ECE317: Lab 6

Closed Loop Feedback System Design: Design of an effective feedback compensator for a closed loop dc-to-dc converter system

PORTLAND STATE UNIVERSITY

MASEEH COLLEGE OF ENGINEERING & COMPUTER SCIENCE
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

Authors:

STEPHEN JOHNSTON

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Maseeh College of Engineering and Computer Science
PORTLAND STATE UNIVERSITY

ECE 317: LAB 6

CLOSED LOOP FEEDBACK SYSTEM DESIGN: DESIGN OF AN EFFECTIVE FEEDBACK COMPENSATOR FOR A CLOSED LOOP DC-TO-DC CONVERTER SYSTEM

Introduction

The objective of this lab is to design a dominant pole with lead compensator and apply it both in simulations and in real life. The compensator is composed of both a dominant pole and lead compensator, two different compensators that are handled separately. When applied, there will be significant drop in response to impedance change and in steady state error.

Compensator design

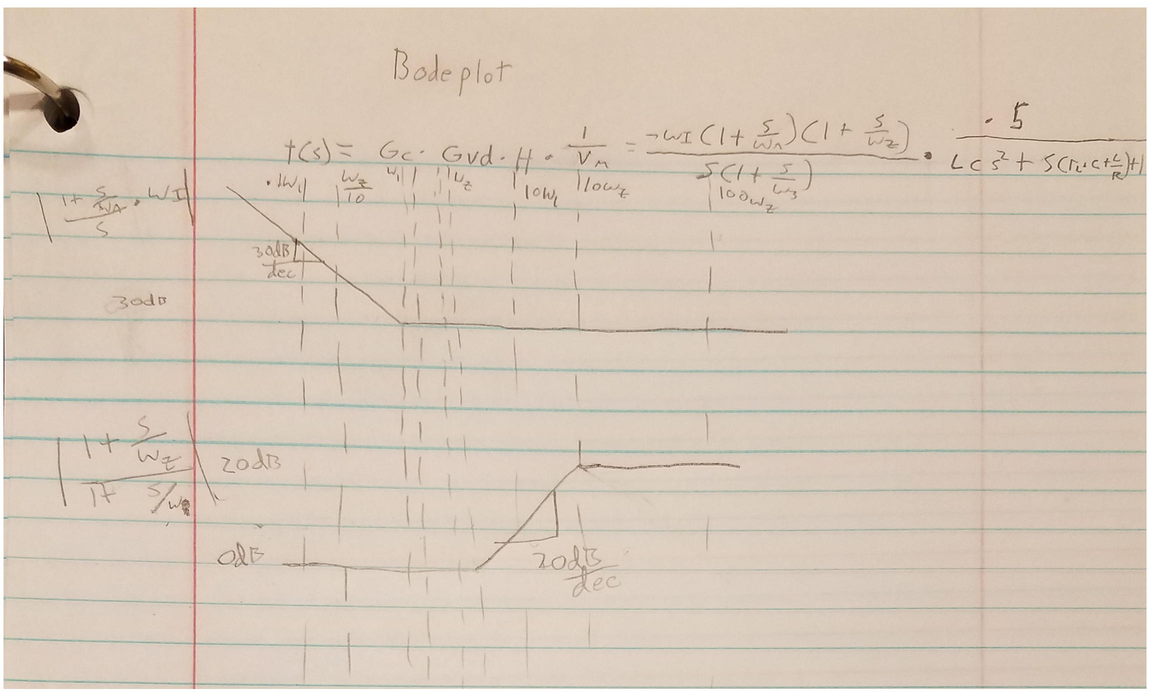


