ECEN 4517/5517

Power Electronics and Photovoltaic Power Systems Laboratory

Lecture 9

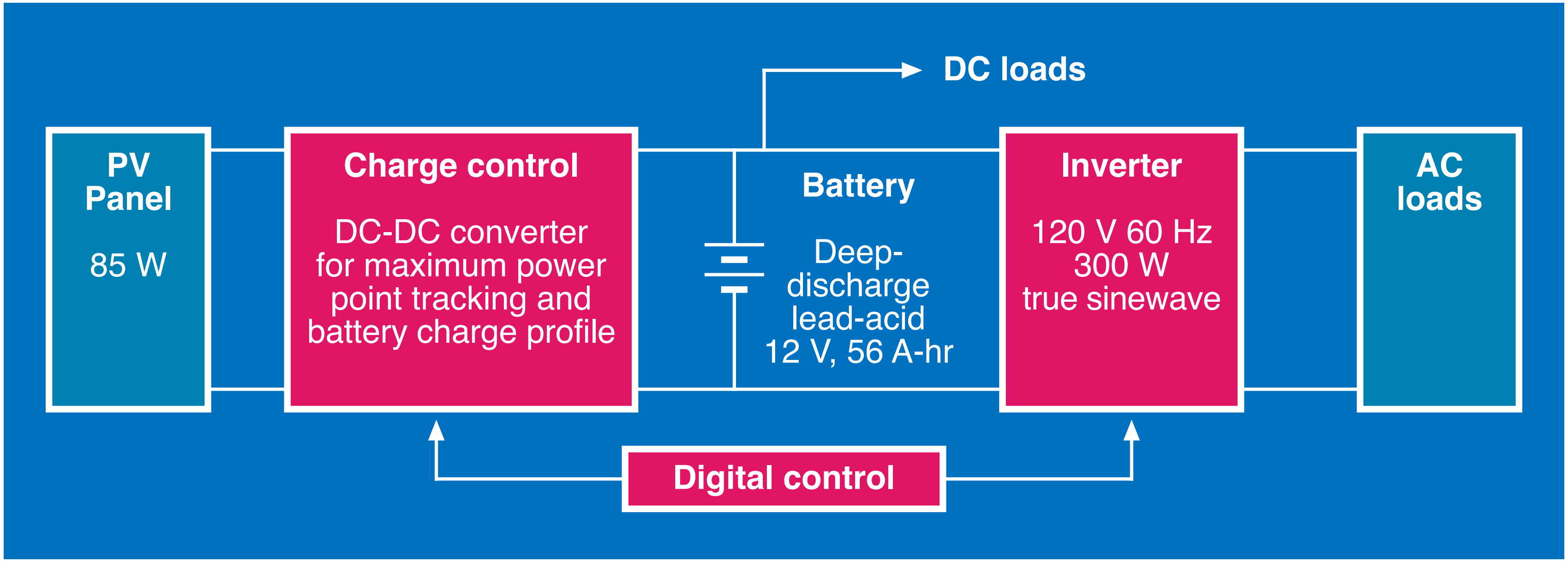
Compensator Design

and Modified Sine Wave Inverter

Announcements

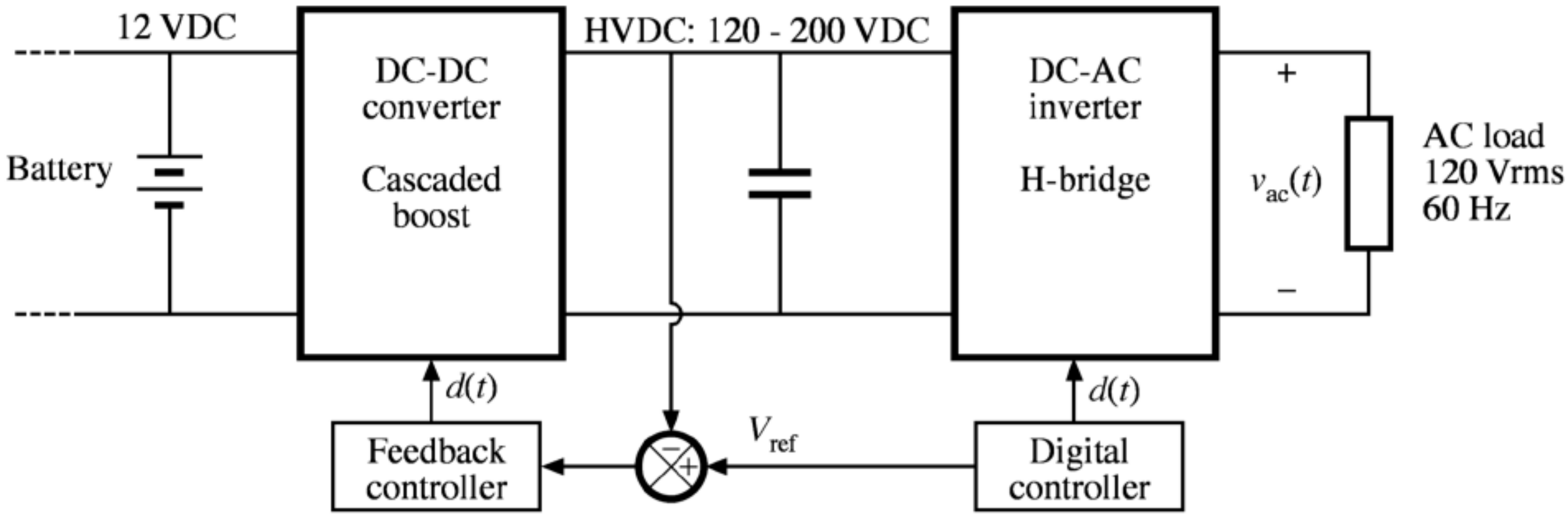
- This week's lab: Finish Experiment 4
  - Exp 4 Lab Report due by 11:59 pm (MT) on Friday April 7, 2017
- Following this: Experiment 5
  - Experiment 5 has a pre-lab (due 11:59 pm on Friday March 24, 2017)
  - Have 2 weeks to work on Experiment 5 (after Spring Break)
  - Exp 5 Lab Report due by 11:59 pm (MT) on Friday April 21, 2017
- Quiz 2 on Monday April 24, 2017
  - In-class 40-minute quiz administered during lecture time
  - Closed book/notes, calculator allowed
  - Will cover Experiment 4 and 5 material
- Expo (Final Demo) on Thursday May 4, 2017

Experiments



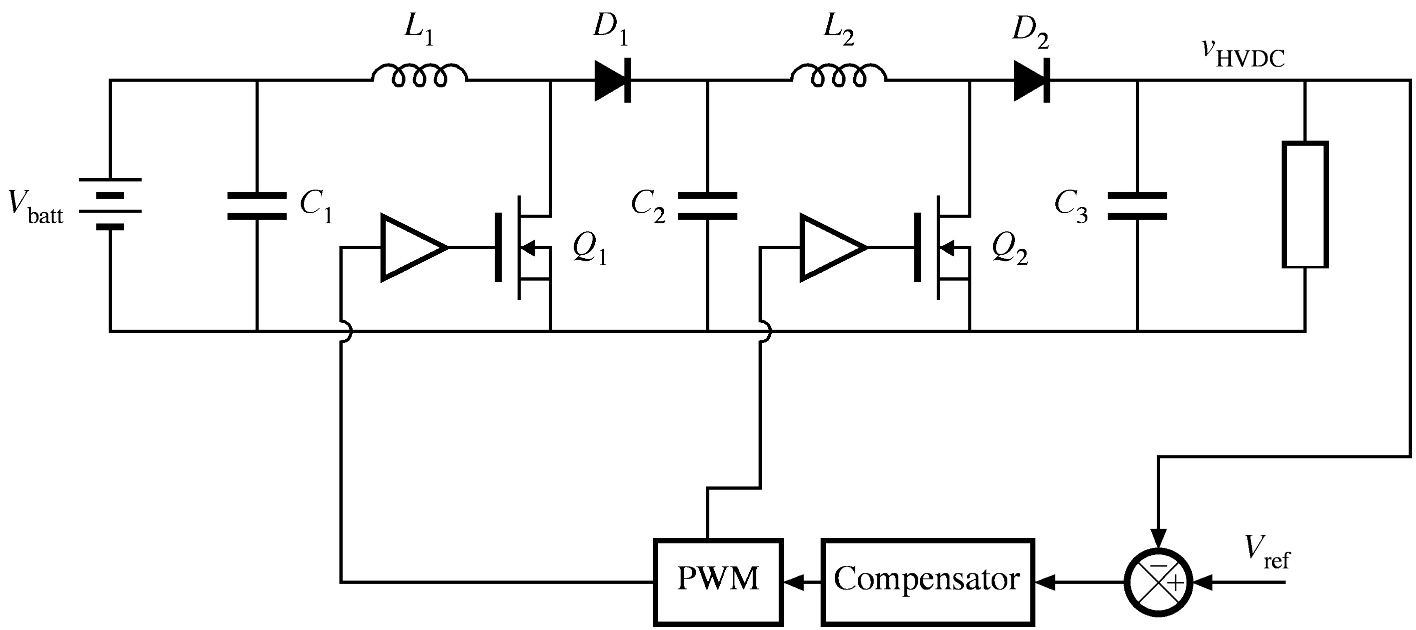
- Exp 1 – PV panel and battery characteristics and direct energy transfer
- Exp 2 – TI MSP430 microcontroller introduction
- Exp 3-1, 3-2 – Buck dc-dc converter for PV MPPT and battery charge control
- Exp 4 – Step-up 12V-200V dc-dc converter
- Exp 5 – Single-phase dc-ac converter (inverter)
- Expo –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

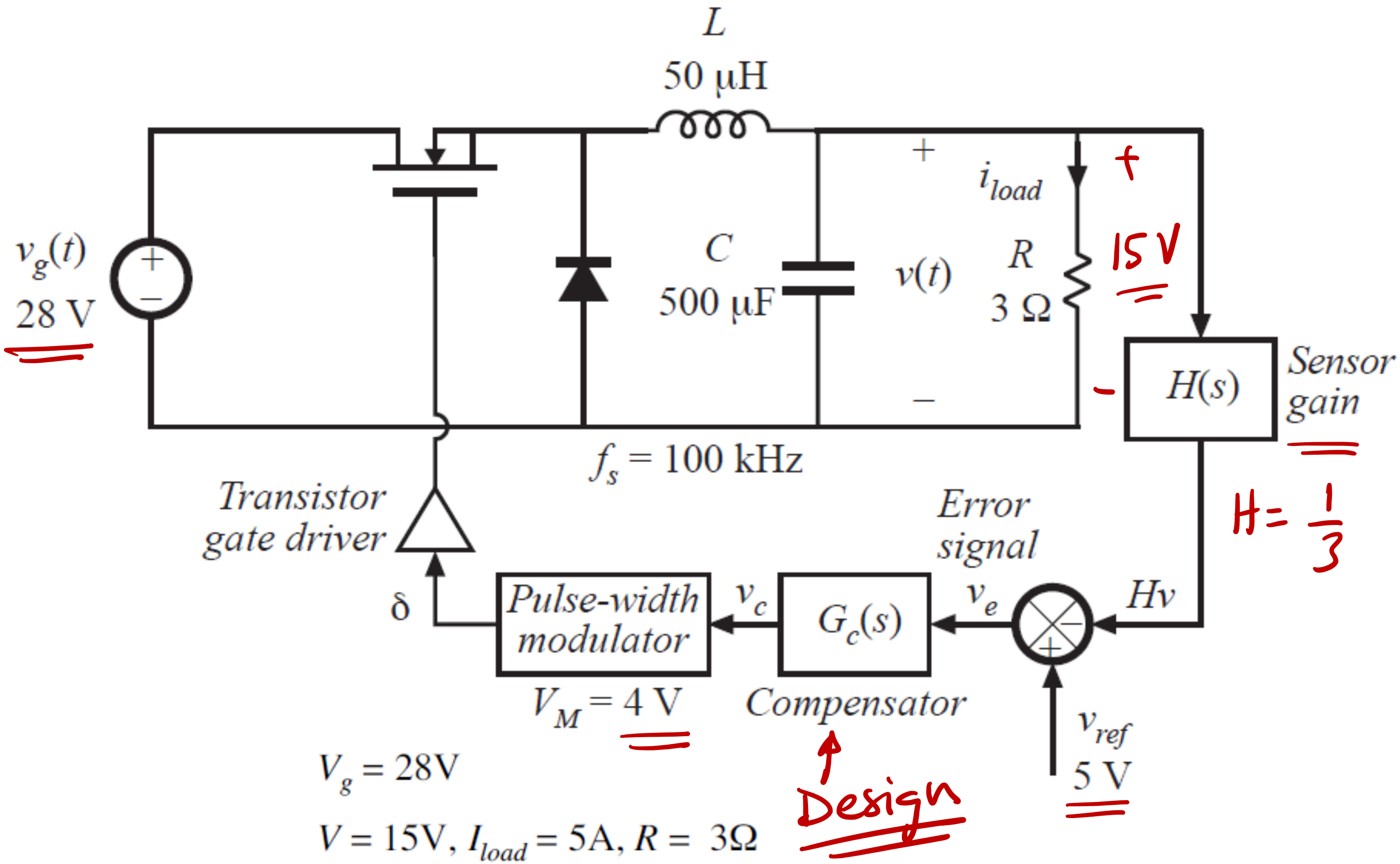
Experiment 4 - Cascaded Boost Converters



