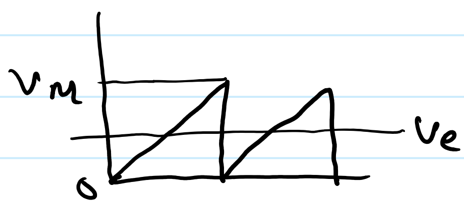
magnitude $= 1$ & phase same as ① & ②

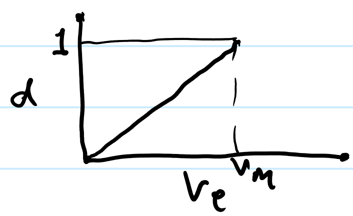
①, ② & ③ work well only for $\frac{f}{F_{sw}} << 1$

Continuous Time Model



$$G_{pwm} = \frac{\partial \hat{d}}{\partial v_e} = \frac{1}{V_M}$$

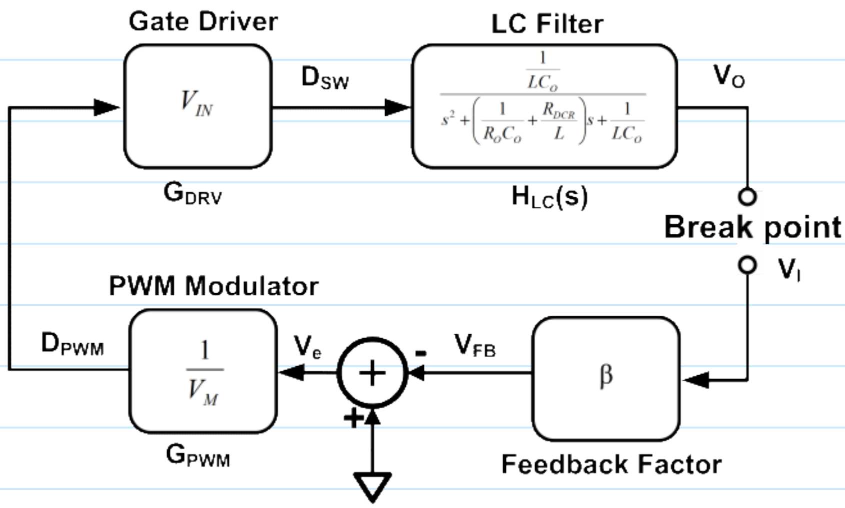




$$V_o = \frac{D\, V_{in} \left(\frac{1}{L C_o} \right)}{s^2 + \left(\frac{1}{R_o C_o} + \frac{R_{dcr}}{L} \right) s + \frac{1}{L C_o}}$$

$$\frac{\partial V_o}{\partial \hat{d}} = V_{in} \left[\frac{\frac{1}{L C_o}}{s^2 + \frac{w_o}{Q_o} \cdot s + \frac{1}{L C_o}} \right]$$