Figure 1: Compensator bodie plot part 1

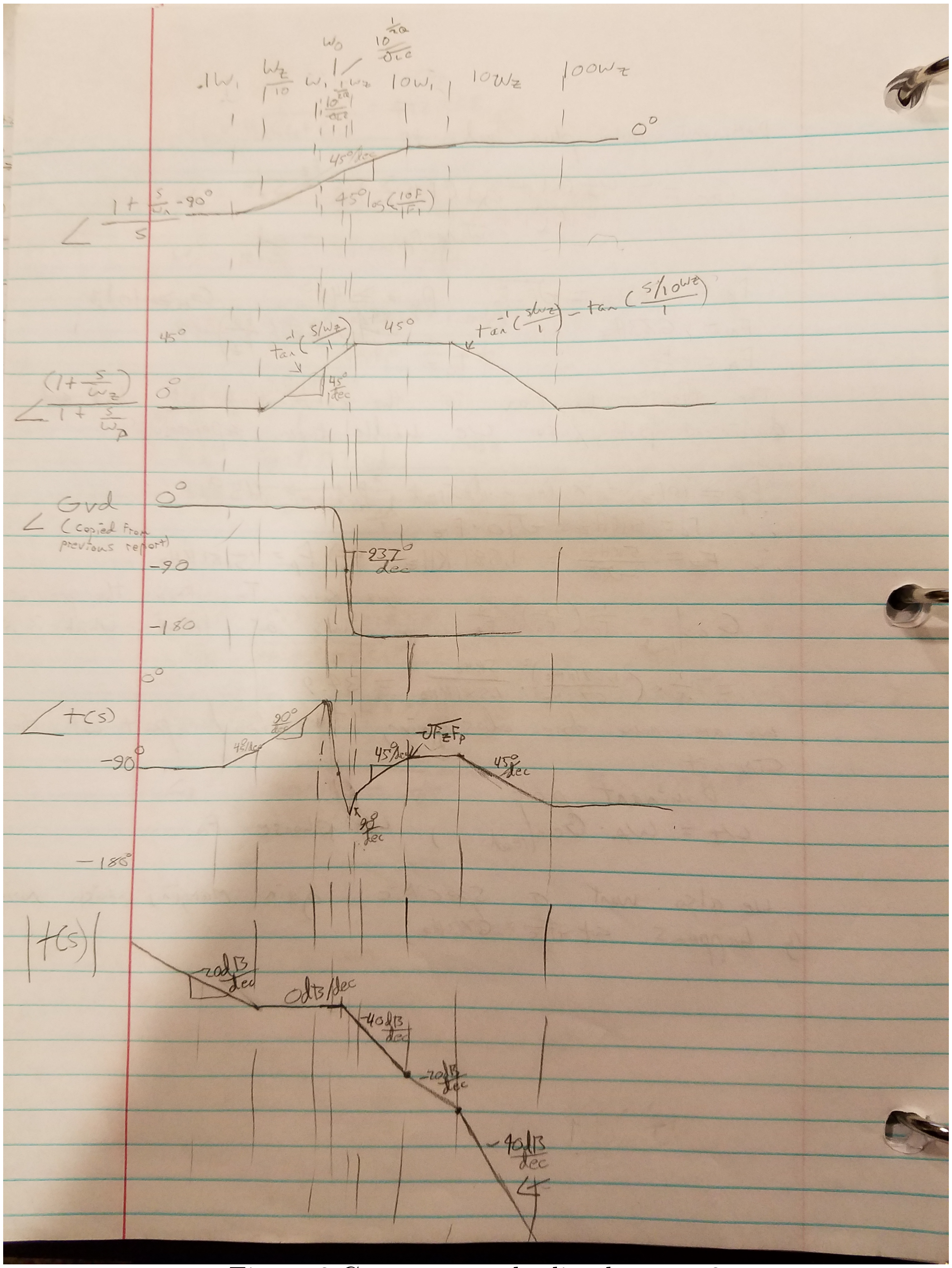
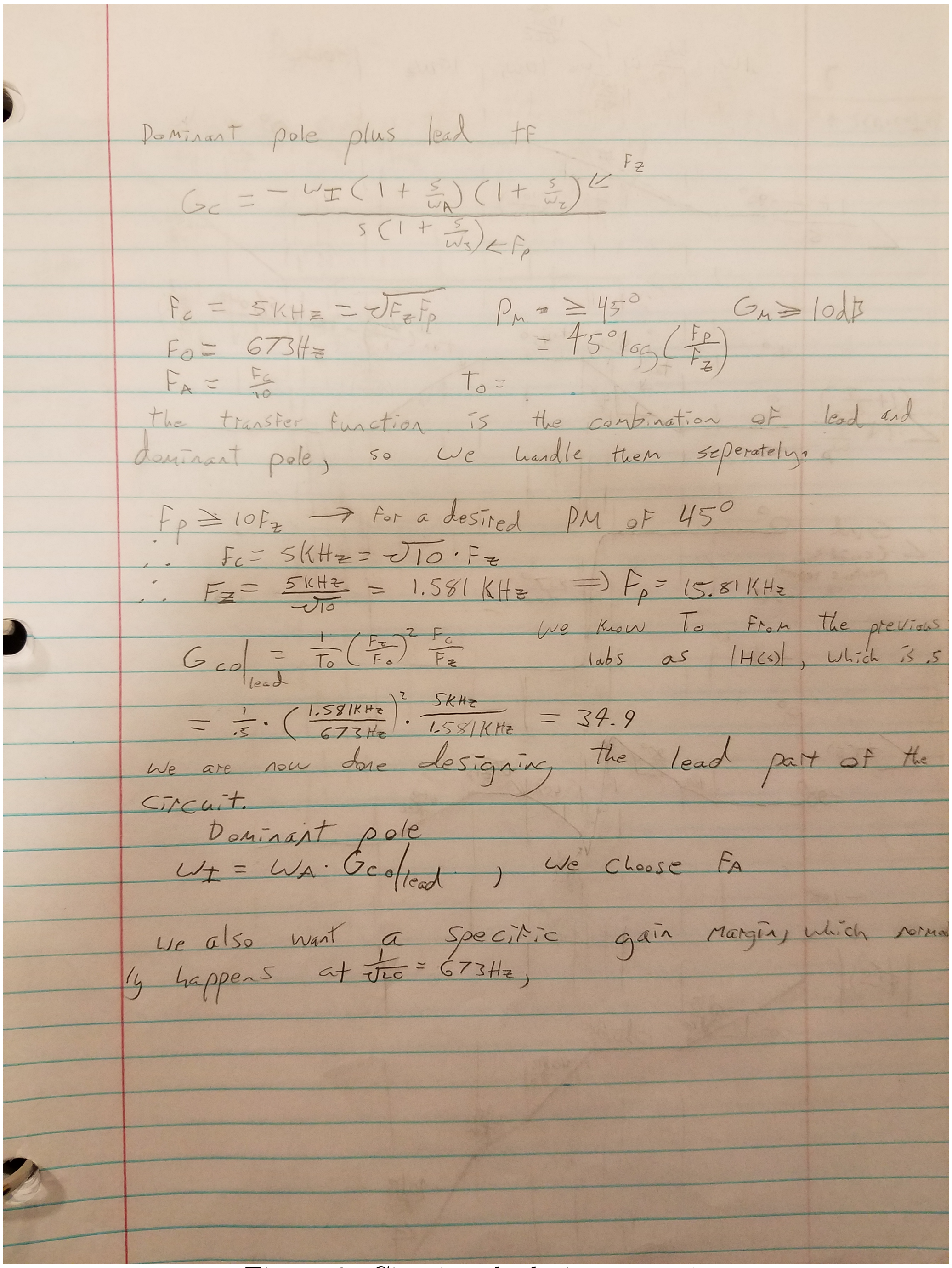


Figure 2:Compensator bodie plot part 2



Dominant pole plus lead tF

$$G_c = \frac{-\omega_I\left(1+\frac{s}{\omega_A}\right)\left(1+\frac{s}{\omega_z}\right)}{s\left(1+\frac{s}{\omega_3}\right)}$$ F_z, F_p

$F_c = 5KHz = \sqrt{F_z F_p}$ $P_M \geq 45^\circ$ $G_M \geq 10dB$

$F_0 = 673Hz$ $= 45^\circ \log\left(\frac{F_P}{F_z}\right)$

$F_A = \frac{F_c}{10}$ $T_0 =$

the transfer function is the combination of lead and dominant pole, so we handle them seperately.

$F_p \geq 10F_z$ → For a desired PM of 45°

$\therefore F_c = 5KHz = \sqrt{10} \cdot F_z$

$\therefore F_z = \frac{5KHz}{\sqrt{10}} = 1.581\,KHz \Rightarrow F_p = 15.81\,KHz$

$G_{co}\big|_{lead} = \frac{1}{T_0}\left(\frac{F_z}{F_0}\right)^2 \frac{F_c}{F_z}$ We know T_0 from the previous labs as $|H(s)|$, which is .5

$= \frac{1}{.5} \cdot \left(\frac{1.581KHz}{673Hz}\right)^2 \cdot \frac{5KHz}{1.581KHz} = 34.9$