- **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

Compensator Design Example

Also see Compensator Design Example notes under Experiment 4 folder on D2L



Input voltage	$V_g = 28\text{V}$
Output	$V = 15\text{V},\ I_{load} = 5\text{A},\ R = 3\Omega$
Quiescent duty cycle	$D = 15/28 = 0.536$
Reference voltage	$V_{ref} = 5\text{V}$
Quiescent value of control voltage	$V_c = DV_M = 2.14\text{V}$
Gain $H(s)$	$H = V_{ref}/V = 5/15 = 1/3$

Design Specifications

f_c = 5 kHz

ϕ_m = 52°

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	$-\frac{D}{D'}$	$\frac{V}{D\,D'^2}$	$\frac{D'}{\sqrt{LC}}$	$D'R\sqrt{\frac{C}{L}}$	$\frac{D'^2R}{D\,L}$

Uncompensated Loop Gain

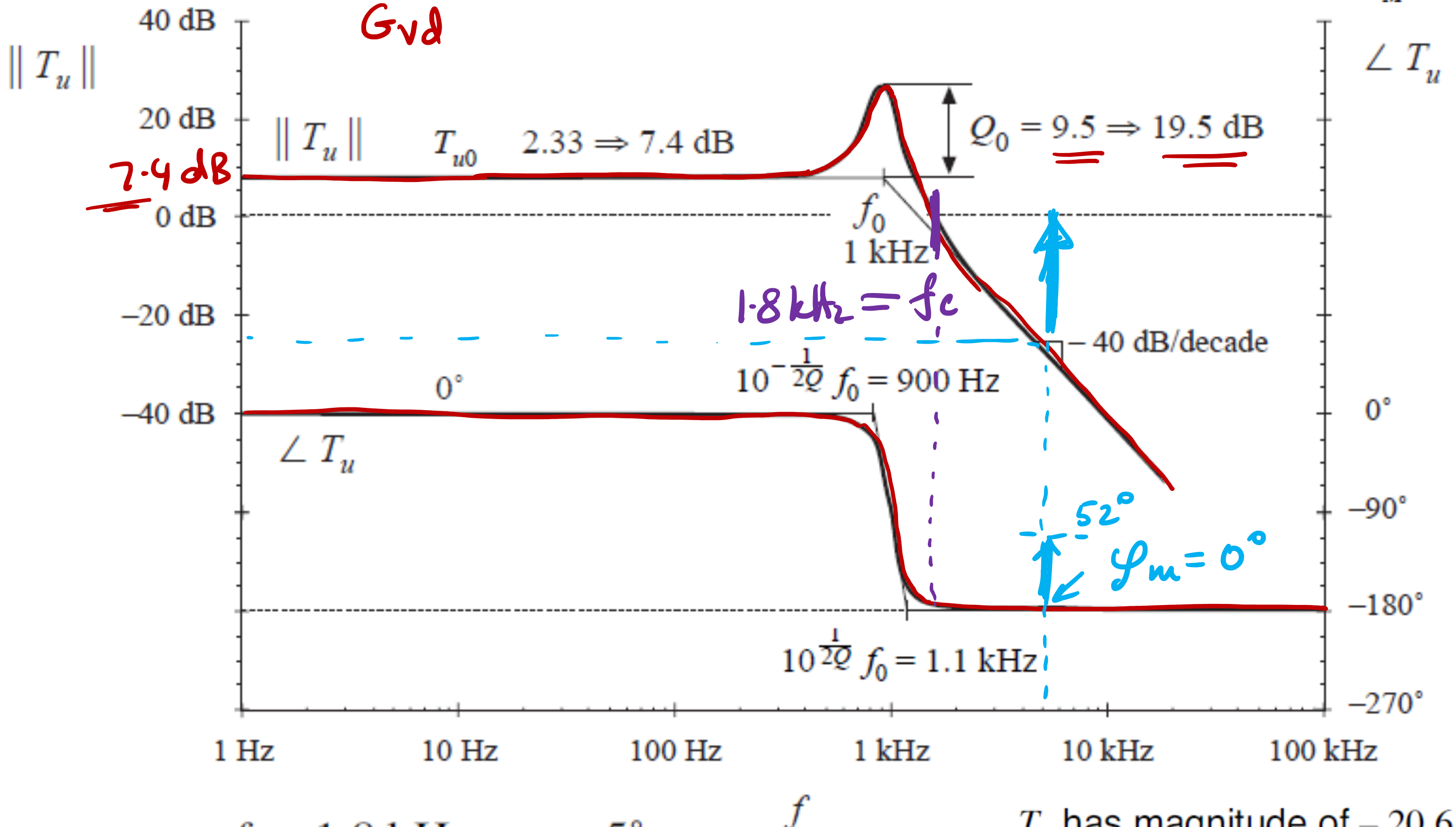
$$T(s) = \frac{\cancel{G_c(s)}\, H(s)}{V_M} \frac{V}{D} \frac{1}{1 + \frac{s}{Q_0 \omega_0} + \left(\frac{s}{\omega_0}\right)^2} \Rightarrow T_u(s) = T_{u0} \frac{1}{1 + \frac{s}{Q_0 \omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

$\frac{28}{12} = 2.33$

G_{vd}

T_u

$$T_{u0} = \frac{H\,V}{D\,V_M} = 2.33 \Rightarrow 7.4\text{dB}$$



Want

$f_c = 5$ kHz

$\phi_m = 52°$

$f_c = 1.8$ kHz, $\varphi_m = 5°$

T_u has magnitude of – 20.6 dB at 5 kHz

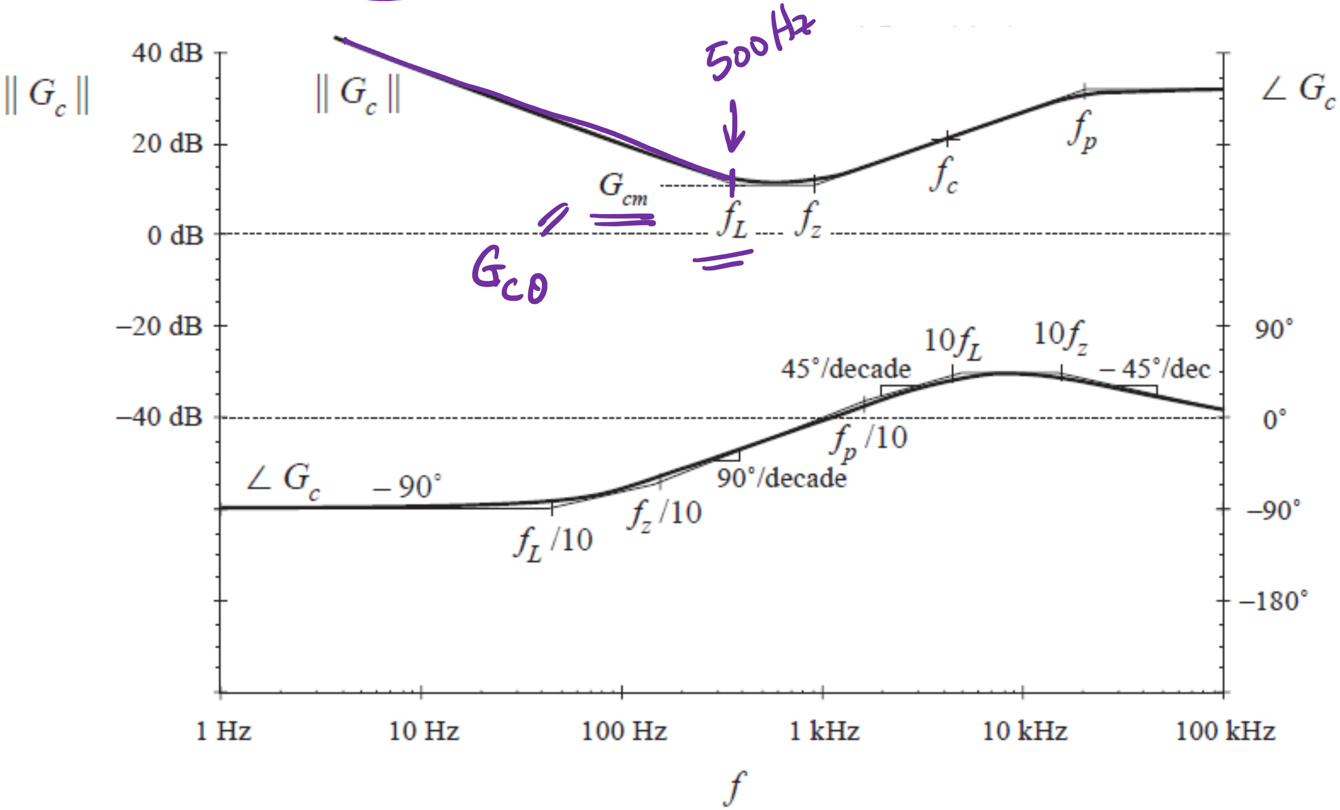
T_u has phase of approximately – 180° at 5 kHz

Improved Compensator (PID)

PD

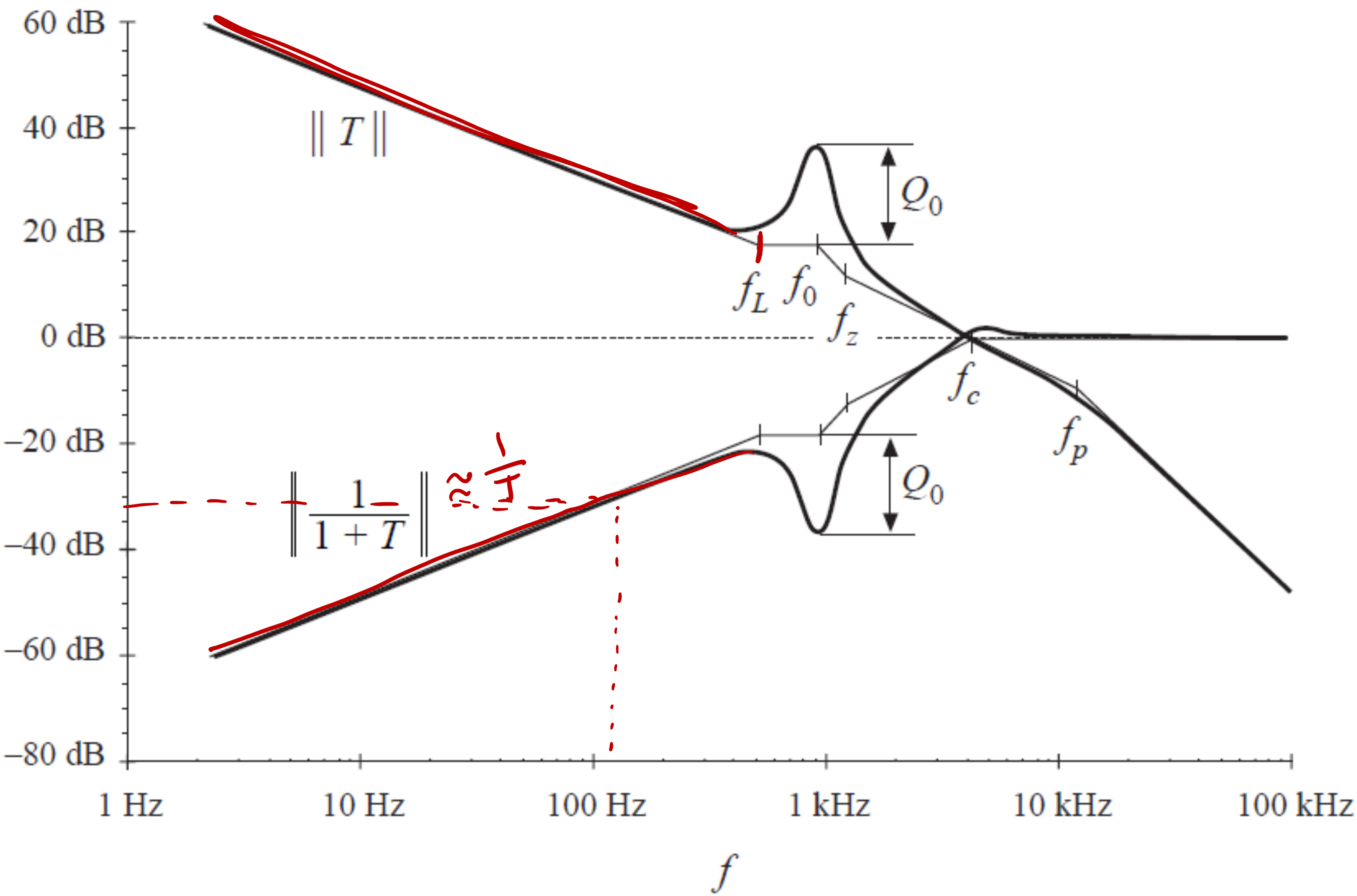
$$G_c(s) = G_{cm} \frac{\left(1 + \frac{s}{\omega_z}\right)\left(1 + \frac{\omega_L}{s}\right)}{\left(1 + \frac{s}{\omega_p}\right)}$$

