ECEN 4517/5517

Power Electronics and Photovoltaic Power Systems Laboratory

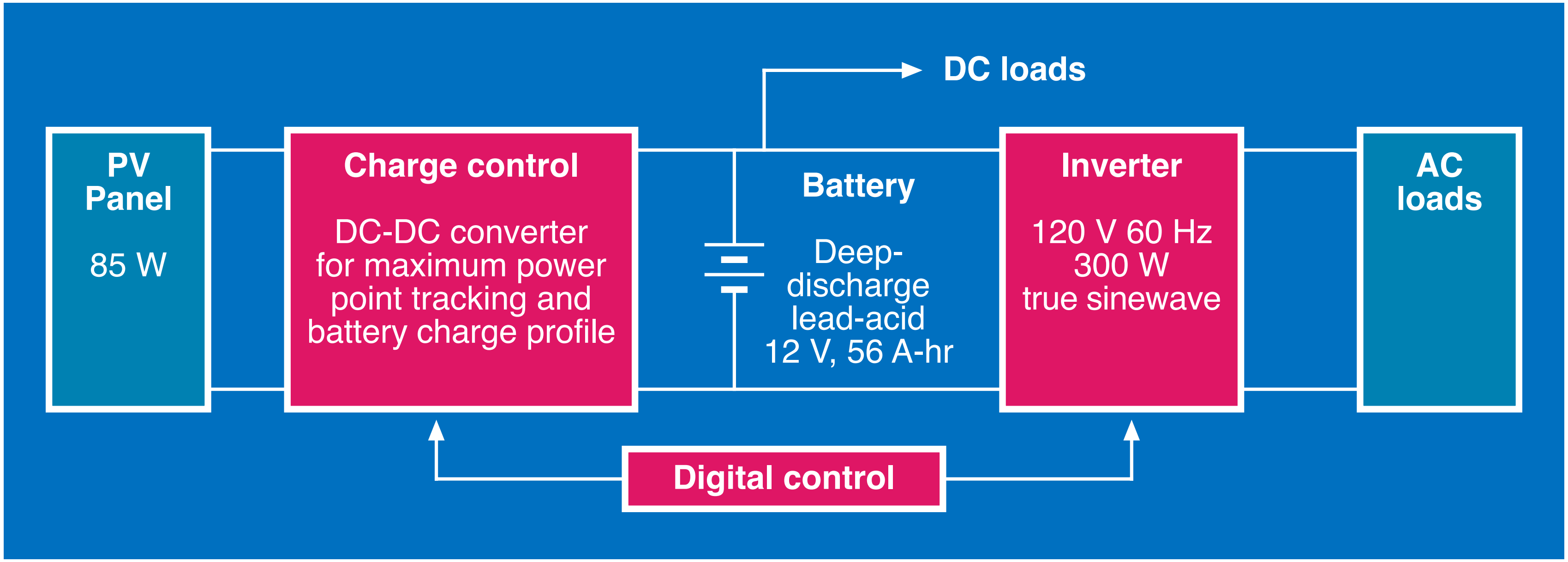
Lecture 8

Feedback Control

Announcements

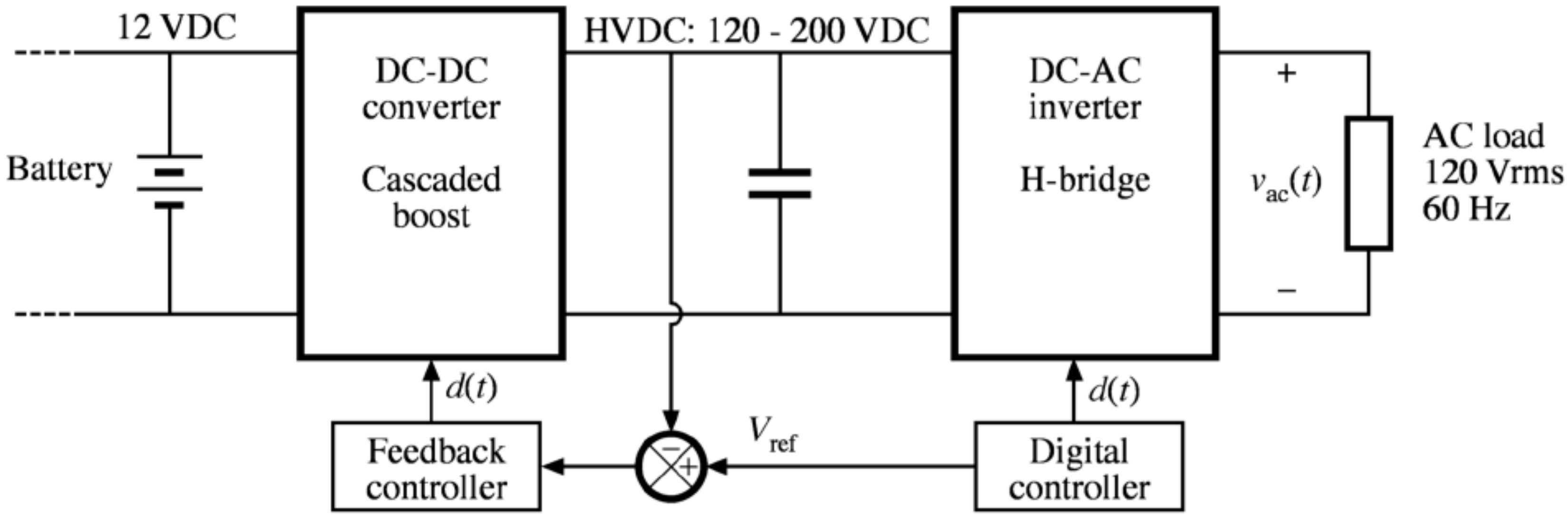
- This week's lab: Continue Experiment 4
  - Have 2 more weeks to work on Experiment 4
  - Exp 4 Lab Report due by 11:59 pm (MT) on Friday April 7, 2017
- Following this: Experiment 5
  - Experiment 5 has a pre-lab (due 11:59 pm on Friday March 24, 2017)
  - Have 2 weeks to work on Experiment 5 (after Spring Break)
  - Exp 5 Lab Report due by 11:59 pm (MT) on Friday April 21, 2017