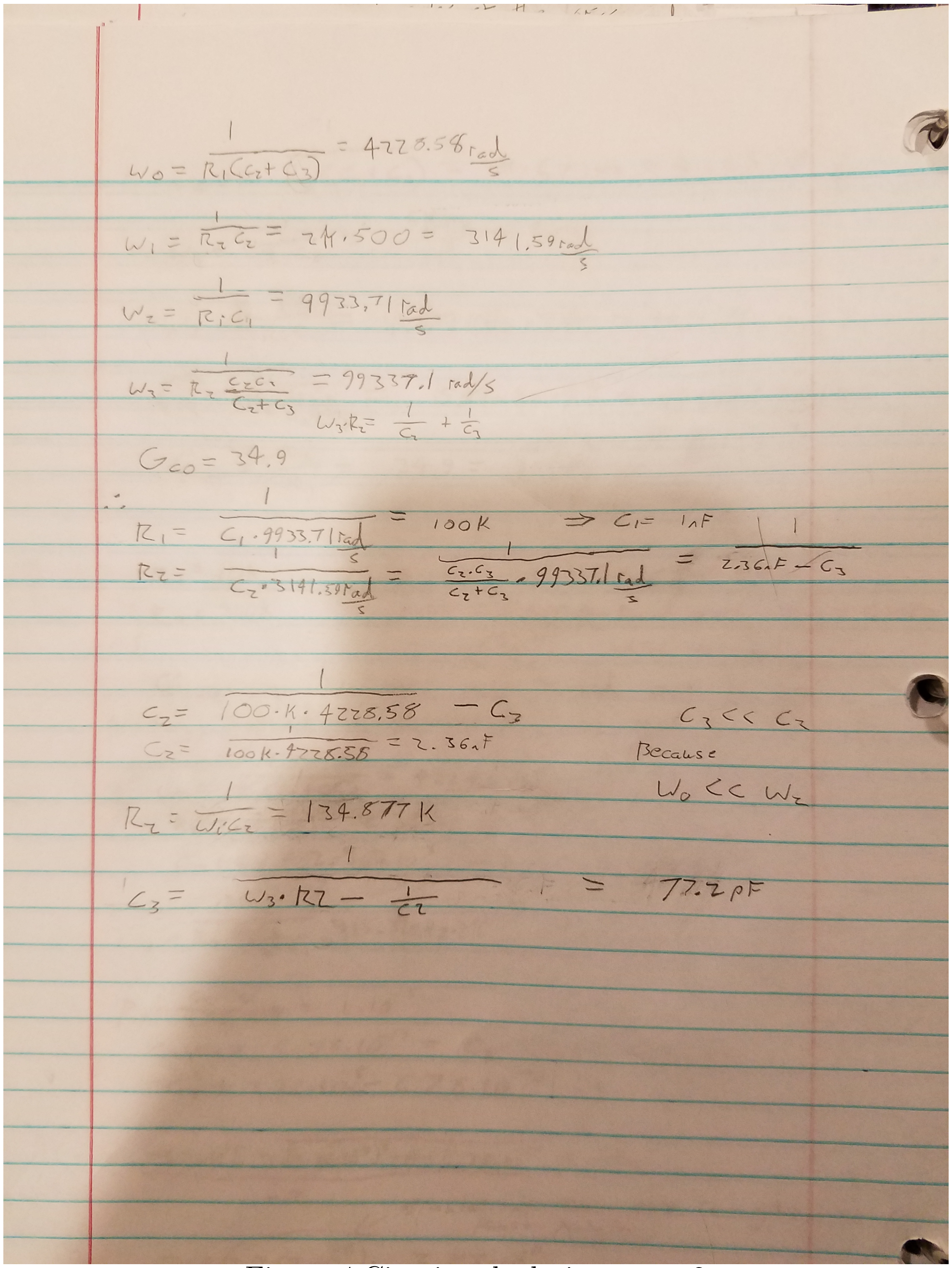
We are now done designing the lead part of the circuit.

Dominant pole

$\omega_I = \omega_A \cdot G_{co}\big|_{lead}$, we choose F_A

We also want a specific gain margin, which normally happens at $\frac{1}{\sqrt{LC}} = 673Hz$,

Figure 3: Circuit calculations part 1.



$$W_0 = \frac{1}{R_1(C_2+C_3)} = 4228.58 \frac{rad}{s}$$

$$W_1 = \frac{1}{R_2 C_2} = 2\pi \cdot 500 = 3141.59 \frac{rad}{s}$$

$$W_2 = \frac{1}{R_1 C_1} = 9933.71 \frac{rad}{s}$$

$$W_3 = \frac{1}{R_2 \frac{C_2 C_3}{C_2+C_3}} = 99337.1 \ rad/s$$

$$W_3 R_2 = \frac{1}{C_2} + \frac{1}{C_3}$$

$$G_{c0} = 34.9$$

$$\therefore R_1 = \frac{1}{C_1 \cdot 9933.71 \frac{rad}{s}} = 100K \Rightarrow C_1 = 1nF$$

$$R_2 = \frac{1}{C_2 \cdot 3141.59 \frac{rad}{s}} = \frac{1}{\frac{C_2 \cdot C_3}{C_2+C_3} \cdot 99337.1 \frac{rad}{s}} = \frac{1}{2.36nF - C_3}$$

$$C_2 = \frac{1}{100 \cdot K \cdot 4228.58} - C_3$$

$$C_2 = \frac{1}{100K \cdot 4228.58} = 2.36nF$$

$C_3 << C_2$ Because $W_0 << W_2$

$$R_2 = \frac{1}{W_1 C_2} = 134.877 K$$

$$C_3 = \frac{1}{W_3 \cdot R2 - \frac{1}{C2}} = 77.2pF$$

Figure 4:Circuit calculations part 2

$C_1 = 1nf$ $C_2 = 2.34nf$ $C_3 = 77.2pf$

$R_1 = 100k\Omega$ $R_2 = 134k\Omega$

MATLAB simulations

Task 2a

$$C = \frac{-\omega_I(1+\frac{s}{\omega_A})(1+\frac{s}{\omega_z})}{s(1+\frac{s}{\omega_p})} \qquad G_{vg} = \frac{10}{LCs^2+s(R_lC+\frac{L}{R})+1+\frac{Rl}{R}}$$

$$G_l = \frac{1}{V_m} \cdot G_{vg} \cdot \frac{1}{2} \cdot C = \frac{-\omega_I(1+\frac{s}{\omega_A})(1+\frac{s}{\omega_z})}{s(1+\frac{s}{\omega_p})} \cdot \frac{10}{LCs^2+s(R_lC+\frac{L}{R})+1+\frac{Rl}{R}} \cdot \frac{1}{10} \cdot \frac{1}{2} =$$

```
Gl =

             0.001757 s^2 + 22.97 s + 5.482e04
  ------------------------------------------------
  5.637e-13 s^4 + 5.646e-08 s^3 + 5.547e-05 s^2 + s
```