PI



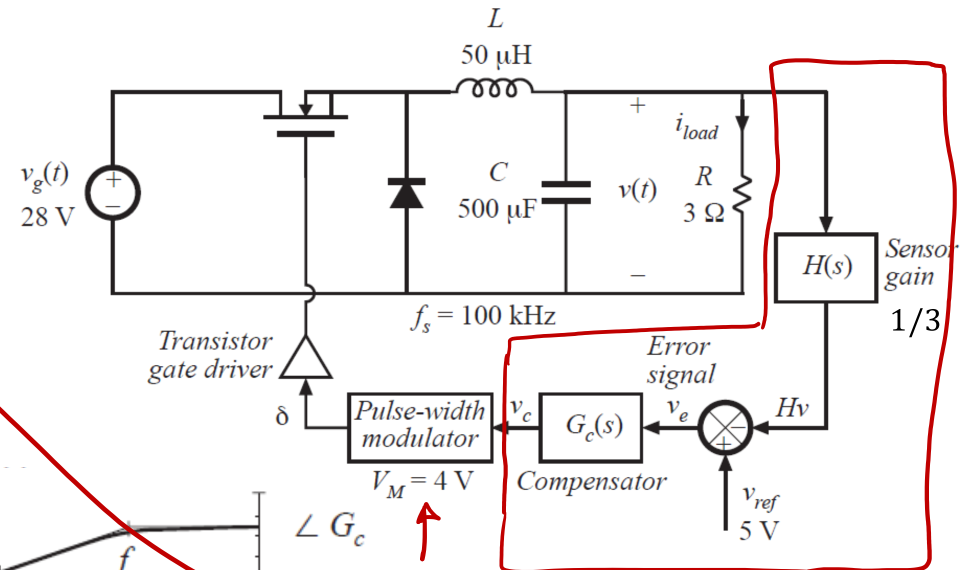
- add inverted zero to PD compensator, without changing dc gain or corner frequencies
- choose f_L to be $f_c/10$, so that phase margin is unchanged

Loop Gain and 1/(1+T) with PID Compensator

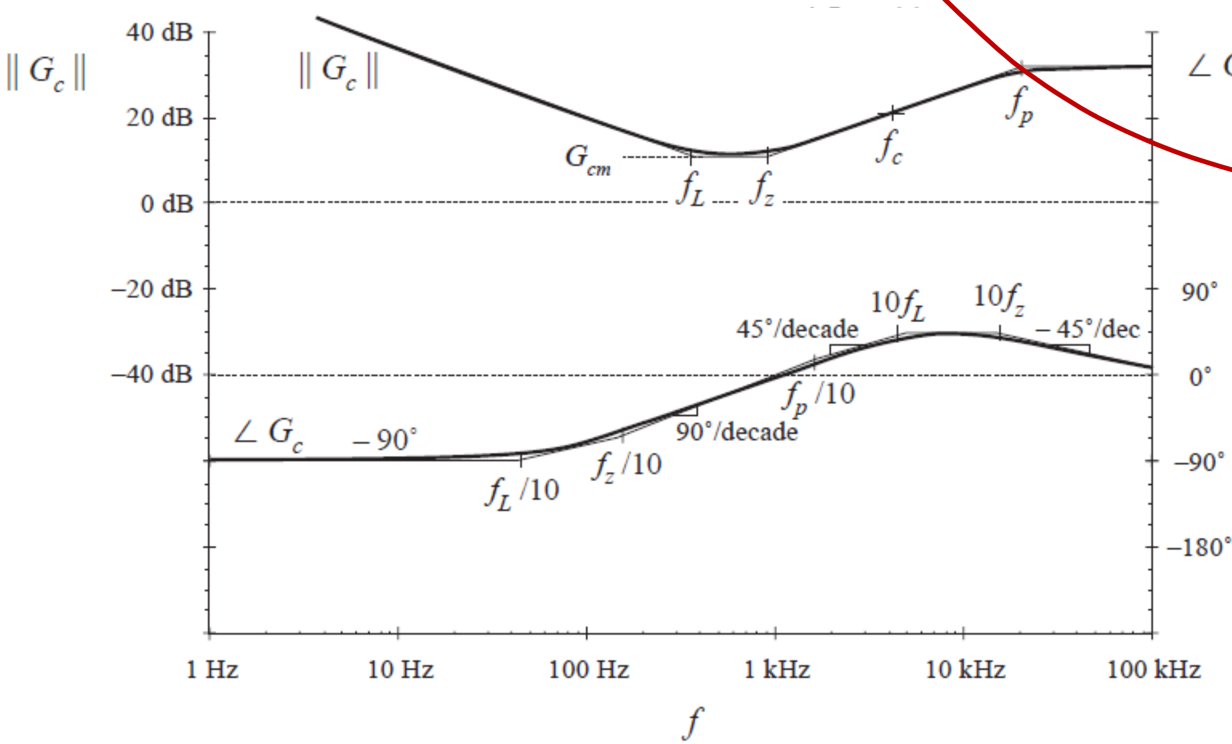


Compensator Implementation

$$\boxed{v_c = G_c\left(v_{ref} - Hv\right)}$$



Today's Focus

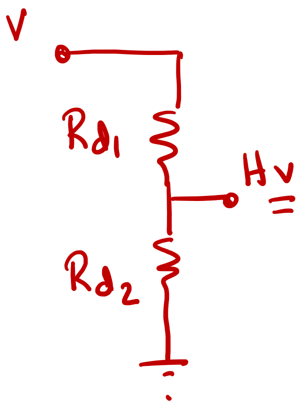


$$H = \frac{1}{3}$$

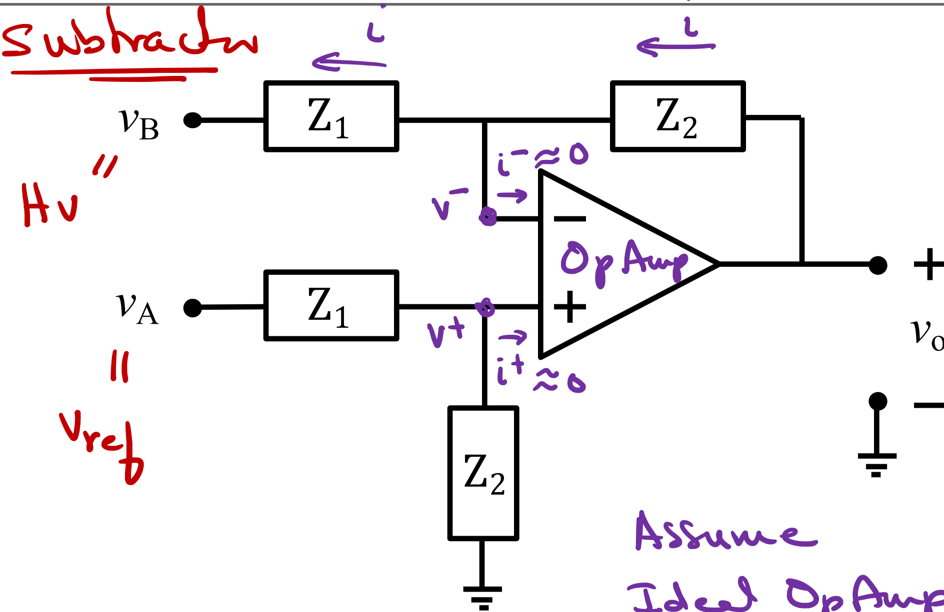
$$v_{ref} = 5\text{ V}$$

Divider and OpAmp Subtractor

$$v_c = G_c(\underbrace{v_{ref} - Hv})$$



Subtractor



Assume Ideal OpAmp

$$v^+ = \frac{Z_2}{Z_1+Z_2} v_A$$

Because of negative feedback in OpAmp

$$\underline{v^+ \approx v^-}$$

$$v_o = v^- + Z_2 i \quad \& \quad i = \frac{v^- - v_B}{Z_1}$$

$$\Rightarrow v_o = v^- + \frac{Z_2}{Z_1}(v^- - v_B) = v^-\left(\frac{Z_1+Z_2}{Z_1}\right) - \frac{Z_2}{Z_1} v_B$$

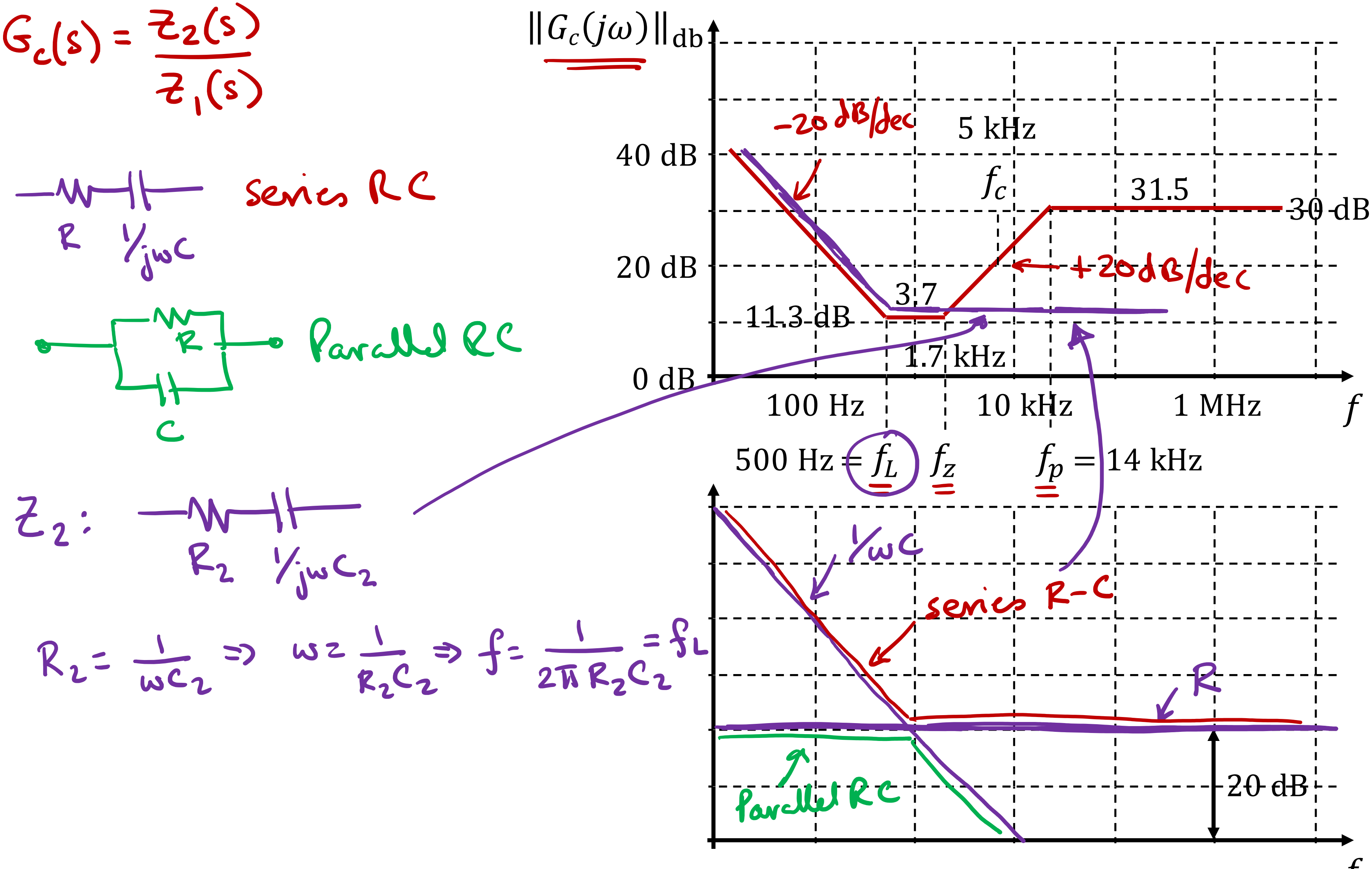
$$\Rightarrow v_o = \frac{Z_2}{\cancel{Z_1+Z_2}}\left(\frac{\cancel{Z_1+Z_2}}{Z_1}\right) - \frac{Z_2}{Z_1} v_B \Rightarrow \boxed{v_o = \frac{Z_2}{Z_1}(v_A - v_B)}$$

$$v_o = \underbrace{\frac{Z_2}{Z_1}}_{= G_c(s)}(v_{ref} - Hv) = v_c$$

$$v_o = \frac{Z_2}{Z_1}(v_A - v_B)$$

Implementing Z_1 and Z_2

$$G_c(s) = \frac{Z_2(s)}{Z_1(s)}$$



$$R_2 = \frac{1}{\omega C_2} \Rightarrow \omega = \frac{1}{R_2 C_2} \Rightarrow f = \frac{1}{2\pi R_2 C_2} = f_L$$

Implementing Z_1 and Z_2 (Cont.)