Experiments



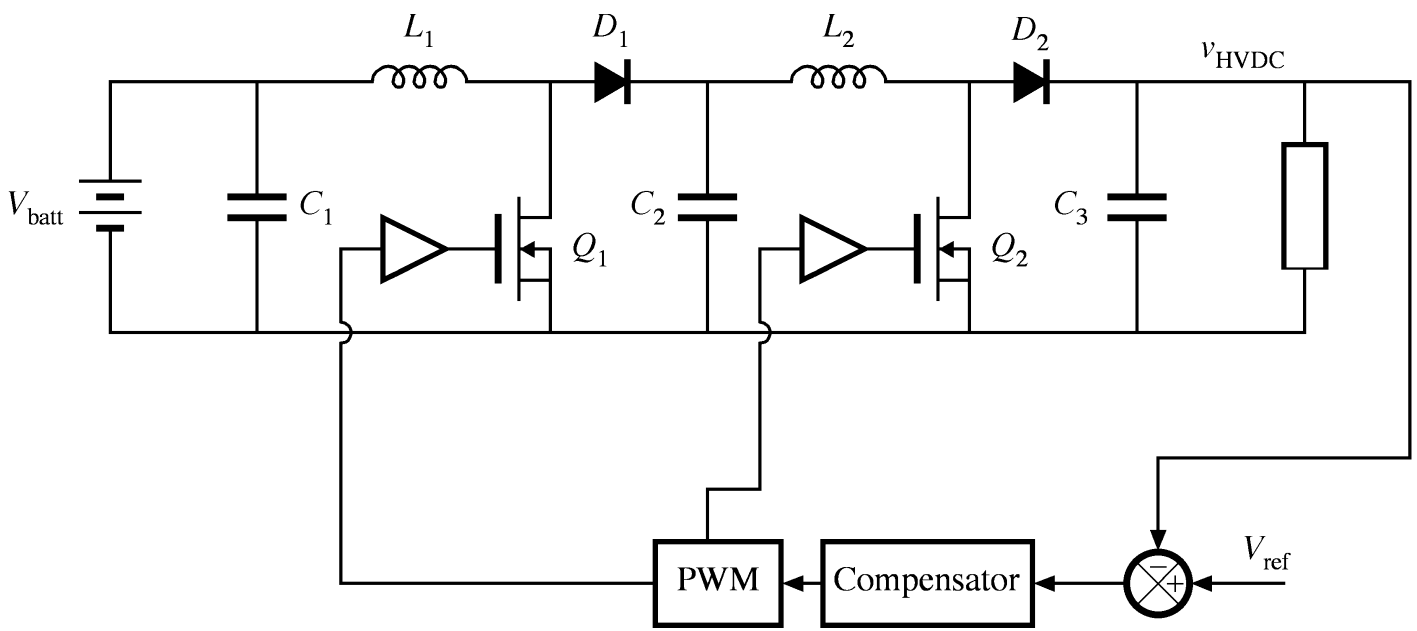
- Exp 1 – PV panel and battery characteristics and direct energy transfer
- Exp 2 – TI MSP430 microcontroller introduction
- Exp 3-1, 3-2 – Buck dc-dc converter for PV MPPT and battery charge control
- Exp 4 – Step-up 12V-200V dc-dc converter
- Exp 5 – Single-phase dc-ac converter (inverter)
- Expo – Complete system demonstration

Experiments 4 and 5



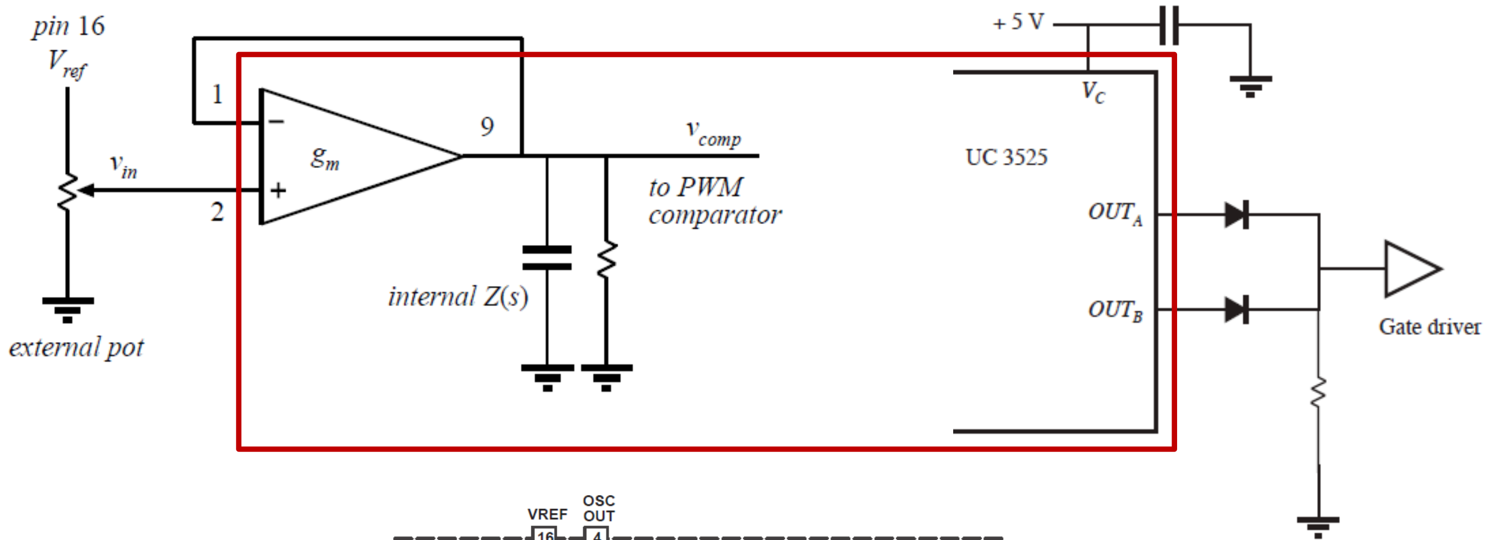
- **Exp 4**: Cascaded boost step-up dc-dc converter (using analog PWM and feedback controller to regulate HVDC)
- **Exp 5**: H-bridge dc-ac inverter