Matlab Loop Gain tf

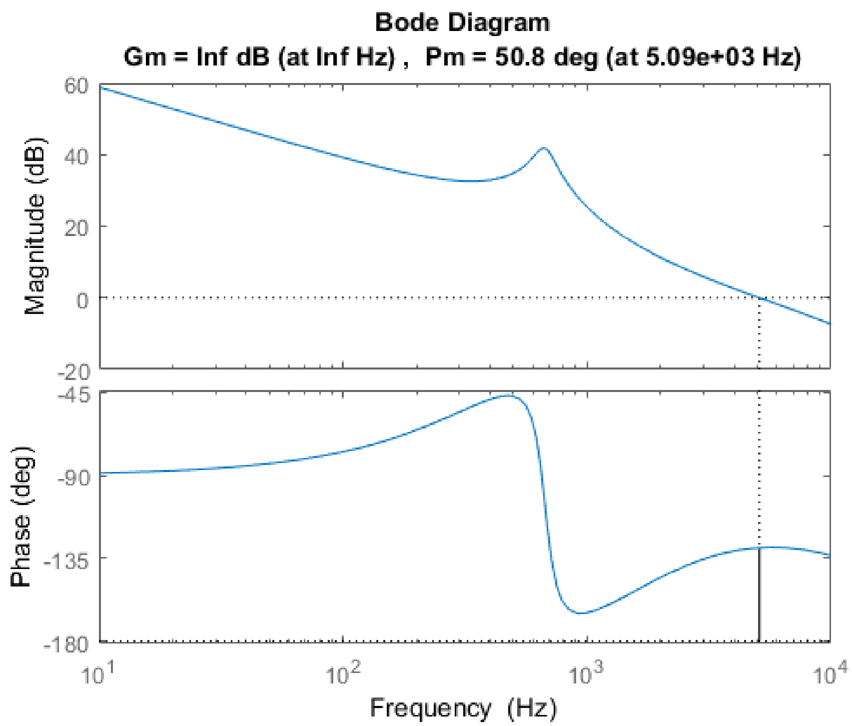


Figure 5: Bode plot of loop gain

Note the frequencies for gain margin and phase margin, inf dB at inf Hz and 50.8 degrees at 5.09kHz.

Task 2b

$$G_{cl} = 2 \cdot \frac{G_l}{1+G_l} =$$

```
Gcl =

        1.981e-15 s^6 + 2.242e-10 s^5 + 2.85e-06 s^4 + 0.01225 s^3 + 52.02 s^2 + 1.096e05 s
  -----------------------------------------------------------------------------------------------
  3.178e-25 s^8 + 6.365e-20 s^7 + 4.24e-15 s^6 + 1.195e-10 s^5 + 1.541e-06 s^4 + 0.006237 s^3
                                                                      + 27.01 s^2 + 5.482e04 s
```

Closed loop expression for the transfer function

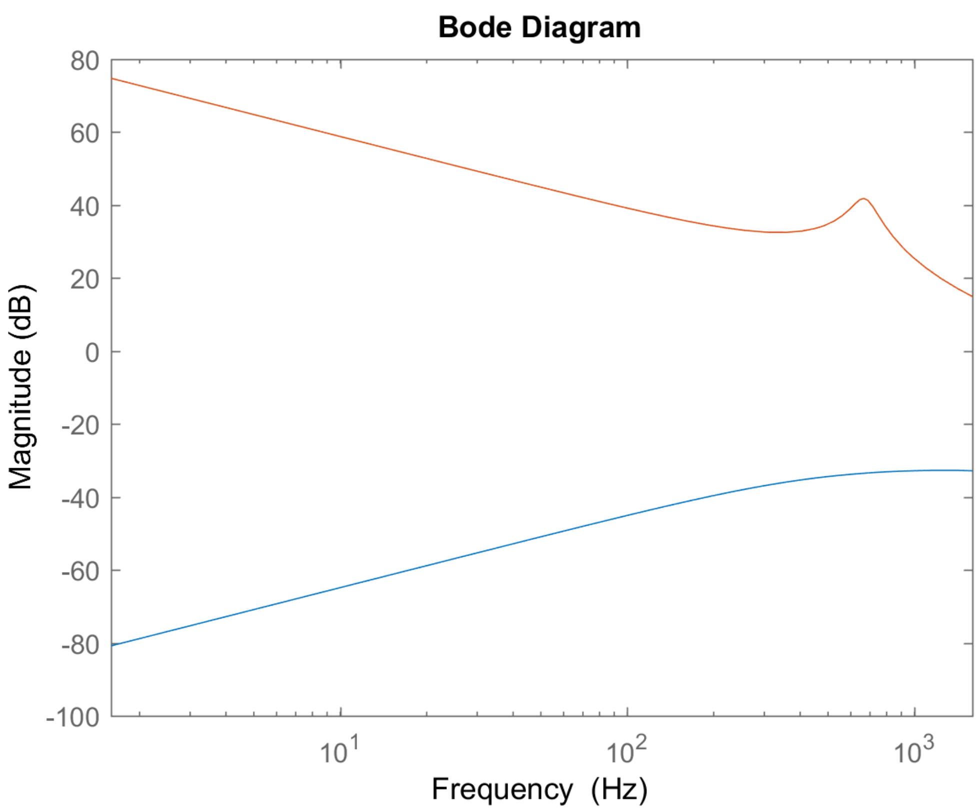


Figure 6: MATLAB Voltage closed loop and open loop plot

```
s = tf('s');
Vg = 10;
D = 0.5;
V = D*Vg;
L = 560*10^(-6);
C = 100*10^(-6);
R = 25;
R2 = 100000;
C2 = 22*10^-9;
w1 = 4226.58;
w2 = 3141.59;
w3 = 9933.7;
w4 = 99337.1;
R3 = 100000; %Given
C3 = 1/(w3*R3);
C4 = 1/(w1*R3); %Using the approximation C5 << C4
R4 = 1/(w2*C4);
C5 = 1/(w4*R4 - 1/C4);
vm = 10;
vg = 10;
Rl = 230*10^(-3);
Glpf = 1/(L*C*s^2 + s*(Rl*C + L/R) + 1); % input your loop gain expression as a function of s
Z = (L*s+Rl)*(C*s)*(1/(R))/(R + C*s*R*(L*s+Rl) + (L*s+Rl));
Kvd = vg;
H = .5;
K1 = 1/(R2*C2)
Gvd = Kvd*Glpf;
Gc = ((34.9*1/(R4*C4))*(1 + (s*(R4*C4)))*(1 + (s*(R3*C3))))/(s*(1+s*((R4*C5*C4)/(C5 + C4))));
Gpwm = 1/(vm);
%G_loop = Gvd*Gpwm*H*Gc;
Kvg = .5;

Gvg = Kvg*Glpf ; % input your expression for Gvg as a function of s
Gl = Gvd*H*(1/vm)*Gc
Gcl = 2*Gl/(1+Gl)
Gvgcl = Gvg/(1+Gl)
bodemag(Gl,Gcl)
```