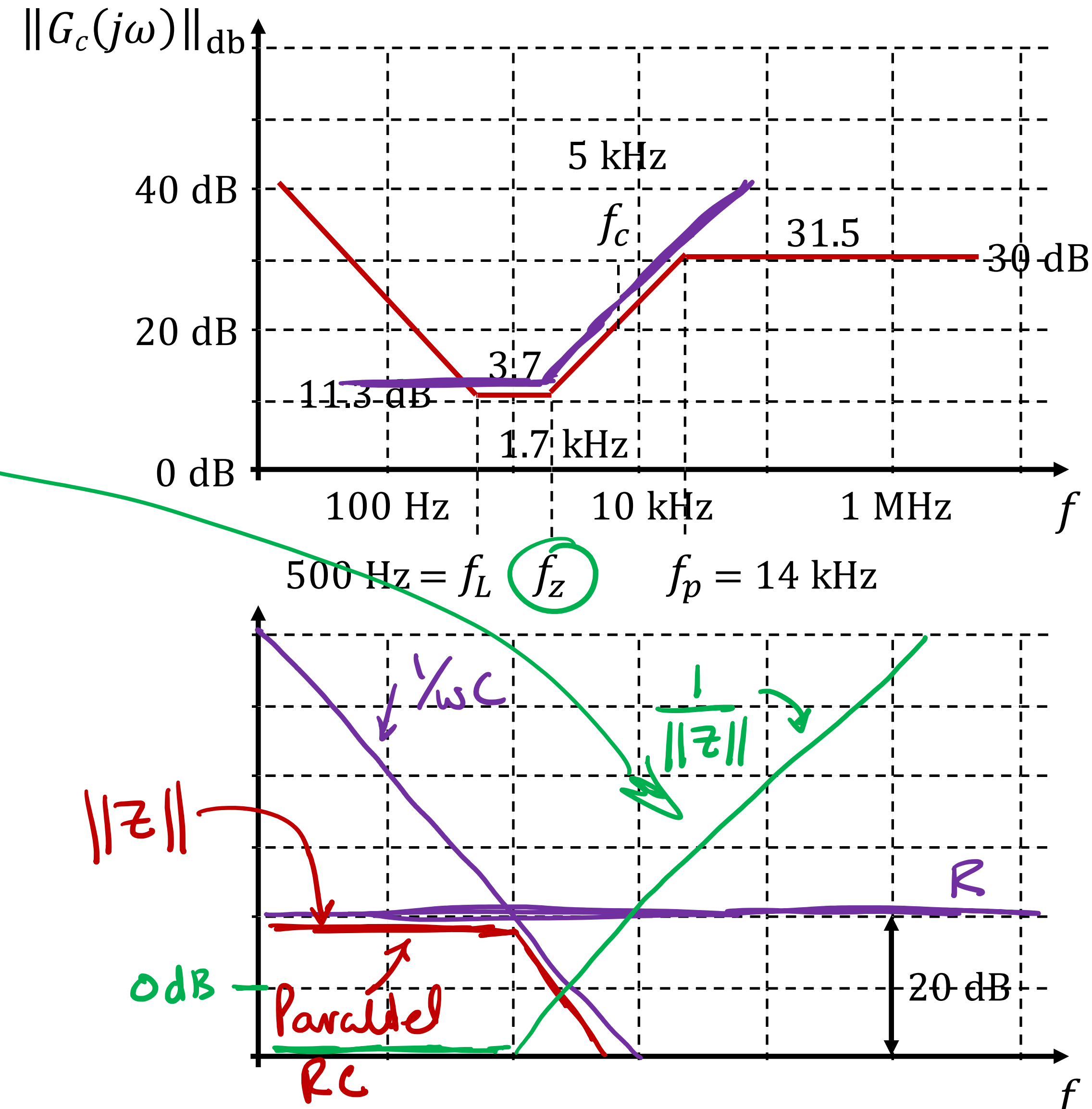
$$G_c(s) = \frac{Z_2}{Z_1} = Z_2 \cdot \frac{1}{Z_1}$$

Z_1:

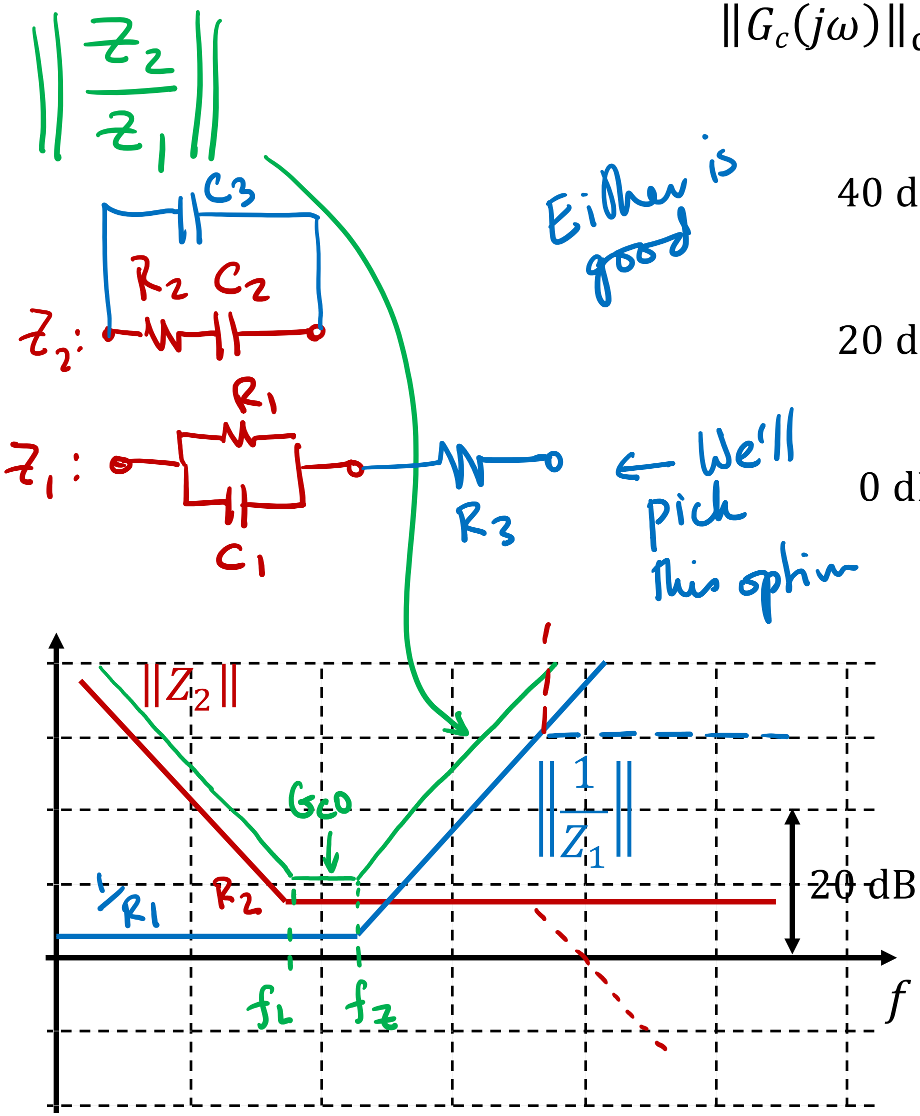
R_1

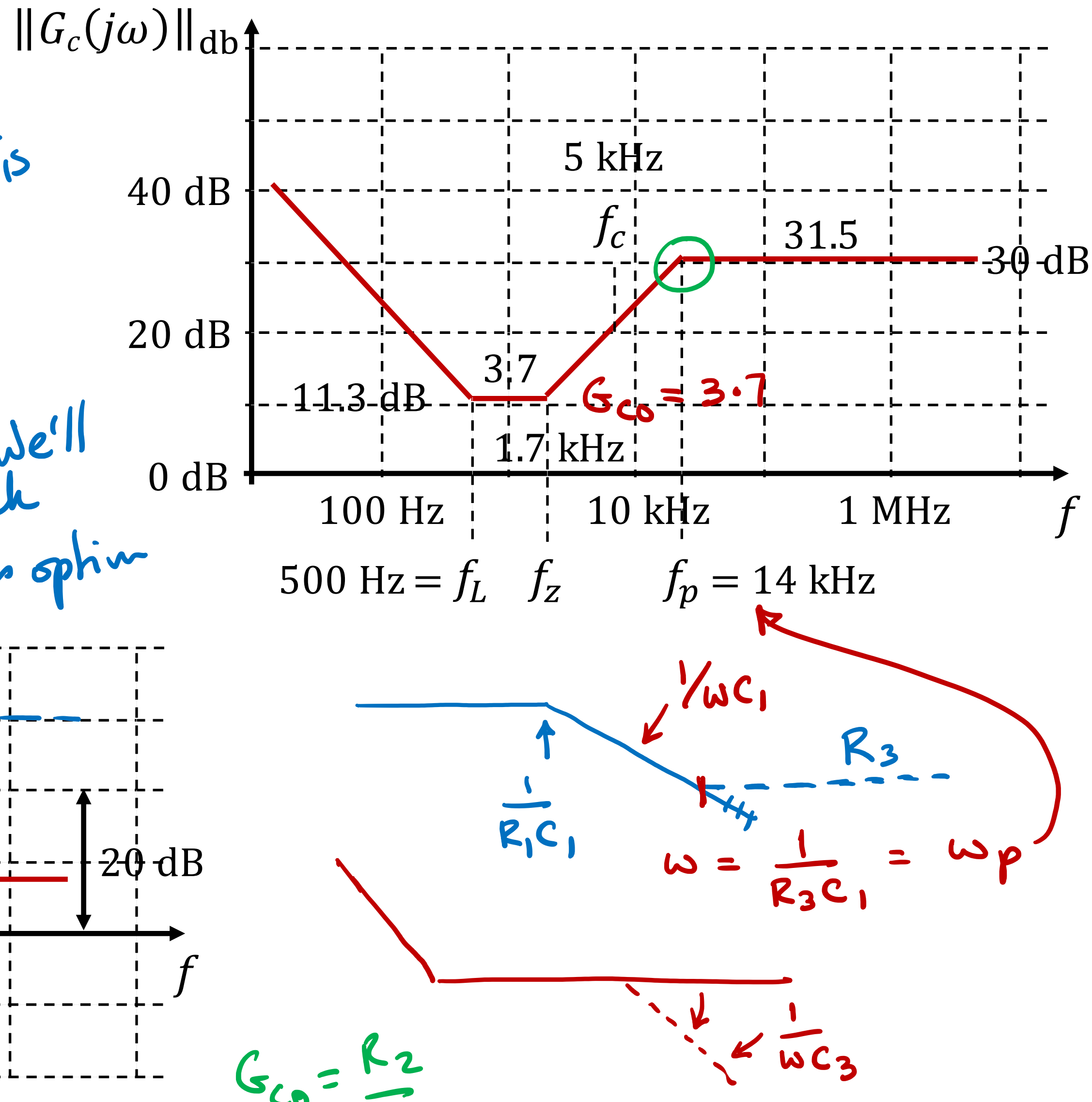
C_1

$$f = \frac{1}{2\pi R_1 C_1} = f_z$$



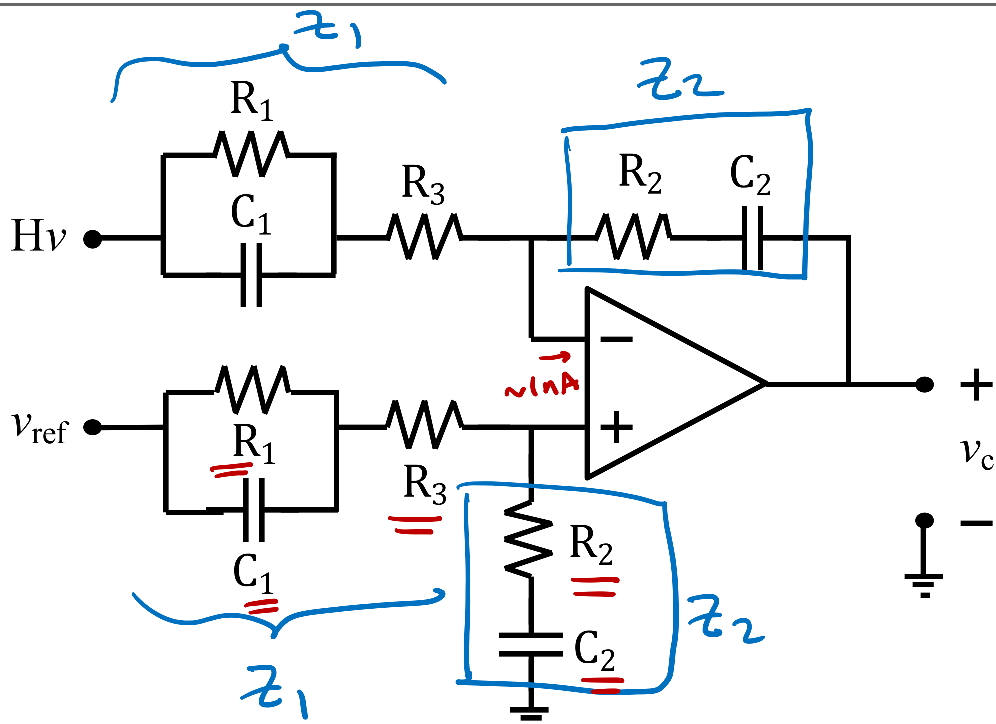
Z_2/Z_1 Bode Plot





$G_{c0} = \frac{R_2}{R_1}$

OpAmp Based Compensator



Design Equations

$$G_{c0} = \frac{R_2}{R_1}$$

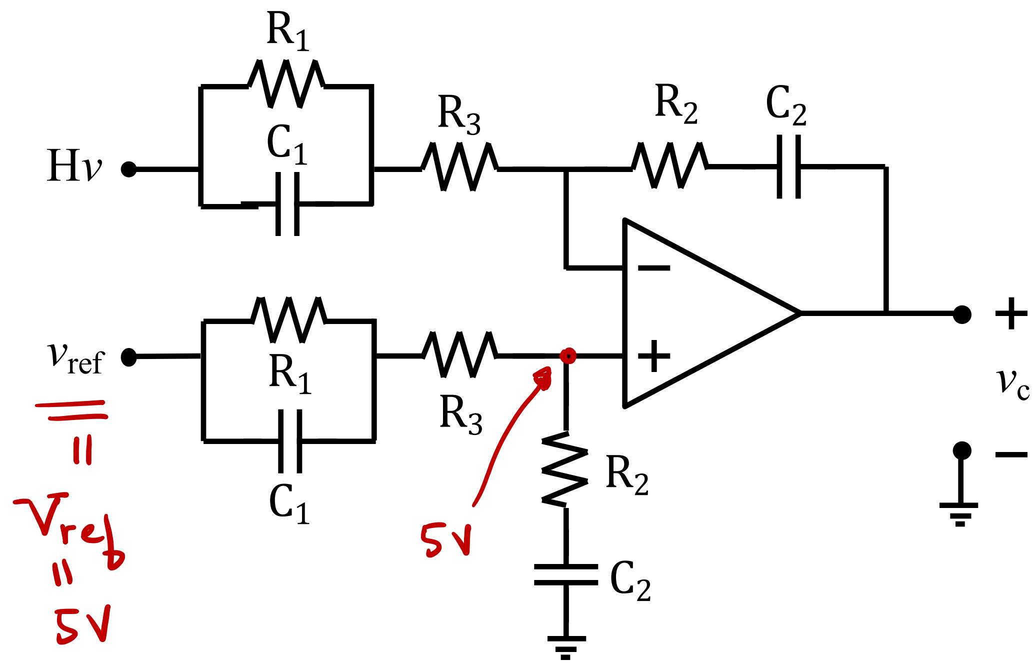
$$f_L = \frac{1}{2\pi R_2 C_2}$$

$$f_z = \frac{1}{2\pi R_1 C_1}$$

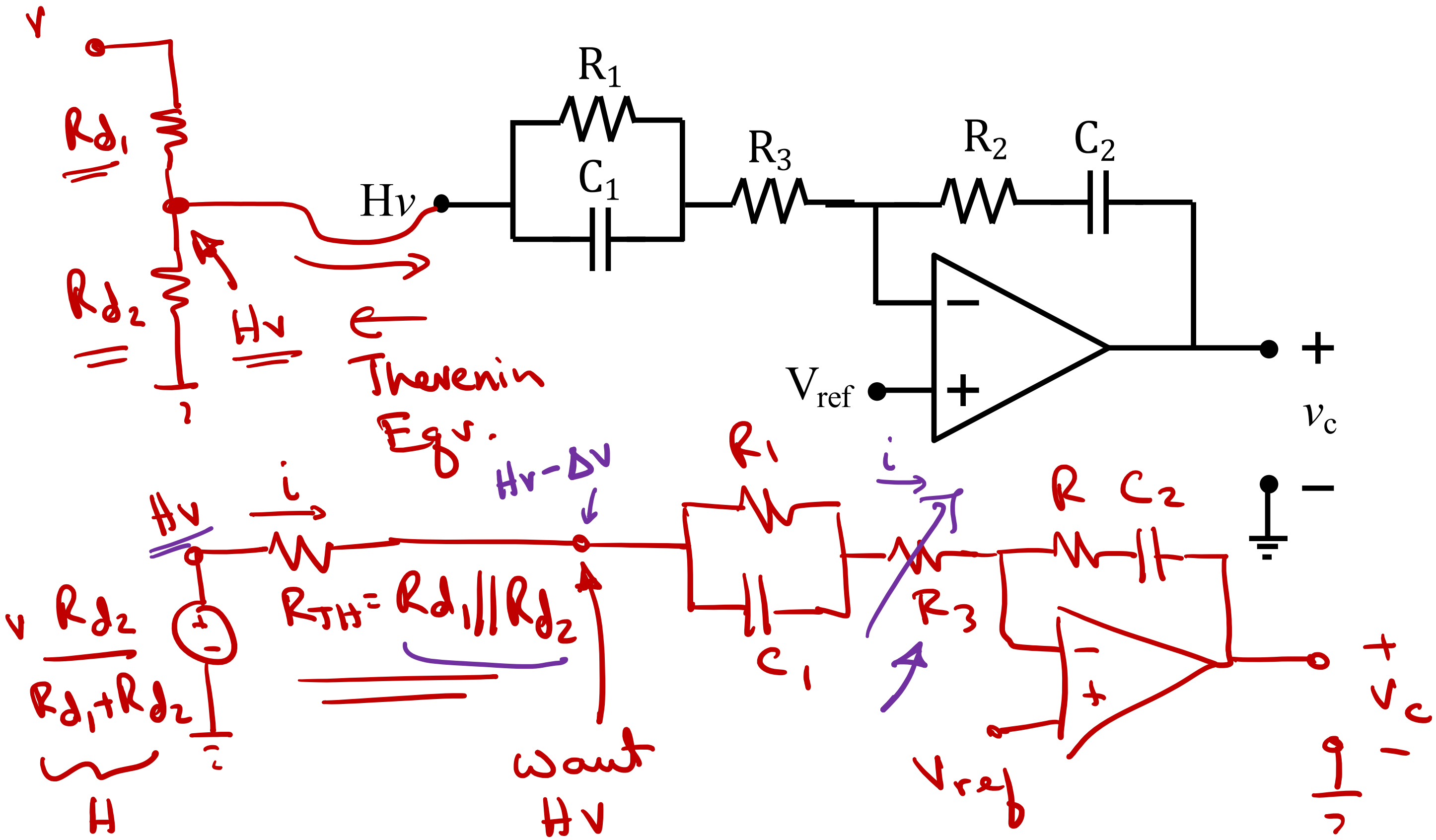
$$f_p = \frac{1}{2\pi R_3 C_1}$$

$R_2 = 100\,k\Omega$

Possible Simplification for Fixed Reference Voltage

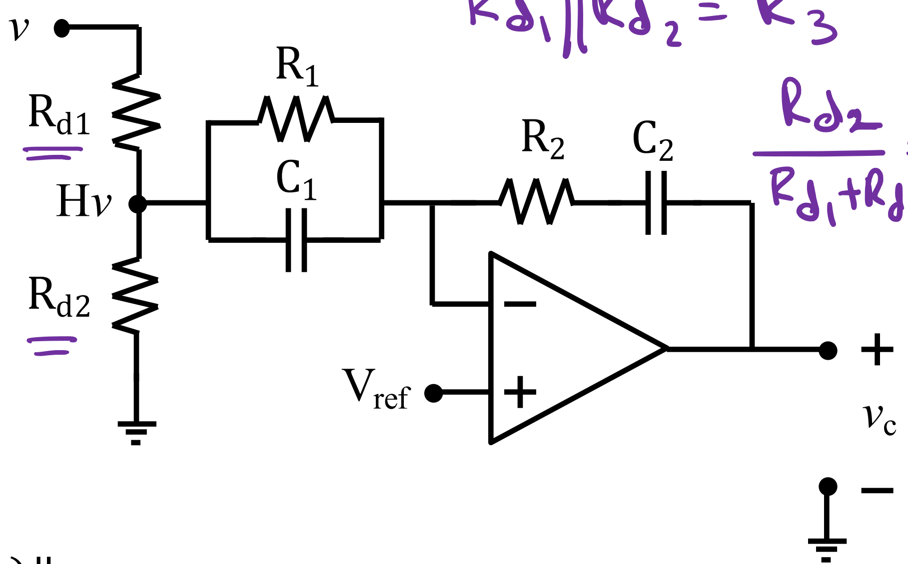


Incorporating the Divider and Loading Effect



$R_{d_1} \| R_{d_2} = R_3$

Final Design



$$R_{d_1} \| R_{d_2} = R_3$$

$$\frac{R_{d_2}}{R_{d_1}+R_{d_2}} = \frac{1}{3}$$

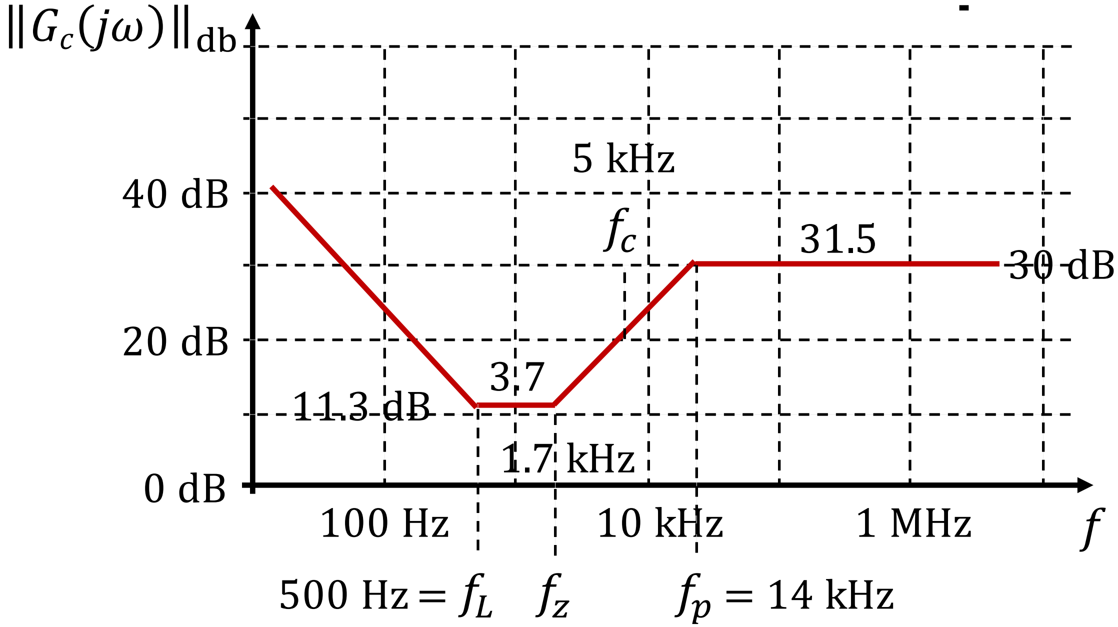
$$\Rightarrow \begin{cases} R_{d1} = 10\ \text{k}\Omega \\ R_{d2} = 5\ \text{k}\Omega \end{cases}$$