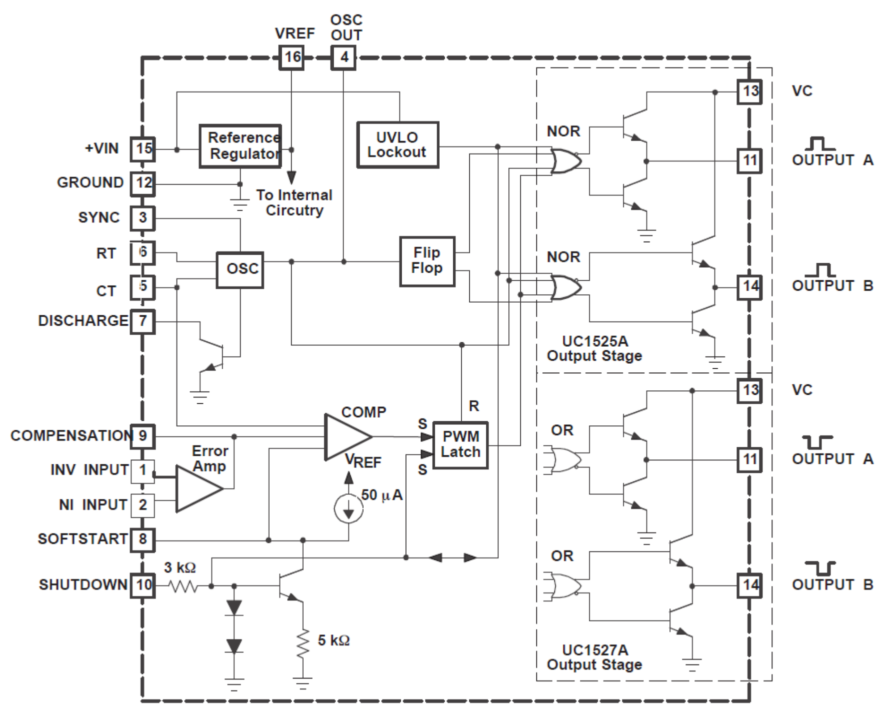
Experiment 4 - Cascaded Boost Converters



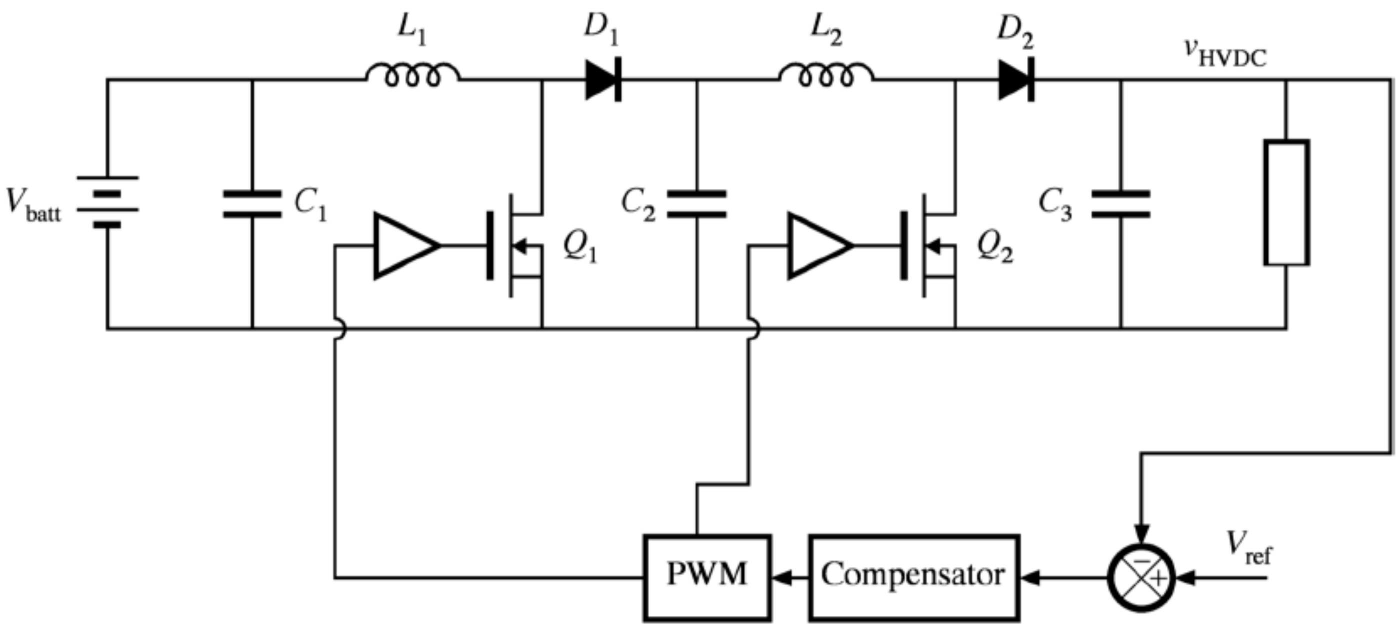
- **Controller IC**: Demonstrate operating PWM controller IC (UC 3525)
- **Power Stage**: Demonstrate operating cascaded boost power converters
- **Closed-Loop Analog Control**: Demonstrate analog feedback system that regulates the dc output voltage; and measure and document loop gain and compensator design
- **Additional Analysis** [ECEN 5517 Only]: Develop and verify system loss budget; and analytical model of control-to-output transfer function

Pulse Width Modulator (PWM) using UC3525A IC





Regulation of Output Voltage via Feedback



Feedback Controller (Exp 4 – Task 3)

- Measure and simulate open-loop control-to-output transfer function $G_{vd}(s)$
- Design and build feedback loop
- Demonstrate closed-loop regulation of v_{HVDC}

Transfer Functions for Basic CCM Converters

Open-loop control-to-output transfer function:

$$G_{vd}(s) = G_{d0} \frac{\left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)}$$