Listing 1: Matlab Code for bodeplot of loop gain and closed loop gain

Task 2c

```
Zocl =

            -3.157e-16 s^5 - 3.175e-11 s^4 - 4.405e-08 s^3 - 0.0005728 s^2 - 0.23 s
  -------------------------------------------------------------------------------------------------
  3.157e-20 s^6 + 3.187e-15 s^5 + 1.046e-10 s^4 + 1.481e-06 s^3 + 0.005987 s^2 + 26.68 s + 5.533e04
```

Impedance closed loop transfer function

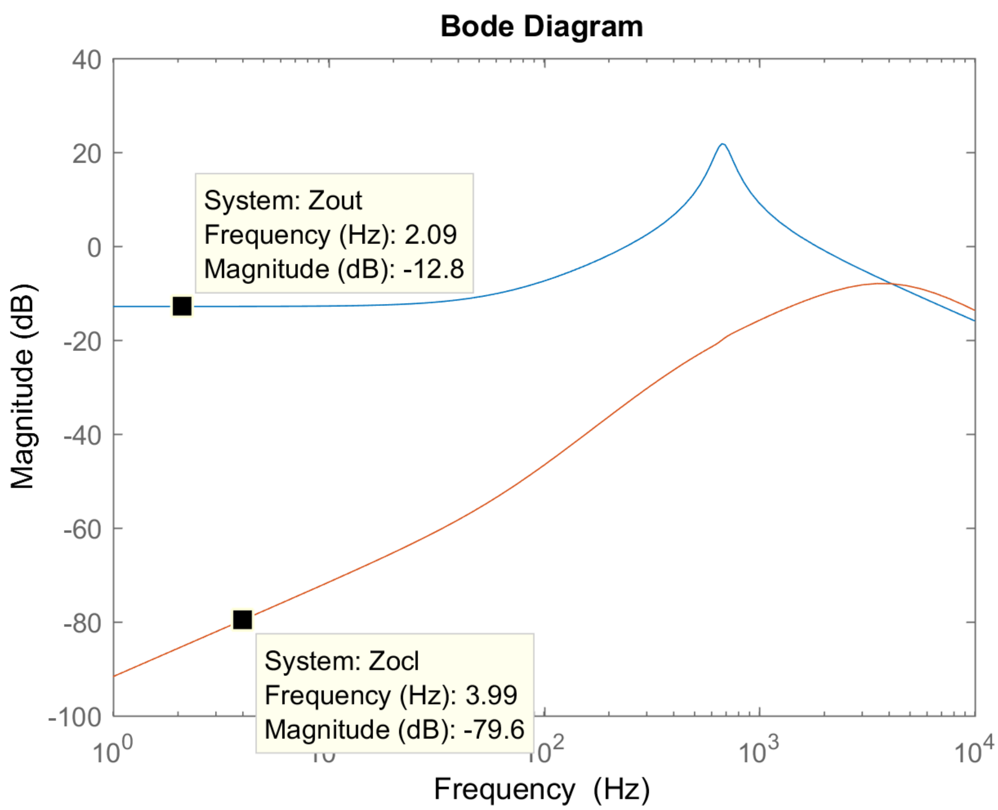


Figure 7: MATLAB impedance closed loop and open loop plots

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```
s = tf('s');
Vg  =  10;
D  =  0.5;
V  =  D*Vg;
s  =  tf('s');
L = 560*10^(-6);
C = 100*10^(-6);
R = 25;

R2 = 100000;
C2 = 22*10^-9;
w1 = 4226.58;
w2 = 3141.59;
w3 = 9933.7;
w4 = 99337.1;
R3 = 100000; %Given
C3 = 1/(w3*R3);
C4 = 1/(w1*R3); %Using the approximation C5 << C4
R4 = 1/(w2*C4);
C5 = 1/(w4*R4 - 1/C4);
vm = 10;
vg = 10;
Rl = 230*10^(-3);
vm = 10;
vg = 10;
Rl = 230*10^(-3);
Glpf = 1/(L*C*s^2 + s*(Rl*C + L/R) + 1); % input your loop gain
    expression as a function of s
Zout = (L*s+Rl)/(1 + Rl/R + s*(L/R + Rl*C) + s^(2)*L*C);
Kvd = vg;
H = .5;
Gvd = Kvd*Glpf;

Gpwm = 1/(vm);
G_loop = Gvd*Gpwm*H;
Kvg = .5;

Gvg  =  Kvg*Glpf      ;
    ; % input your expression for Zout as a function of s
Vg = 10;
D = 0.5;
V = D*Vg;
Gvg  =  Kvg*Glpf      ;  %  input  your  expression  for  Gvg  as  a
    function  of  s
Gvd = Kvd*Glpf;
Gc = (w1*34.9*(1 + s/(w1))*(1 + s/w2))/(s*(1 + s/w3));
Gl = Gvd*H*(1/vm)*Gc
Gcl = 2*Gl/(1+Gl)
Gvgcl = 2*Gvg/(1+Gl)
Zocl = -Zout/(1 + Gl)
bodemag(Zocl,Zout)
```

Listing 2: Matlab Code for bodeplot of open loop impedance and closed loop impedance

Task 3a, Step response

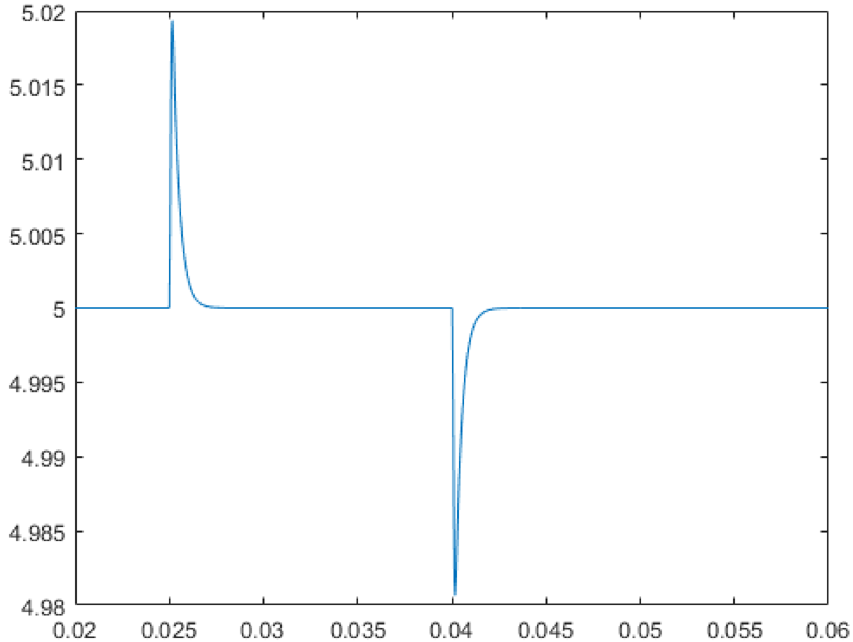

Figure 8: Voltage out step response