$R_1 = 27\ \text{k}\Omega$

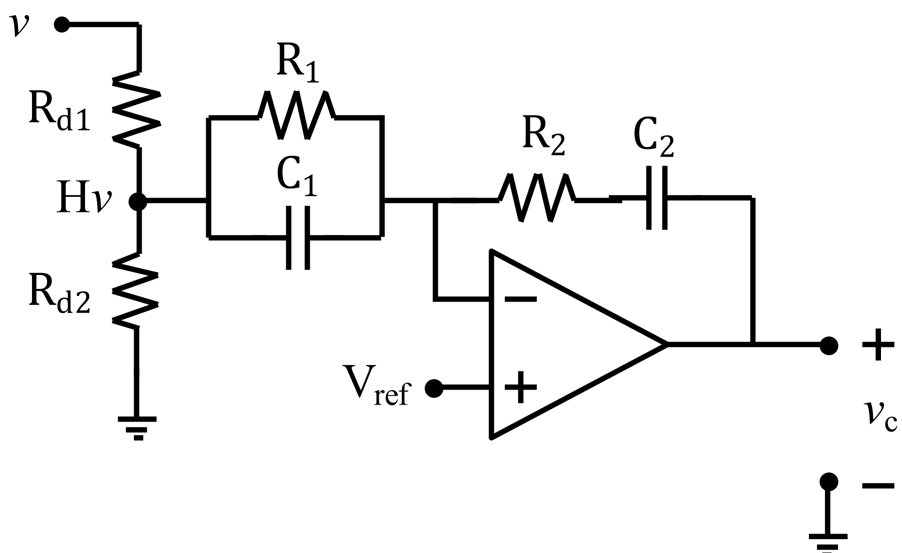
$C_1 = 3.5\ \text{nF}$

$R_2 = 100\ \text{k}\Omega$

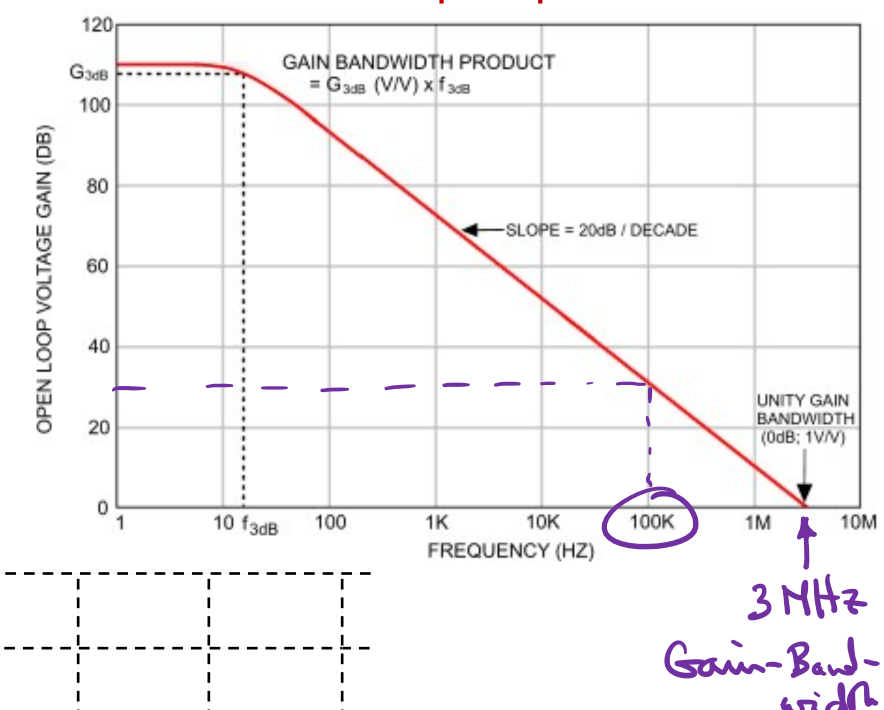
$C_2 = 3.2\ \text{nF}$

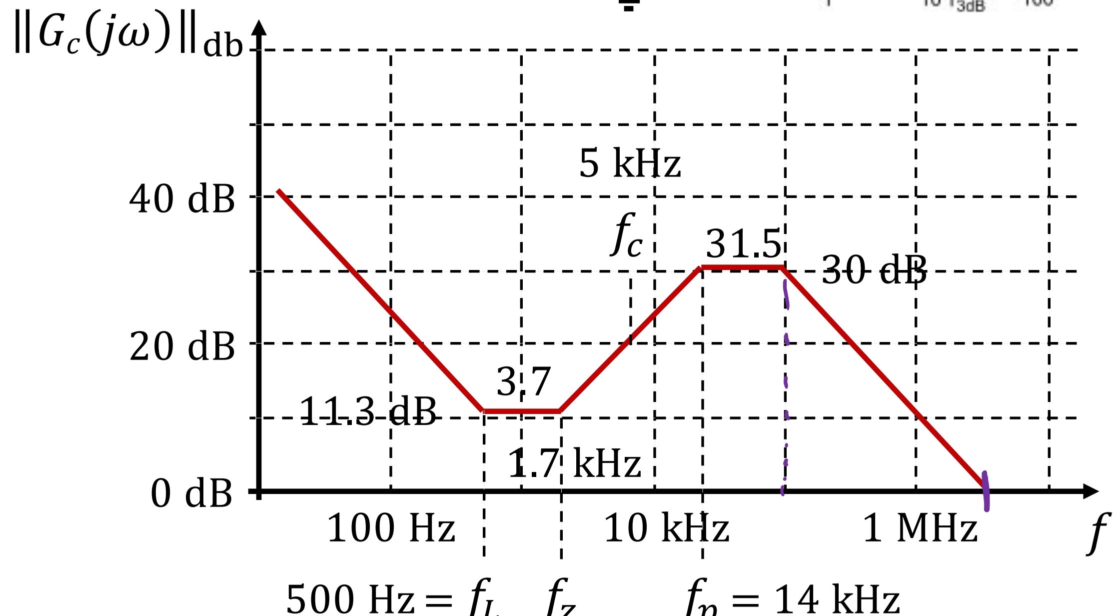


Performance with Real OpAmp

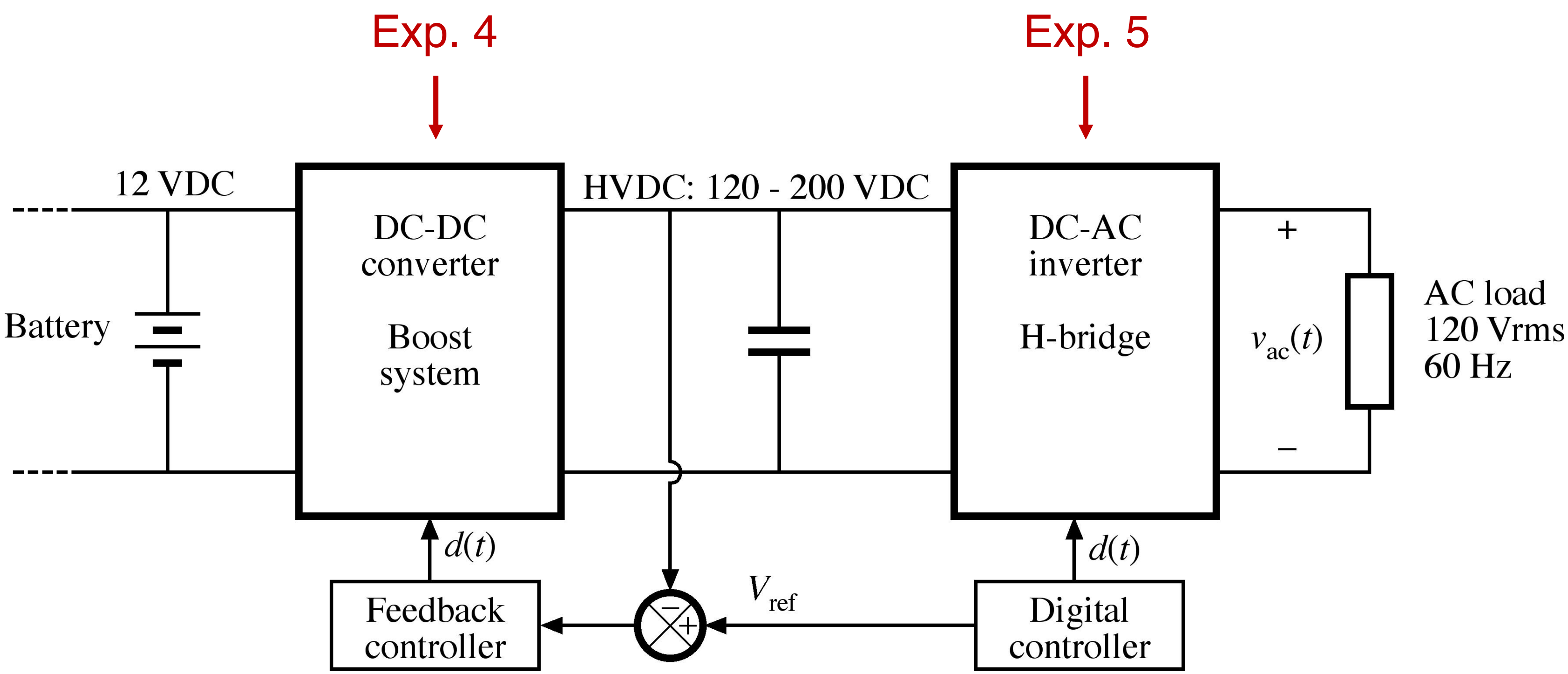


Real OpAmp Gain



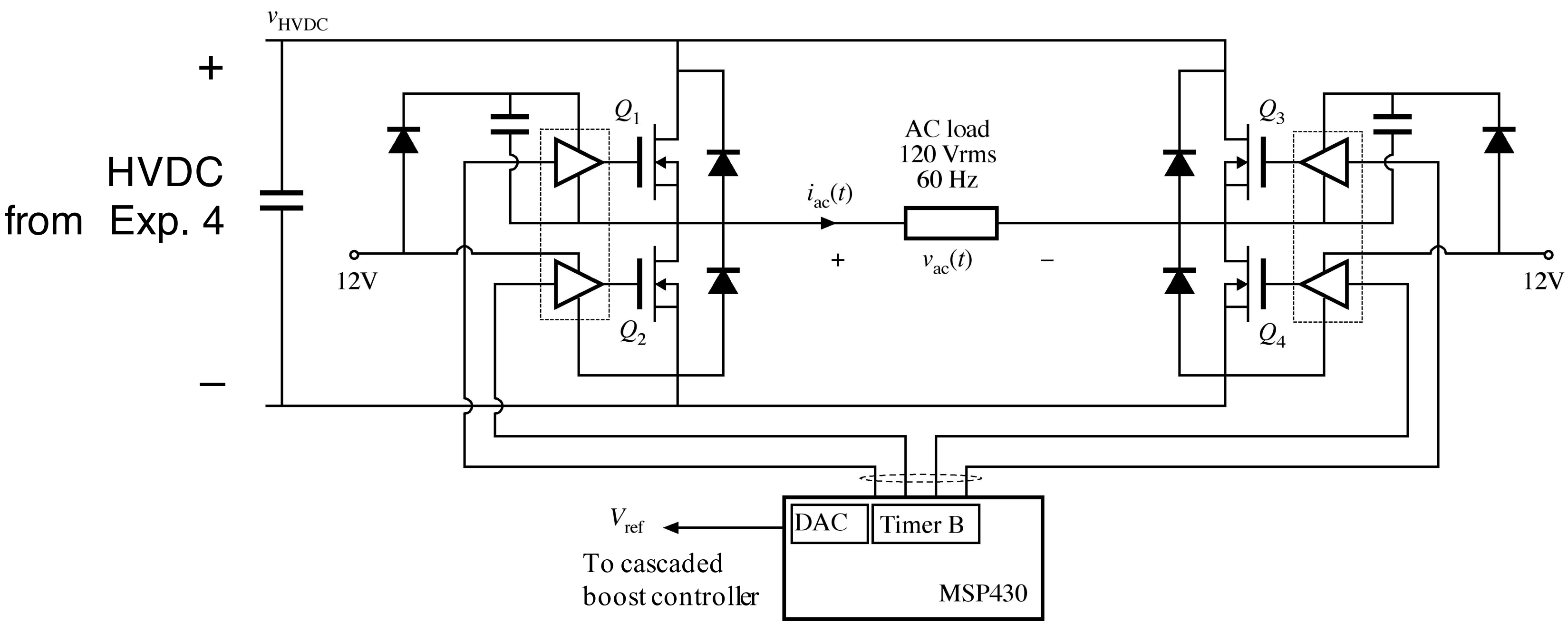


Experiment 5 – Off-Grid Inverter



- **Required**: Demonstrate modified sine-wave inverter
- **Extra Credit**: Demonstrate PWM inverter