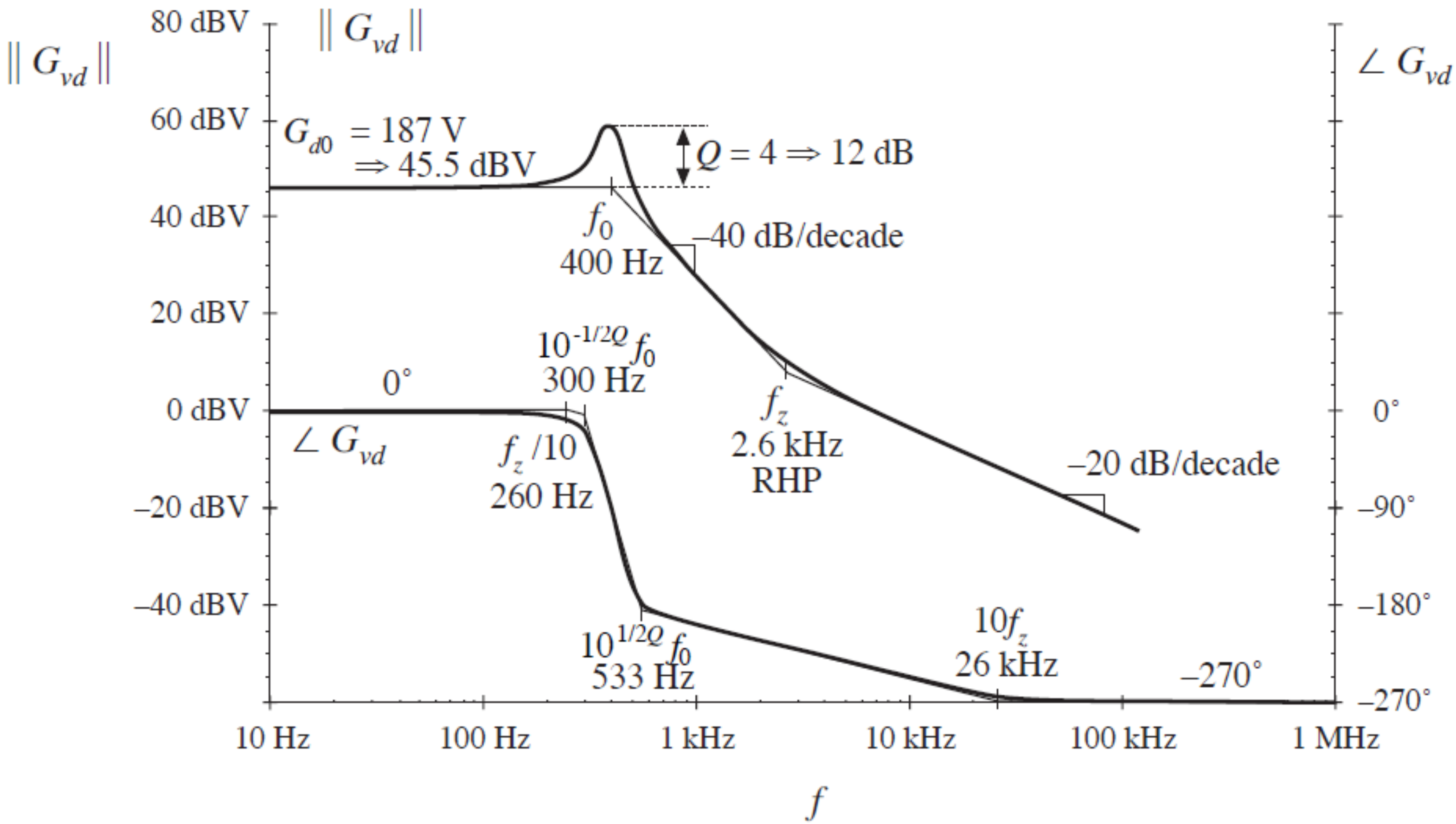
Open-loop line-to-output transfer function:

$$G_{vg}(s) = G_{g0} \frac{1}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

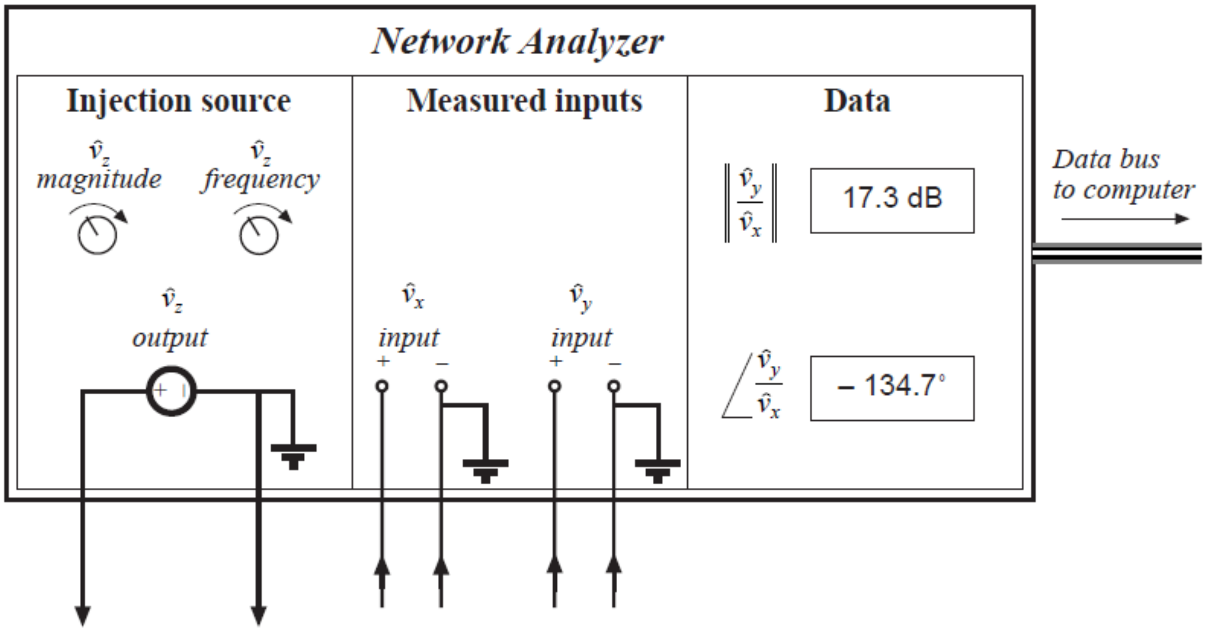
Converter	G_{g0}	G_{d0}	ω_0	Q	ω_z
buck	D	$\frac{V}{D}$	$\frac{1}{\sqrt{LC}}$	$R\sqrt{\frac{C}{L}}$	∞
boost	$\frac{1}{D'}$	$\frac{V}{D'}$	$\frac{D'}{\sqrt{LC}}$	$D'R\sqrt{\frac{C}{L}}$	$\frac{D'^2R}{L}$
buck-boost	$-\frac{D}{D'}$	$\frac{V}{D\,D'^2}$	$\frac{D'}{\sqrt{LC}}$	$D'R\sqrt{\frac{C}{L}}$	$\frac{D'^2R}{D\,L}$