```
del_v =

    0.0387


SSE =

   8.8354e-18
```

```
s = tf('s');
Vg = 10;
D = 0.5;
V = D*Vg;
L = 560*10^(-6);
C = 100*10^(-6);
R = 25;
R2 = 100000;
C2 = 22*10^-9;
w1 = 4226.58;
w2 = 3141.59;
w3 = 9933.7;
w4 = 99337.1;
R3 = 100000; %Given
C3 = 1/(w3*R3);
C4 = 1/(w1*R3); %Using the approximation C5 << C4
R4 = 1/(w2*C4);
C5 = 1/(w4*R4 - 1/C4);
vm = 10;
vg = 10;
Rl = 230*10^(-3);
Glpf = 1/(L*C*s^2 + s*(Rl*C + L/R) + 1); % input your loop gain expression as a function of s
Z = (L*s+Rl)*(C*s)*(1/(R))/(R + C*s*R*(L*s+Rl) + (L*s+Rl));
Kvd = vg;
H = .5;
K1 = 1/(R2*C2)
Gvd = Kvd*Glpf;
Gc = ((34.9*1/(R4*C4))*(1 + (s*(R4*C4)))*(1 + (s*(R3*C3))))/(s*(1+s*((R4*C5*C4)/(C5 + C4))));
Gpwm = 1/(vm);
%G_loop = Gvd*Gpwm*H*Gc;
Kvg = .5;

Gvg = Kvg*Glpf ; % input your expression for Gvg as a function of s
Gl = Gvd*H*(1/vm)*Gc
Gcl = 2*Gl/(1+Gl)
Gvgcl = Gvg/(1+Gl)
t = linspace(0.02, 0.06, 1000);
u = zeros(size(t));
ind = find(t>=0.025 & t<=0.04);% step is between 0.025<t<0.04
Vg_diff = 1;
u(ind) = u(ind) + Vg_diff;% form input vector containing the step
figure(2)
y = lsim(Gvgcl, u, t); % simulate the step response
plot(t,y+V) % add steady state voltage to the output and plot it
del_v = max(y) - min(y) % peak-to-peak voltage deviation
SSE = y(ind(end)) % steady state error
```

Listing 3: MATLAB code for Voltage step response

Task 3b, Impedance step response

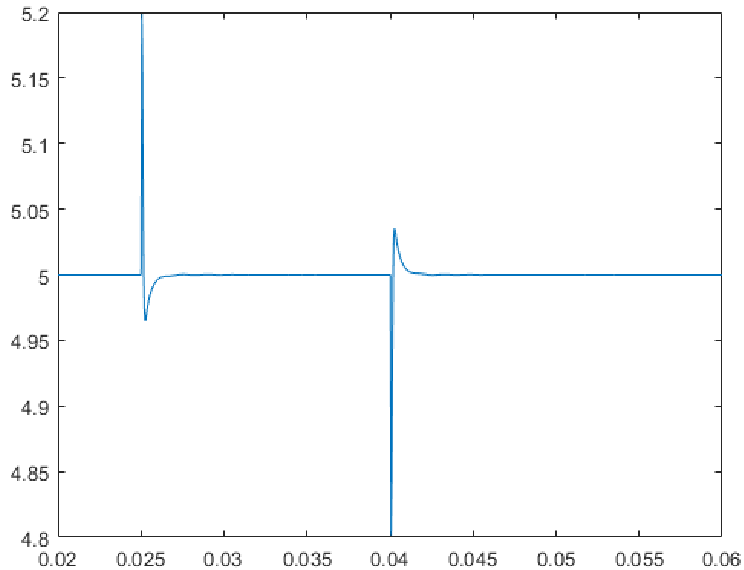

Figure 9: Impedance step response

```
del_v =

    0.3970


SSE =

  -1.1100e-06
```

```
s = tf('s');
Vg  =  10;
D  =  0.5;
V  =  D*Vg;
s  =  tf('s');
L = 560*10^(-6);
C = 100*10^(-6);
R = 25;

R2 = 100000;
C2 = 22*10^-9;
w1 = 4226.58;
w2 = 3141.59;
w3 = 9933.7;
w4 = 99337.1;
R3 = 100000; %Given
C3 = 1/(w3*R3);
C4 = 1/(w1*R3); %Using the approximation C5 << C4
R4 = 1/(w2*C4);
C5 = 1/(w4*R4 - 1/C4);
vm = 10;
vg = 10;
Rl = 230*10^(-3);
vm = 10;
vg = 10;
Rl = 230*10^(-3);
Glpf = 1/(L*C*s^2 + s*(Rl*C + L/R) + 1); % input your loop gain
    expression as a function of s
Zout = (L*s+Rl)/(1 + Rl/R + s*(L/R + Rl*C) + s^(2)*L*C);
Kvd = vg;
H = .5;
Gvd = Kvd*Glpf;

Gpwm = 1/(vm);
G_loop = Gvd*Gpwm*H;
Kvg = .5;

Gvg  =  Kvg*Glpf      ;
   ; % input your expression for Zout as a function of s
Vg = 10;
D = 0.5;
V = D*Vg;
Gvg  =  Kvg*Glpf      ;  %  input  your  expression  for  Gvg  as  a
    function  of  s
Gvd = Kvd*Glpf;
Gc = (w1*34.9*(1 + s/(w1))*(1 + s/w2))/(s*(1 + s/w3));
Gl = Gvd*H*(1/vm)*Gc
Gcl = 2*Gl/(1+Gl)
Gvgcl = 2*Gvg/(1+Gl)
Zocl = -Zout/(1 + Gl)