Off-Grid H-Bridge Inverter

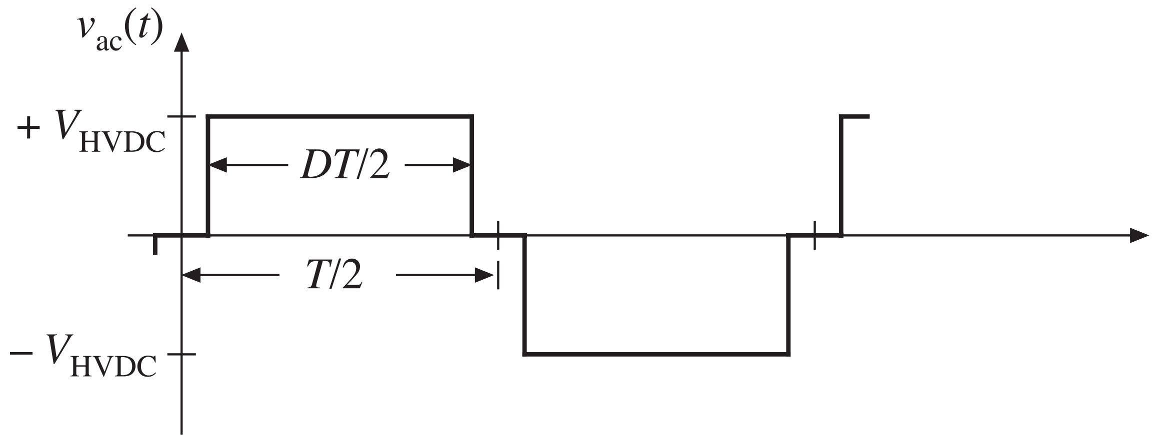


- Need MOSFETs and half-bridge gate drivers
- Filtering of ac output not explicitly shown
- Grid-tied: control i_{ac}(t)
- Off-grid: control v_{ac}(t)

“Modified Sine Wave” Inverter

v_{ac}(t) has a rectangular waveform

Inverter transistors switch at 60 Hz, T = 16.66 msec



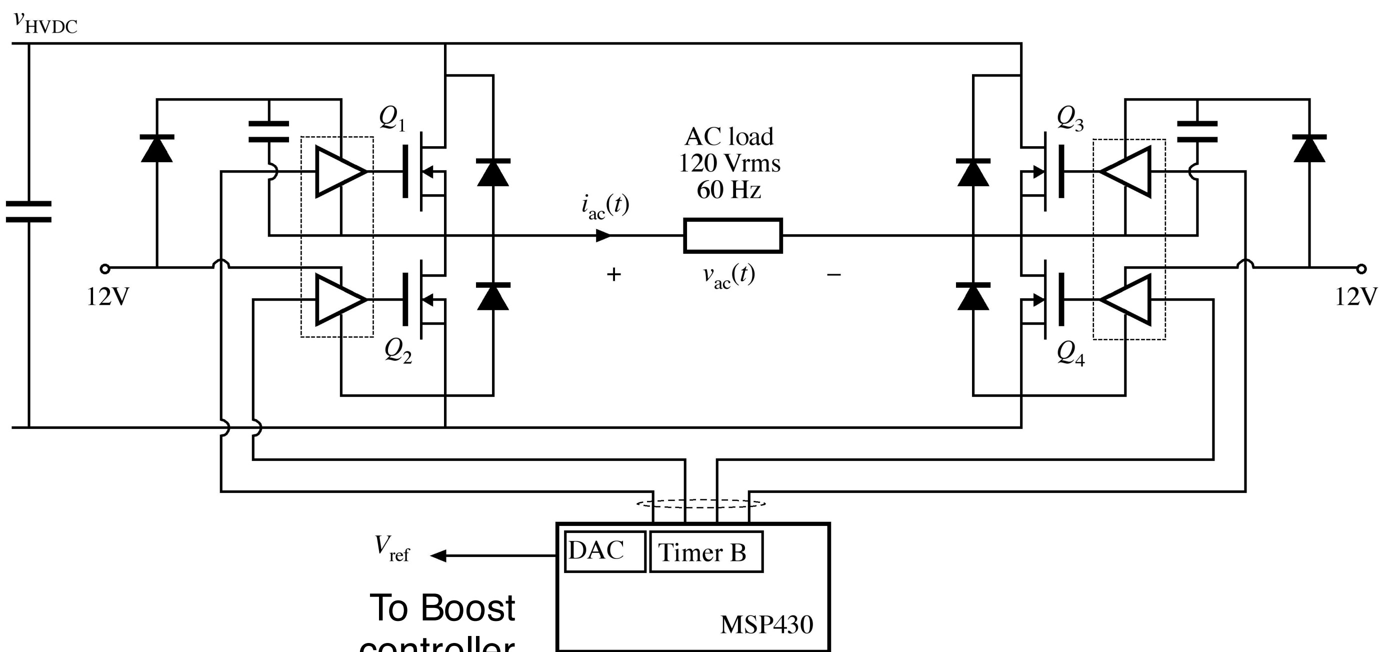
RMS value of v_{ac}(t) is:

$$V_{ac,RMS} = \sqrt{\frac{1}{T}\int_0^T v_{ac}^2(t)\,dt} = \sqrt{D}\,V_{HVDC}$$

- Choose V_{HVDC} larger than desired $V_{ac,RMS}$
- Can regulate value of $V_{ac,RMS}$ by variation of D
- Waveform is highly nonsinusoidal, with significant harmonics

Inverter Control

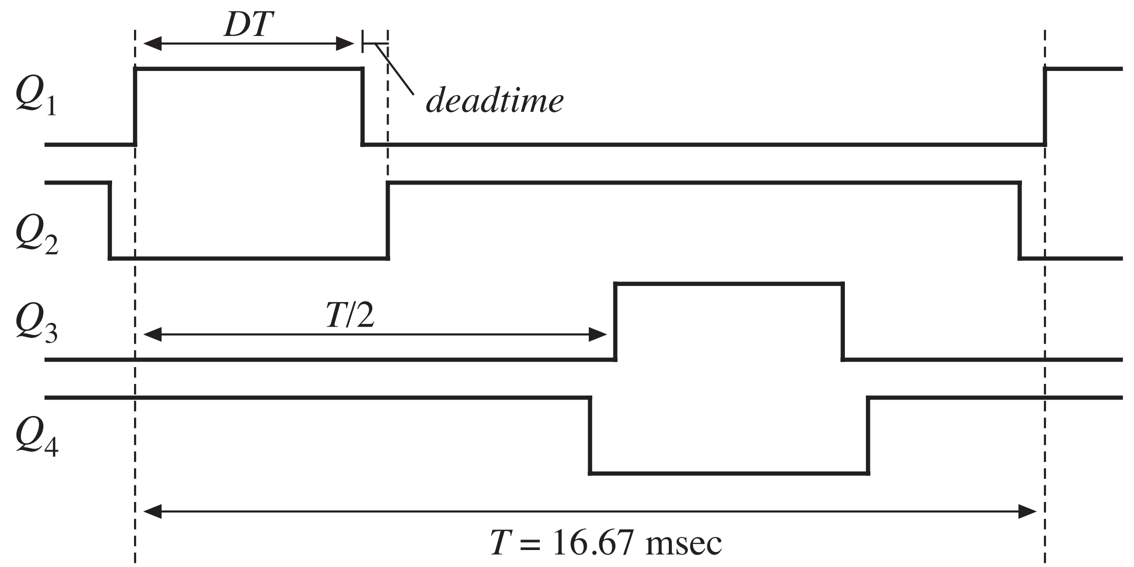
- Use MSP430 to control the MOSFET gate drivers
  - Can use Timer A (or logic outputs) to generate drive signals



To Boost controller

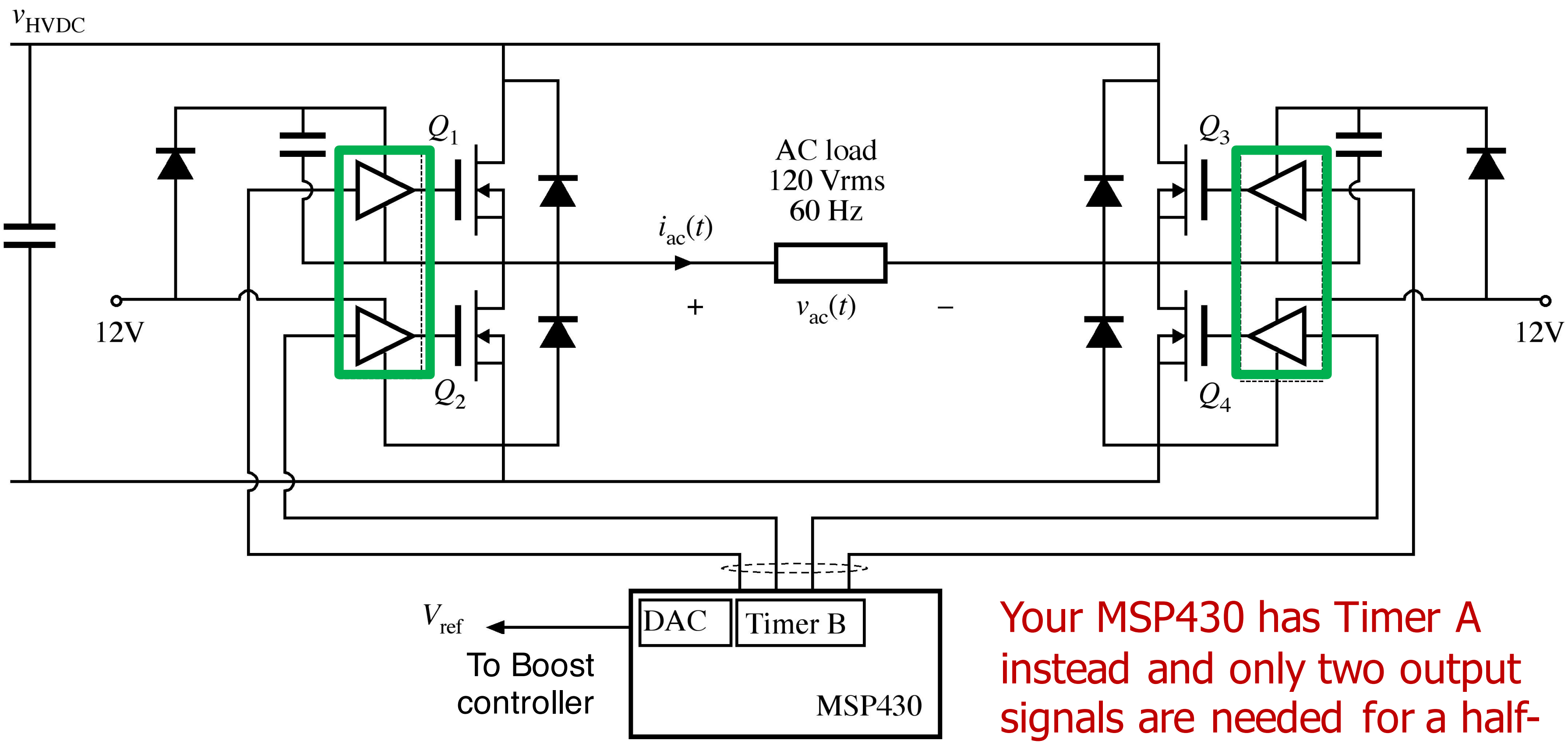
- Your goal: adjust V_{ref} and inverter duty cycle to obtain V_{ac} = 120 V rms

Gate Drive Timing



- For modified sine wave inverter: switch once per ac half cycle
- Adjust duty cycle to control rms voltage
- Require deadtime > (switching/delay times of MOSFETs plus gate drivers); otherwise, simultaneous conduction of Q_1 and Q_2 causes “shoot-through” current that can damage MOSFETs

Half-Bridge Gate Drivers



Your MSP430 has Timer A instead and only two output signals are needed for a half-bridge driver

Half-bridge gate driver examples: IR21094 and FAN 73832
(your parts kit has IR21094)

Half-Bridge Gate Driver Functionality

Contains two MOSFET drivers:
- Low side driver
- High side driver

High side driver includes
- Level-shifting circuitry
- Provisions for bootstrap power supply

Undervoltage lockout circuitry holds MOSFETs off when driver power supply is below threshhold