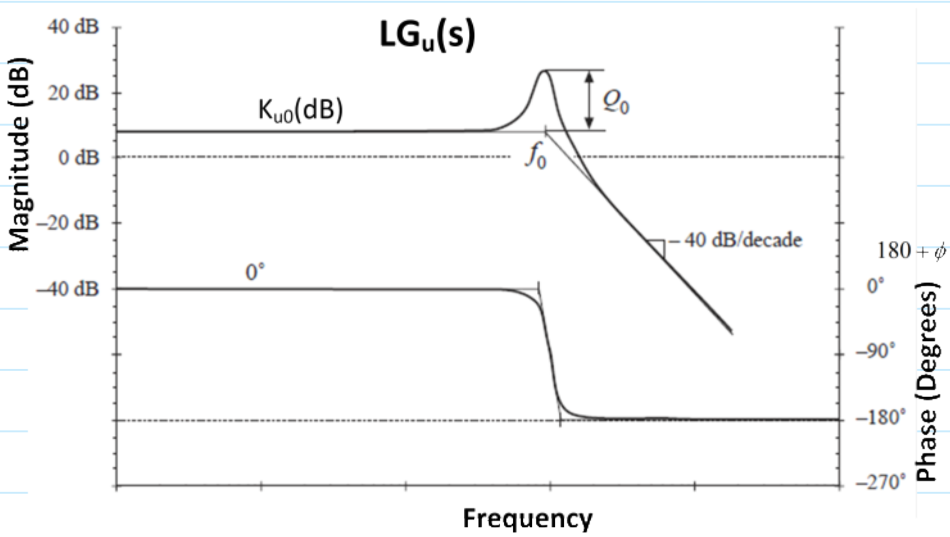
Loop Gain of Un-Compensated Buck



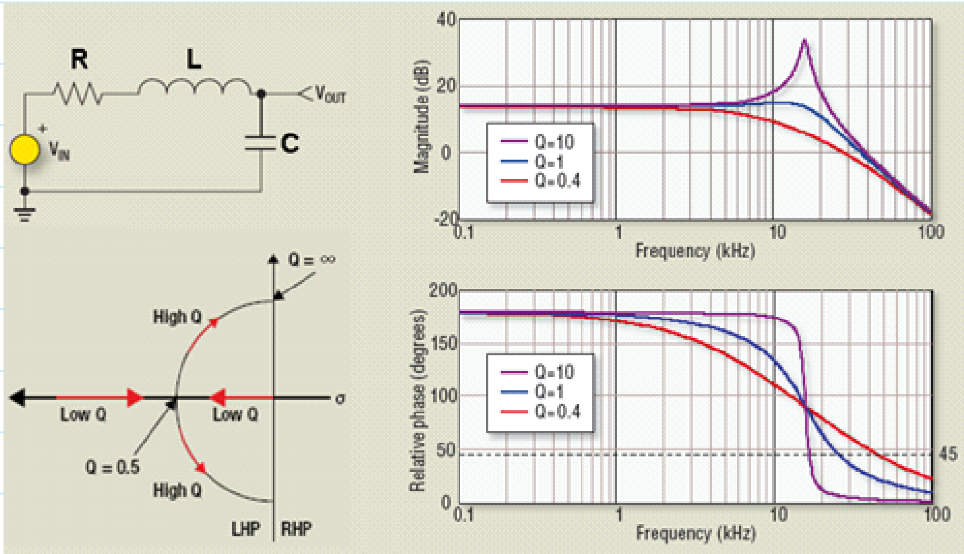
$$LG_u(s) = -\frac{R_2}{R_1+R_2}\cdot\frac{V_{IN}}{V_M}\cdot\frac{\frac{1}{LC_O}}{s^2+\left(\frac{1}{R_O C_O}+\frac{R_{DCR}}{L}\right)s+\frac{1}{LC_O}}$$

$$f_o = \frac{1}{2\pi\sqrt{LC_O}}$$

$$K_{u0} = \frac{R_2}{R_1+R_2}\cdot\frac{V_{IN}}{V_M}$$

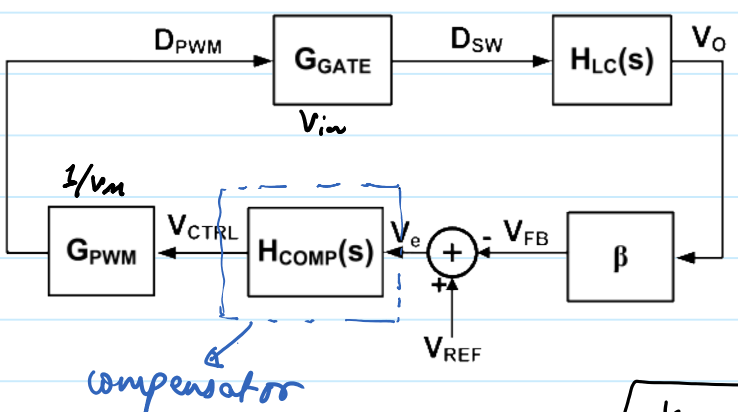


Compensation



complex poles due to LC filter may cause 90° – 180° phase shift around f_o (resonance freq.) and making system unstable.

we need a compensator to stabilize the loop.



$$\boxed{K_{mo} = \beta \frac{V_{in}}{V_M}}$$

Loop Gain T.F.

$$\boxed{LG(s) = K_{mo} \cdot H_{comp}(s) \cdot H_{LC}(s)}$$

Compensation - Cancelling Complex Poles

$H_{comp}(s) \rightarrow$ T.F. of the compensator

if we design

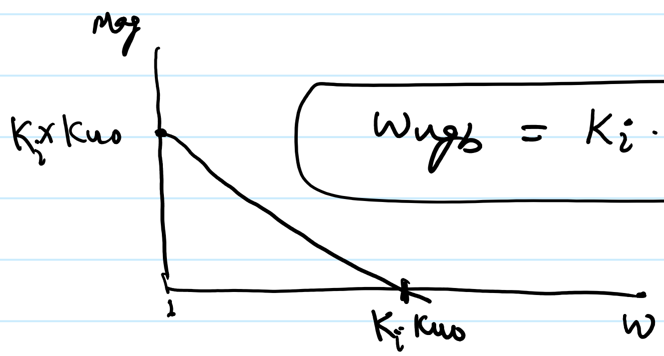
$$H_{comp}(s) = \frac{1}{H_{LC}(s)} \times \frac{K_i}{s}$$

complex poles due to LC are perfectly cancelled

Integrator $\frac{K_i}{s}$ is needed for high DC gain (good regulation) and to control BW.

Loop gain T.F. after compensation

$$LG(s) = K_{uo} \frac{K_i}{s}$$



$$\boxed{\omega_{ugb} = K_i \cdot K_{uo}}$$

Provides an ideal compensation but not practical to realize as compensation zeroes can't be exactly placed at f_0 due variations in parameters and component across varying operating conditions. Hence this type of compensation is not used.

Type-I Compensation

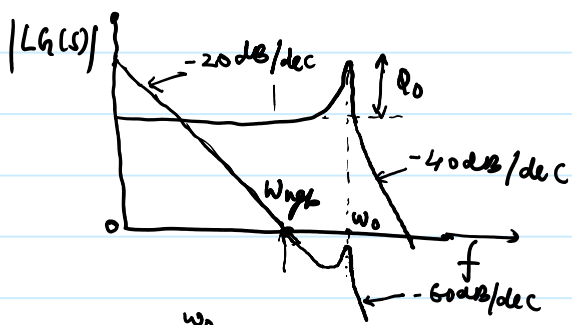
Also called Integral compensation

$$H_{comp}(s) = \frac{K_i}{s}$$

$$LG(s) = K_{uo} \cdot \frac{K_i}{s} H_{LC}(s)$$

If $K_{uo} \cdot K_i << \omega_o$ then complex poles are pushe outside ω_{ugb}

peaking due to high Q_o should be taken into account for enough gain margin.



$\omega_{ugb} = \frac{\omega_o}{Q \times 10}$ for -20dB gain margin

assume $Q = 10$

$$\omega_{ugb} = \frac{\omega_o}{100} \Rightarrow \text{very low B.W.}$$

Type-I compensation is mainly used if B.W. is not a concern.

+ Transient response is poor due to low B.W. hence can't be used for fast changing load currents or line voltages.