Io_1 = V/25; % load current before step.   (25 ohm load)
Io_2 = V/5; % load current after step.   (5 ohm load)
Io_diff = Io_2 - Io_1; % current step
t = linspace(0.02, 0.06, 1000);
u = zeros(size(t));
ind = find(t>=0.025 & t<=0.04);% step is between 0.025<t<0.04
u(ind) = u(ind) + Io_diff;
figure(3)
y = lsim(-Zocl, u, t);
plot(t,y+V)
del_v = max(y) - min(y)
SSE = y(ind(end))
```

Listing 4: code impedance step response

PECS simulations

Task 4a

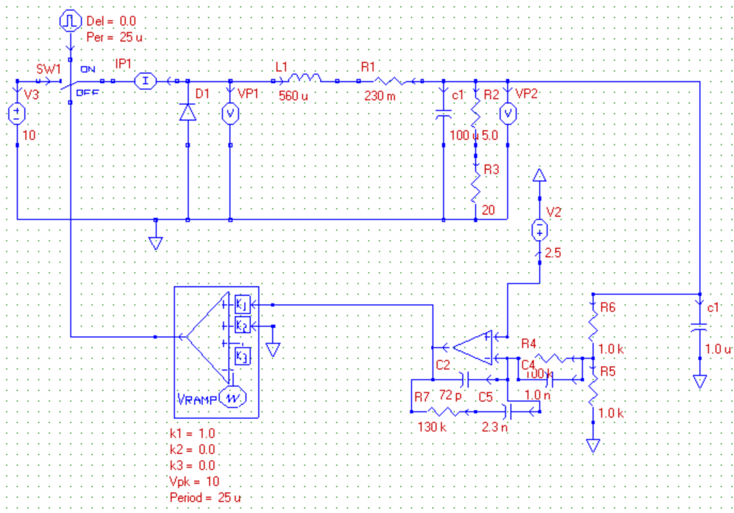

Figure 10: PECS schematic for voltage step response

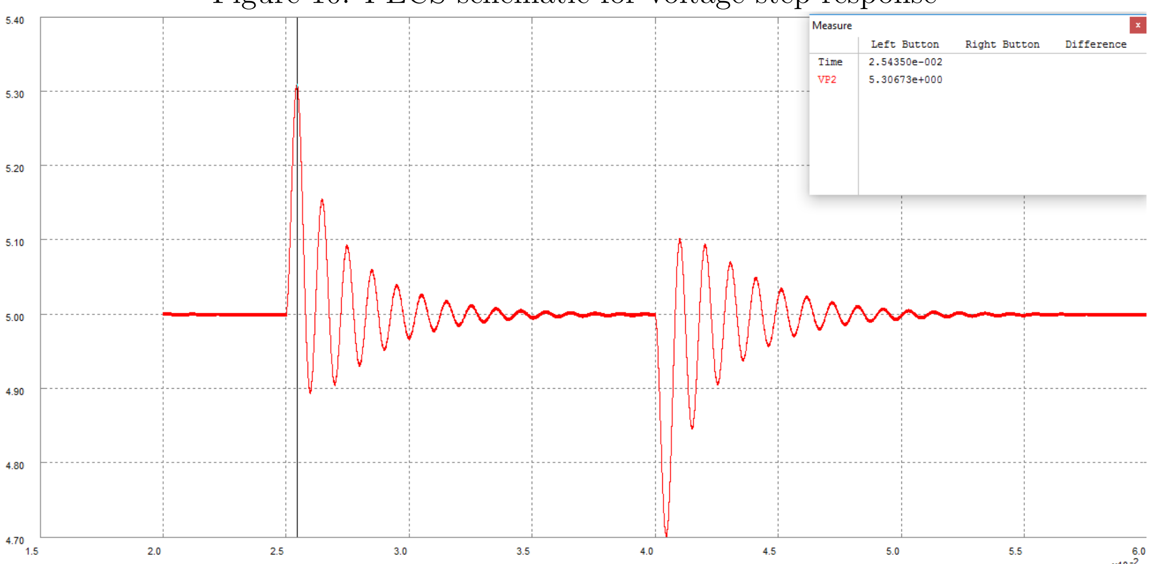

Figure 11: PECS voltage step response

ΔV	SSE
1V	.00005

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Task 4b

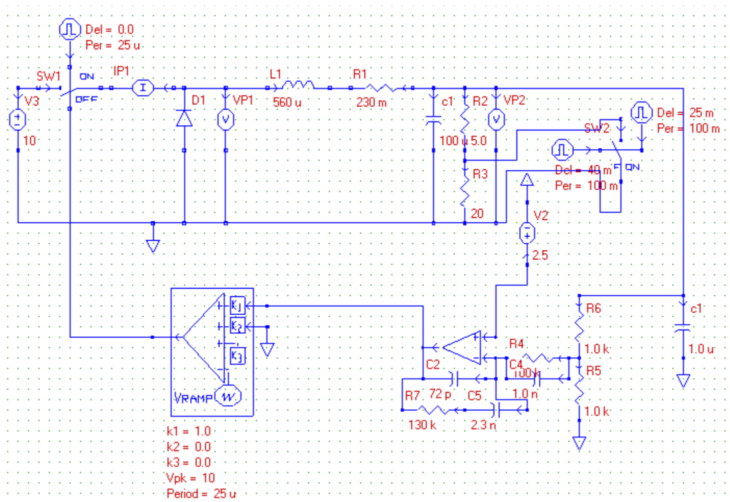

Figure 12: PECS Impedance step response

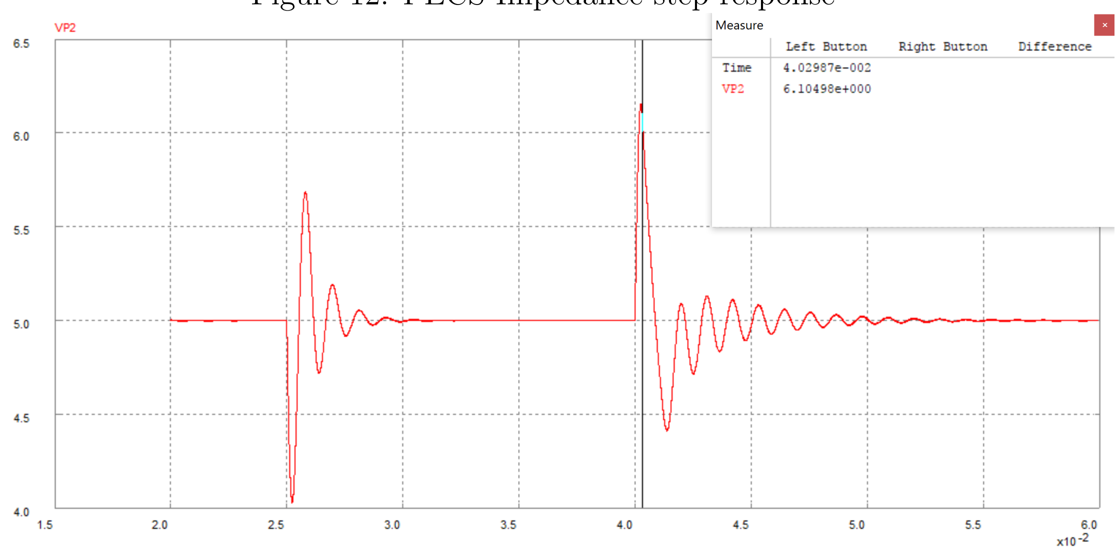

Figure 13: PECS Impedance step response

ΔV	SSE
2.1V	.0002

Circuit testing

Task 5b

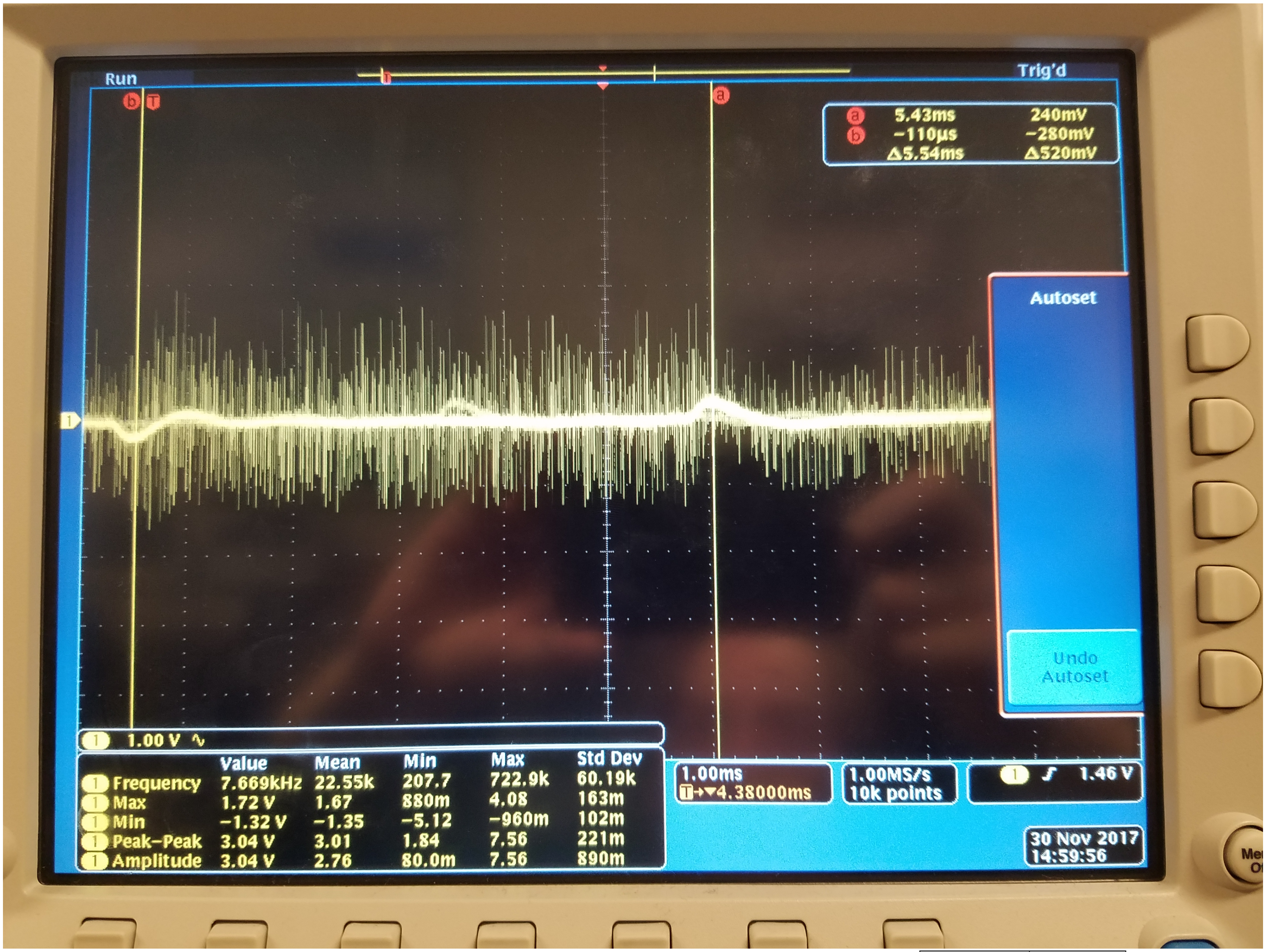