Bode Plot of Control-to-Output Transfer Function

Buck-Boost Converter Example

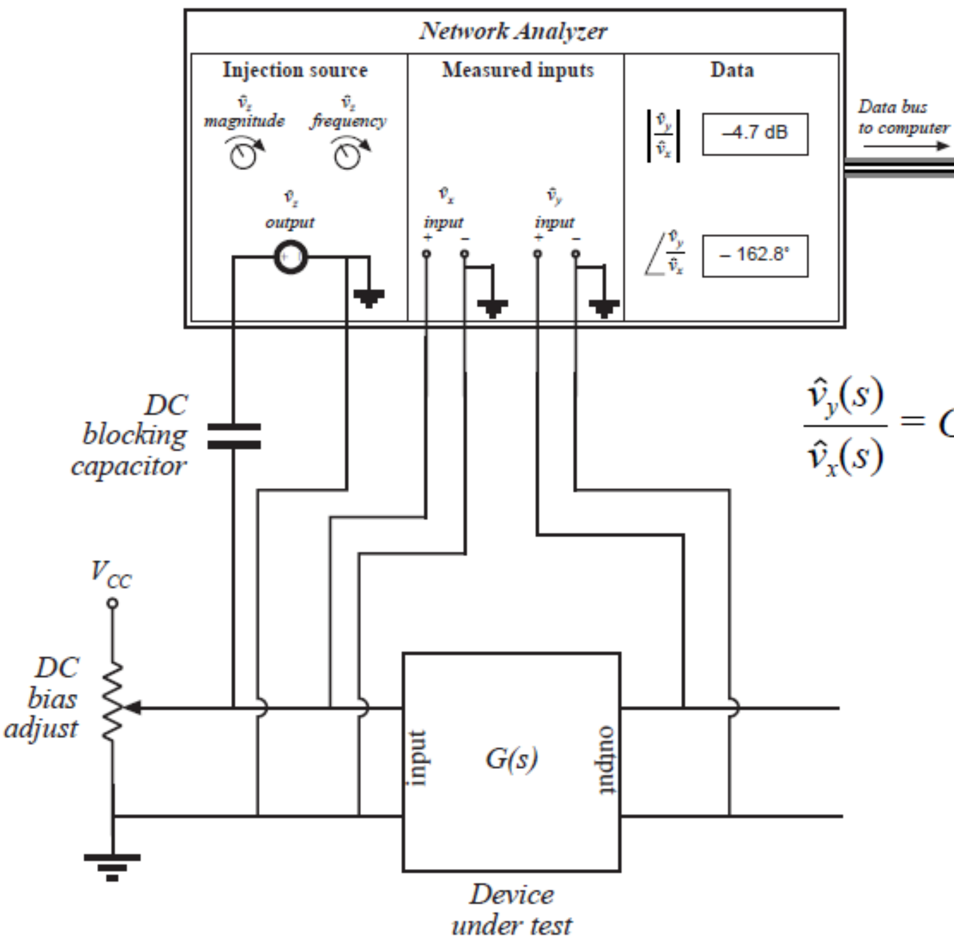


Measurement of AC Transfer Function



- Injection source produces sinusoidal $\hat{v}_z$ of controllable amplitude and frequency
- Signal inputs $\hat{v}_x$ and $\hat{v}_y$ perform function of narrowband tracking voltmeter
  - Component of input at injection source frequency is measured
  - Narrowband function removes switching harmonics and other noise components
- Network analyzer measures: $\left\| \frac{\hat{v}_y}{\hat{v}_x} \right\|$ and $\angle \frac{\hat{v}_y}{\hat{v}_x}$

Measurement of AC Transfer Function (Cont.)

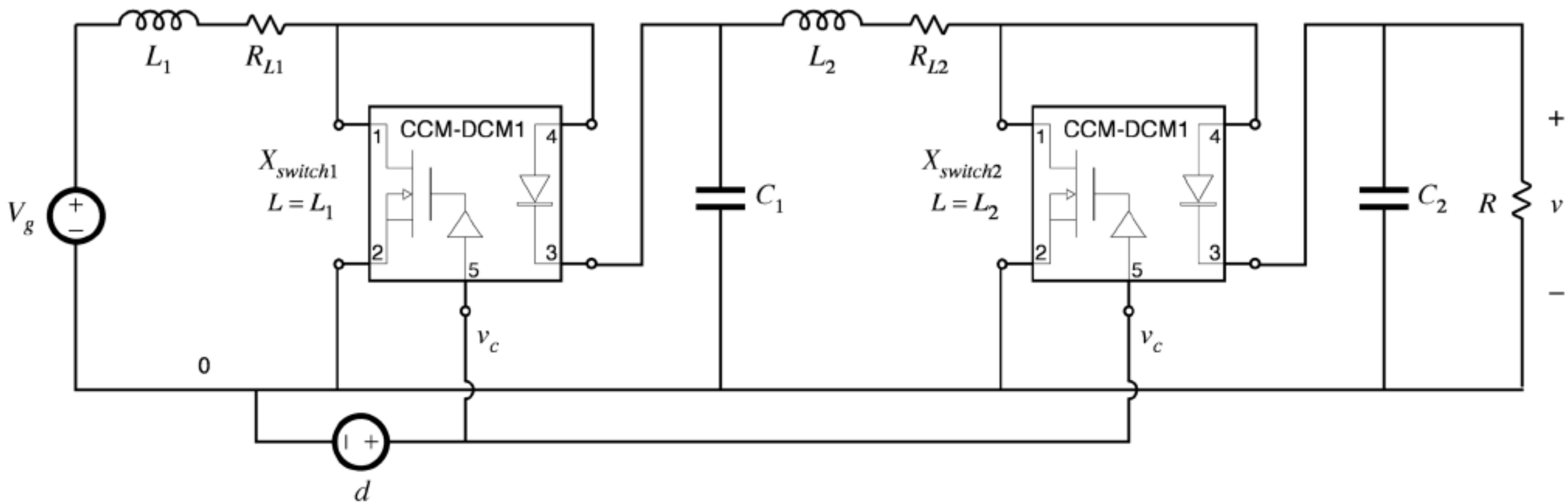


$$\frac{\hat{v}_y(s)}{\hat{v}_x(s)} = G(s)$$

- Potentiometer establishes correct quiescent operating point
- Injection sinusoid coupled to device input via dc blocking capacitor
- Actual device input and output voltages are measured as $\hat{v}_x$ and $\hat{v}_y$
- Dynamics of blocking capacitor are irrelevant