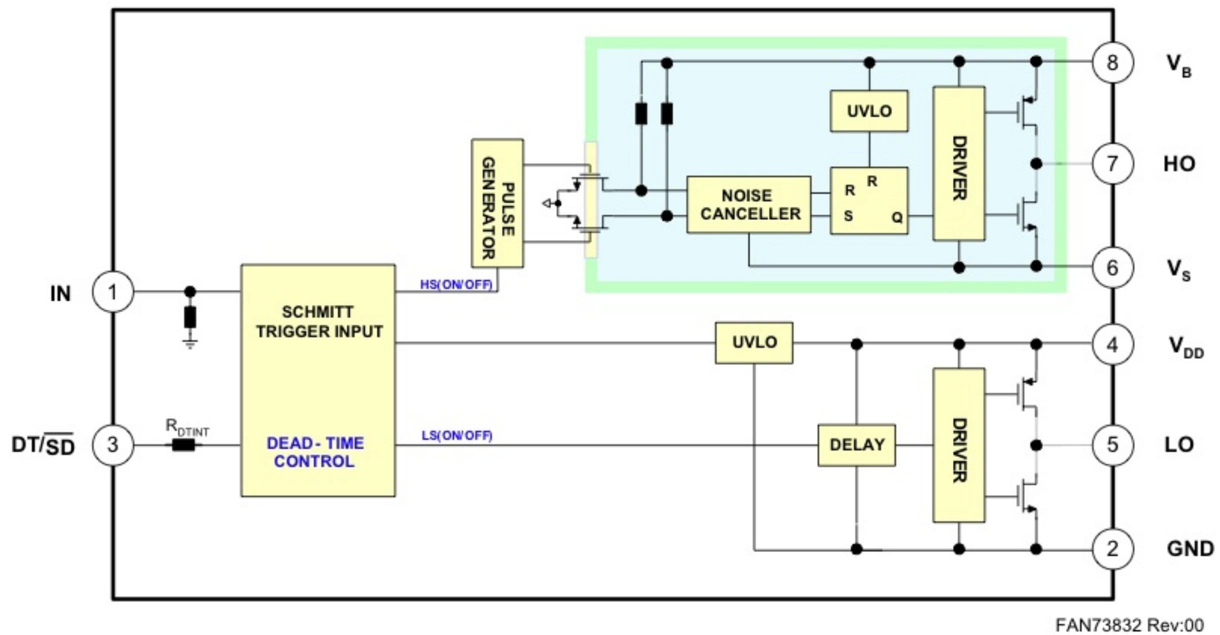
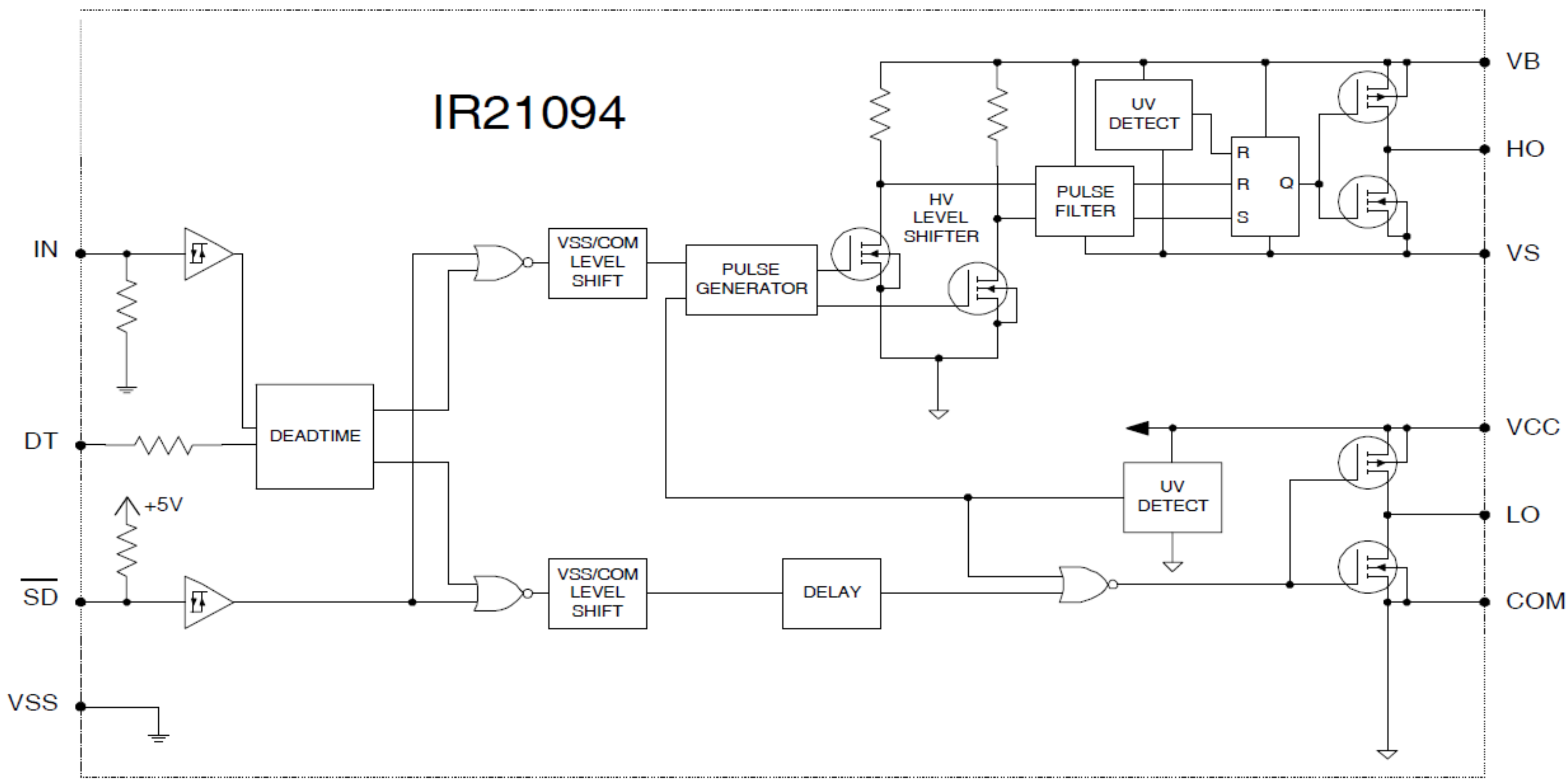
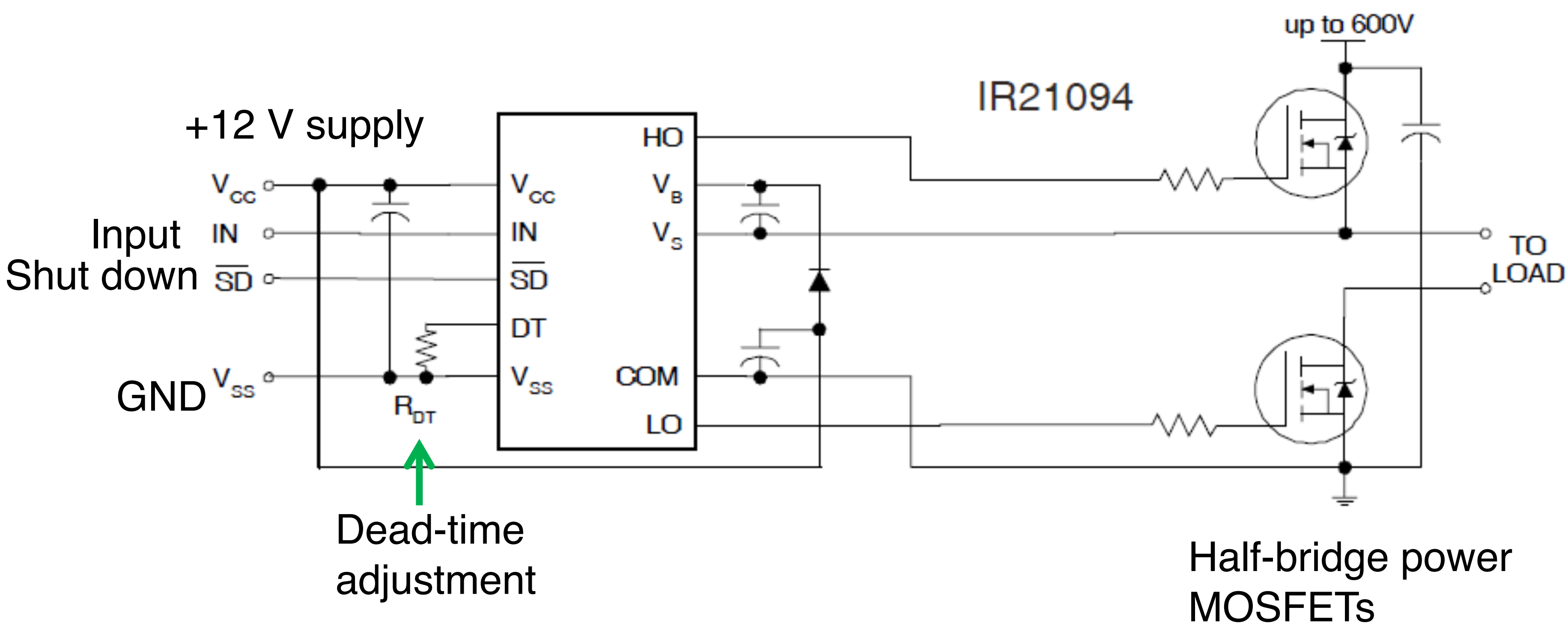


Figure 3. Functional Block Diagram of FAN73832

Half-Bridge Gate Driver - IR21094



Half-Bridge Gate Driver Circuit Example



Half-Bridge Gate Driver Circuit Example

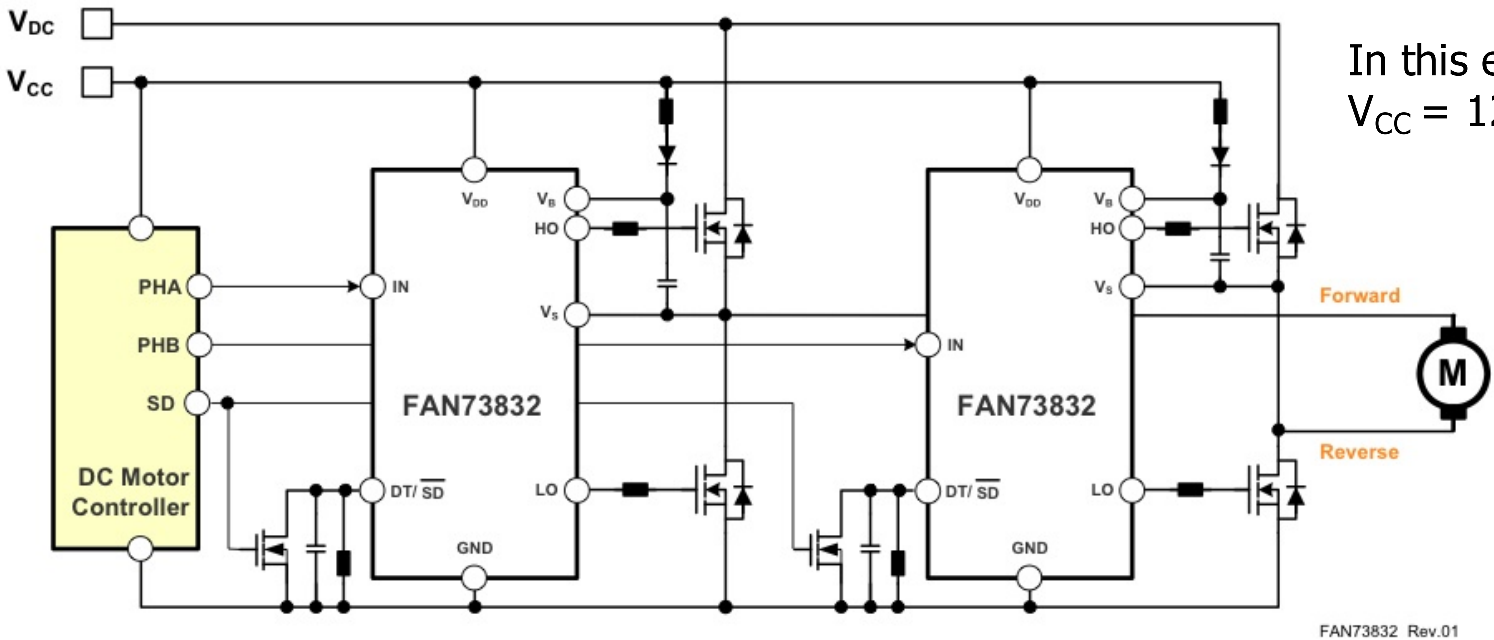


Figure 2. Application Circuit for Full-Bridge DC Motor Driver

In this example, V_{CC} = 12 V

- High side circuitry includes external diode and capacitor for bootstrap power supply
- To charge bootstrap capacitor, low side MOSFET must conduct