Figure 14: Impedance step response in real life

ΔV	SSE
580mV	20mV

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Task 6a

	Phase Margin Φ in degrees	Unity Gain Crossover, f_c	Gain Margin G_m	Phase Crossover Frequency
Asymptotes	45	5k	inf dB	inf Hz
Matlab	50.8	5.09kHz	inf dB	inf Hz

Task 6b

	Openloop (Uncompenstated)	Integral compensator	Integral + lead compensator.
Compensator transfer function	N/A	$\frac{1}{RC \cdot s}$	$\frac{-\omega_I(1+\frac{s}{\omega_A})(1+\frac{s}{\omega_z})}{s(1+\frac{s}{\omega_p})}$
Φ_{PM} in MATLAB	15.6	89	50.8
f_c MATLAB	5.92kHz	34Hz	5.09kHz
i_{out} step ΔV LAB	2.6V	3.8V	580mV
i_{out} step ΔV PECS	2.89	2.47	2.1
i_{out} step ΔV MATLAB	3.4017	3.52	.39V
i_{out} step SSE LAB	.16V	0	20mV
i_{out} step SSE PECS	.17V	.01946	.0002
i_{out} step SSE MATLAB	.1838	.0064	$-1.11 \cdot 10^{-6}$
v_g step ΔV PECS	1.15	1.48V	1
v_g step ΔV MATLAB	2.47	1.6	.0387
v_g step SSE PECS	.498	.01823	.00005
v_g step SSE MATLAB	.9977	.0099	$8.83 \cdot 10^{-18}$