Simulation of Control-to-Output Transfer Function

Cascaded Boost Converters

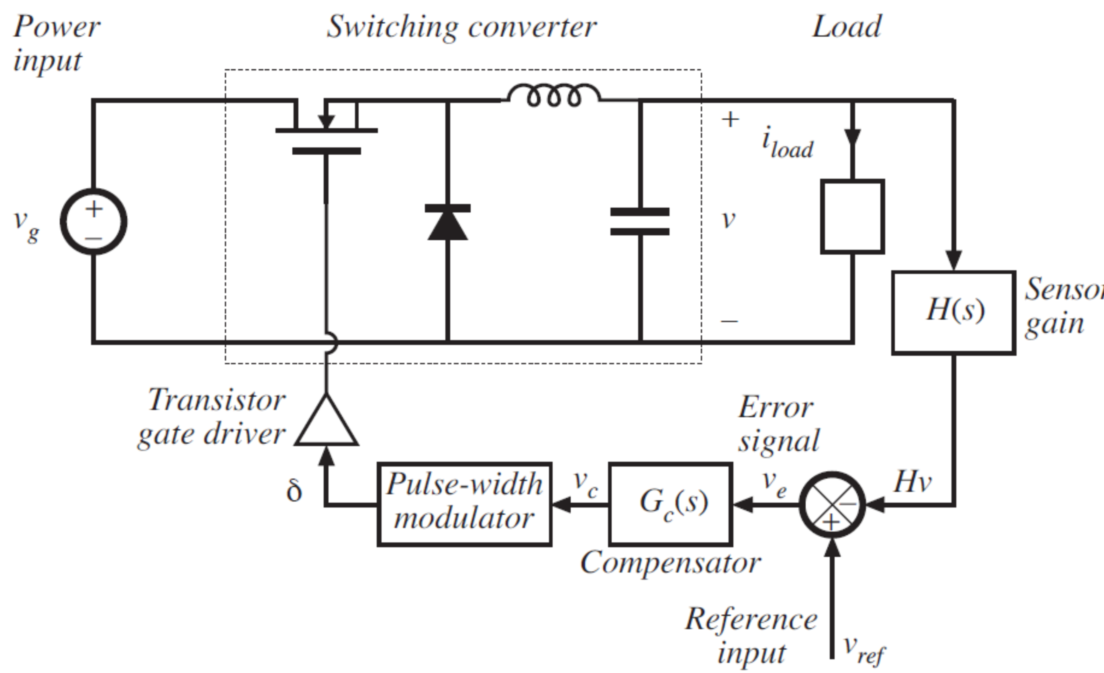


LTspice simulation of open-loop control-to-output transfer function

- Replace boost converter switches with averaged switch model
- CCM-DCM1 switch model is inside switch.lib
- Apply dc voltage (to set steady-state duty ratio) plus ac variation, to terminal 5 of CCM-DCM1 model; plot output voltage magnitude and phase using ac analysis within Spice

Loop Gain T(s)

- Loop gain T(s) = product of gains around the feedback loop
- More loop gain $\|T\|$ leads to better regulation of output voltage



- $T(s) = G_{vd}(s)H(s)G_c(s)/V_M$
- $G_{vd}(s)$ = power stage control-to-output transfer function
- PWM gain = $1/V_M$, where V_M = peak-to-peak amplitude of PWM sawtooth

Phase Margin

A test on $T(s)$, to determine stability of the feedback loop

The crossover frequency f_c is defined as the frequency where

$$\| T(j2\pi f_c) \| = 1, \text{ or } 0 \text{ dB}$$

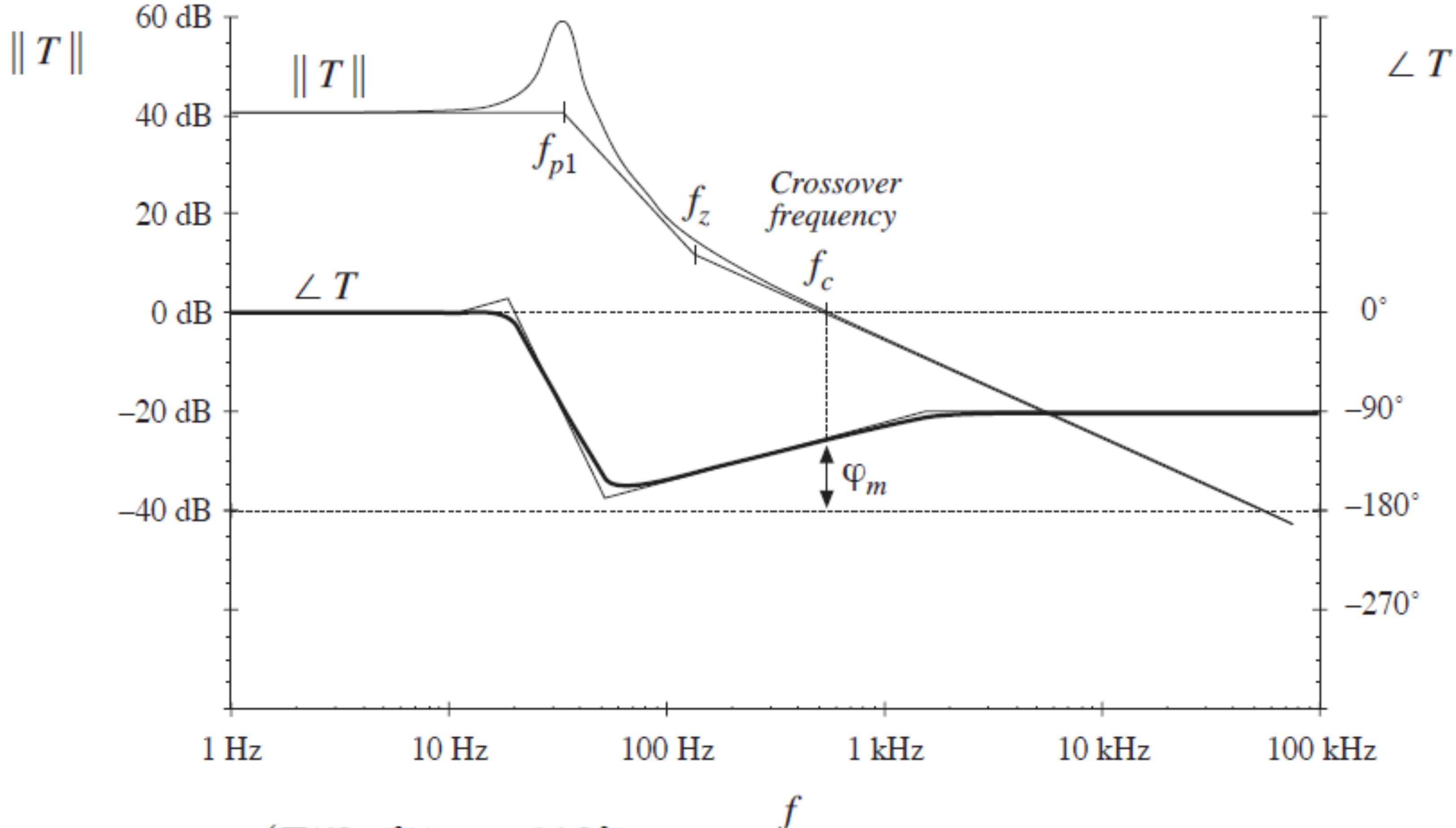
The phase margin φ_m is determined from the phase of $T(s)$ at f_c , as follows:

$$\varphi_m = 180^\circ + \arg(T(j2\pi f_c))$$

If there is exactly one crossover frequency, and if $T(s)$ contains no RHP poles, then

> the quantities $T(s)/(1+T(s))$ and $1/(1+T(s))$ contain no RHP poles whenever the phase margin φ_m is positive.

Example Loop Gain for Stable Closed-Loop System



$$\arg(T(j2\pi f_c)) = -\ 112^\circ$$

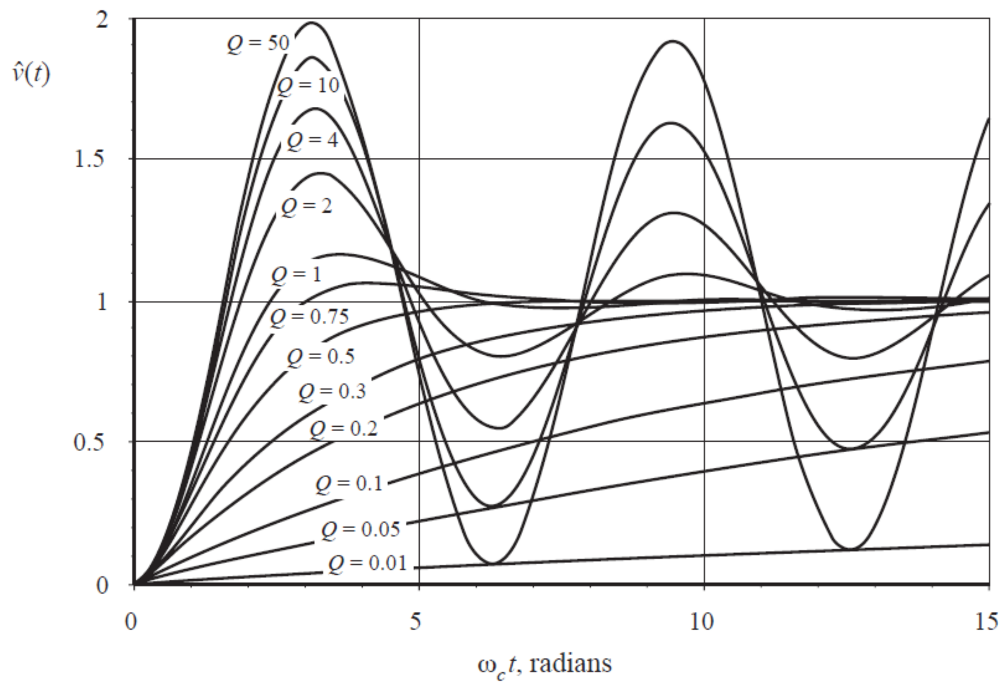
$$\varphi_m = 180^\circ - 112^\circ = +\ 68^\circ$$

How Much Phase Margin Is Enough?

- A small positive phase margin leads to a stable closed-loop system having complex poles near the crossover frequency with high Q
  - Transient response exhibits overshoot and ringing

- Increasing the phase margin reduces the Q

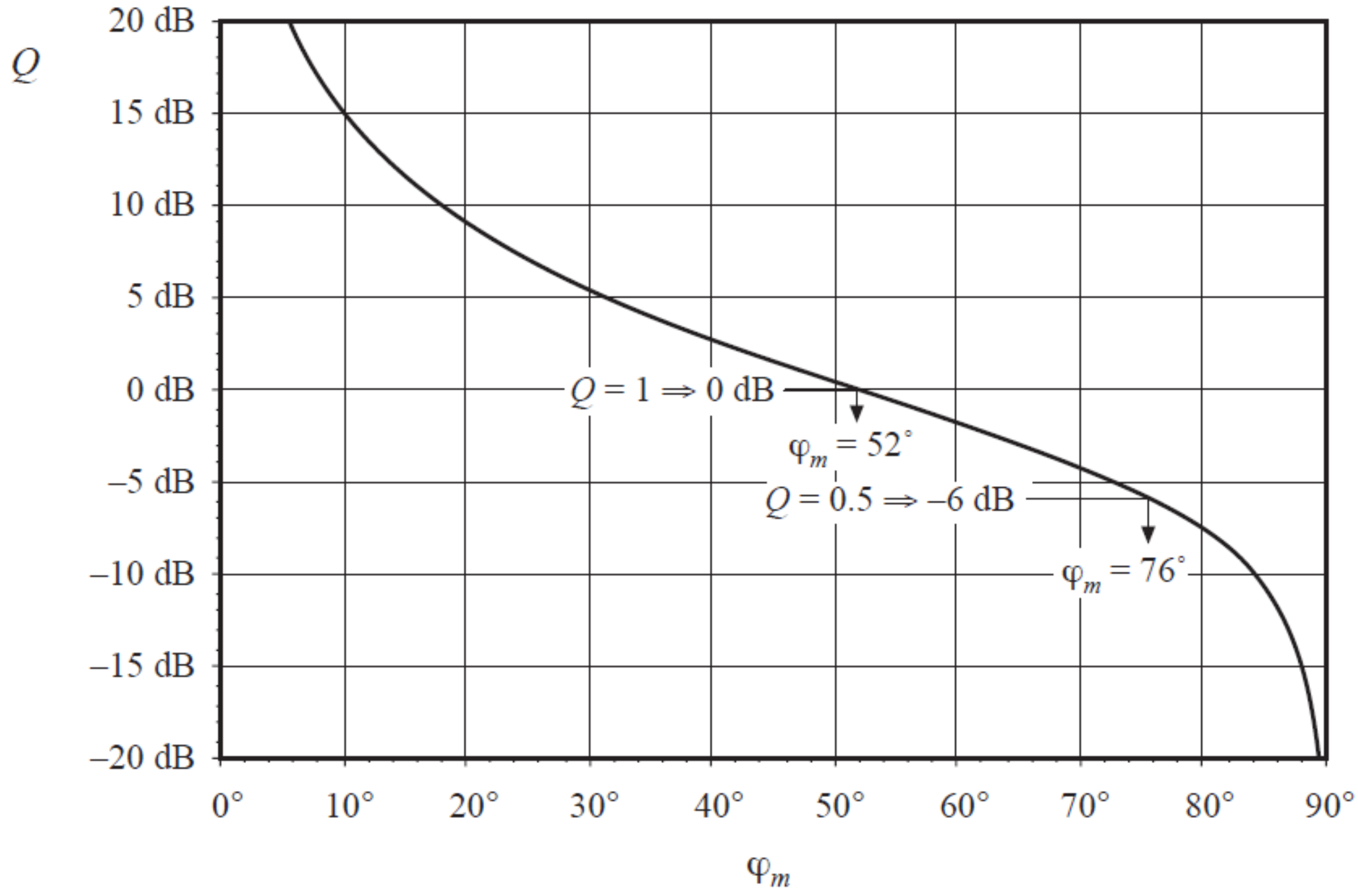
- To obtain real poles (hence no overshoot and ringing) requires a large phase margin



Relationship Between Phase Margin and Q

$$\varphi_m = \tan^{-1}\sqrt{\frac{1+\sqrt{1+4Q^4}}{2Q^4}}$$

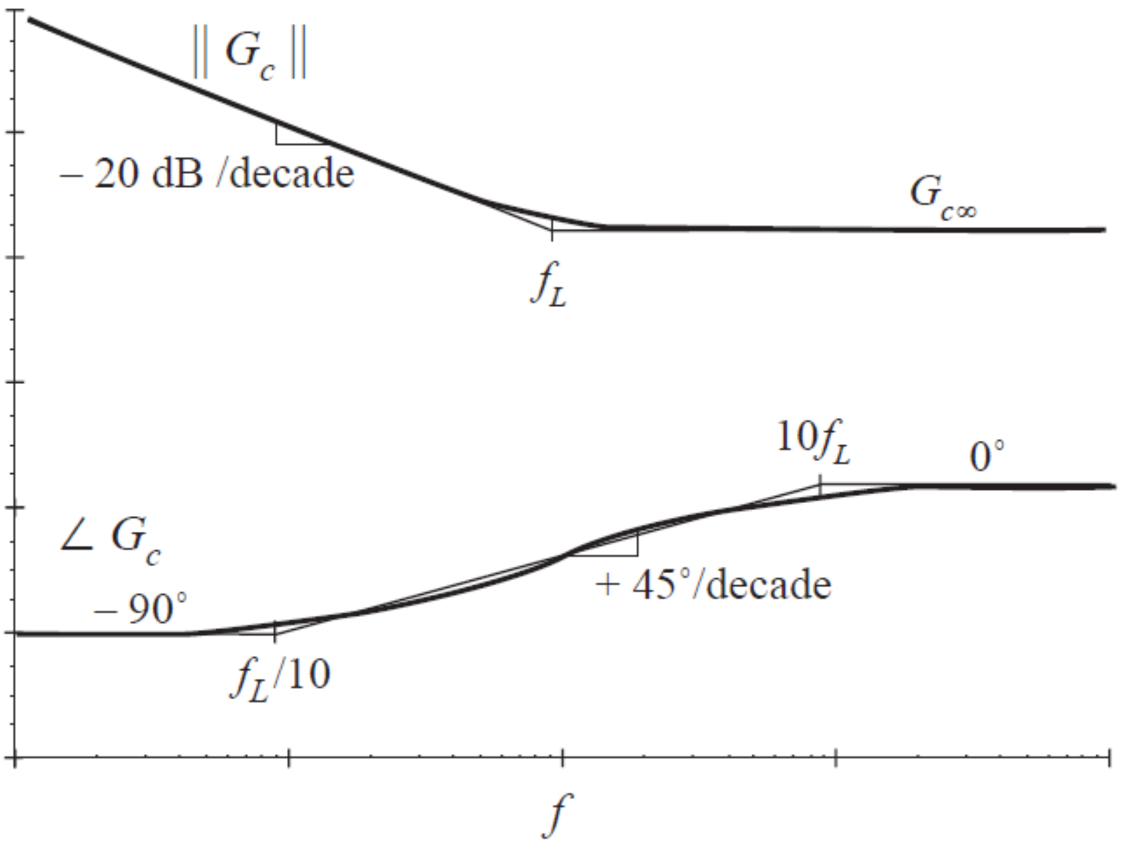
$$Q = \frac{\sqrt{\cos\varphi_m}}{\sin\varphi_m}$$



Lag (PI) Compensation

$$G_c(s) = G_{c\infty}\left(1 + \frac{\omega_L}{s}\right)$$

Used to improve low frequency loop gain



Lag (PI) Compensator Design Example

Original (uncompensated) loop gain: $\boxed{T_u(s) = \dfrac{T_{u0}}{\left(1 + \dfrac{s}{\omega_0}\right)}}$

Compensator: $G_c(s) = G_{c\infty}\left(1 + \dfrac{\omega_L}{s}\right)$

Design strategy: choose

- $G_{c\infty}$ to obtain desired crossover frequency
- ω_L sufficiently low to maintain adequate phase margin