Laboratory #3: System Identification of the dc-to-dc Buck converter

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Date of Report submission: 04/27/2020

ECE 317 - Signals and Systems III

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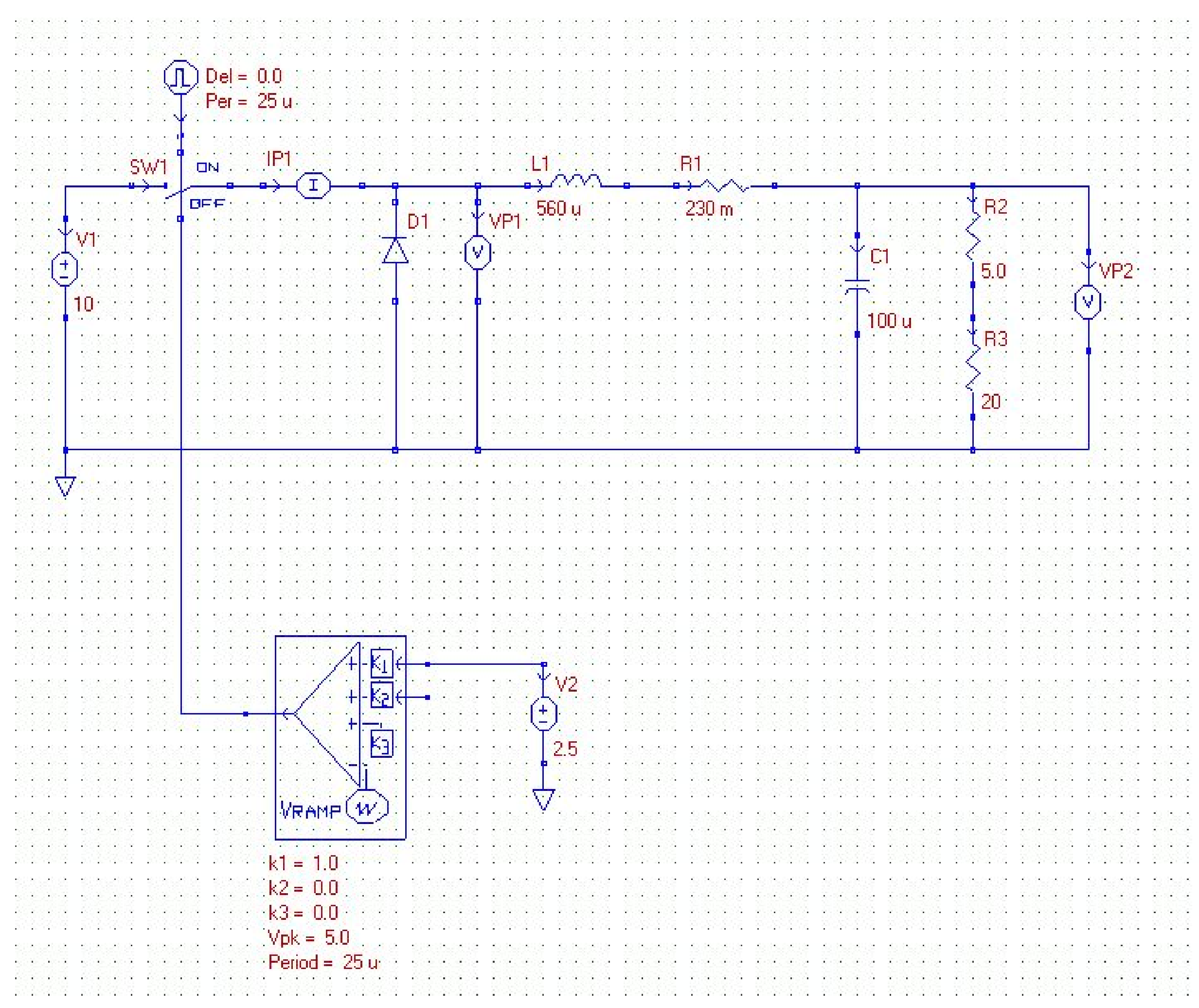
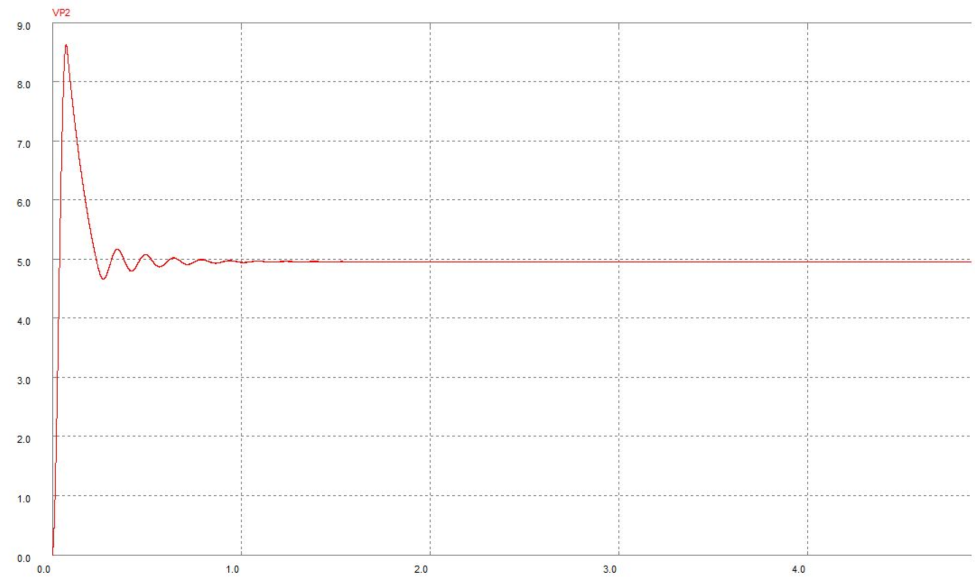
Task 1:



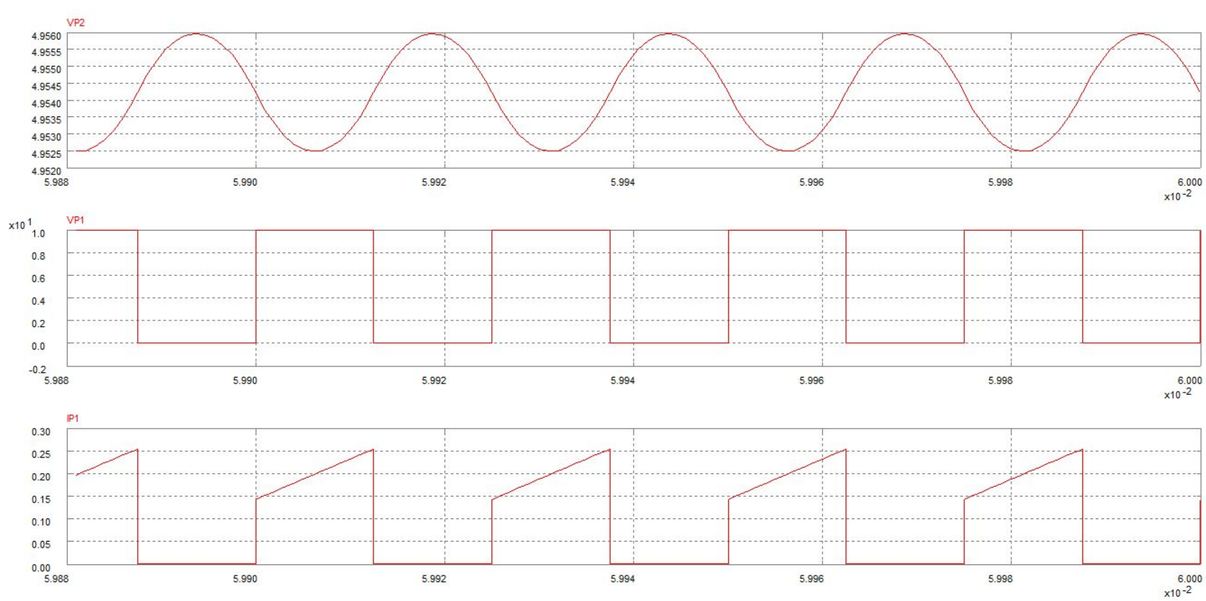
The figure above shows the PECS schematic of the buck converter for task 1.



The figure above shows the voltage across the load resistor (VP2)

As the figure above shows, there is a large start-up transient before the steady state voltage is established. This steady state voltage is 4.95 V.

Task 2:

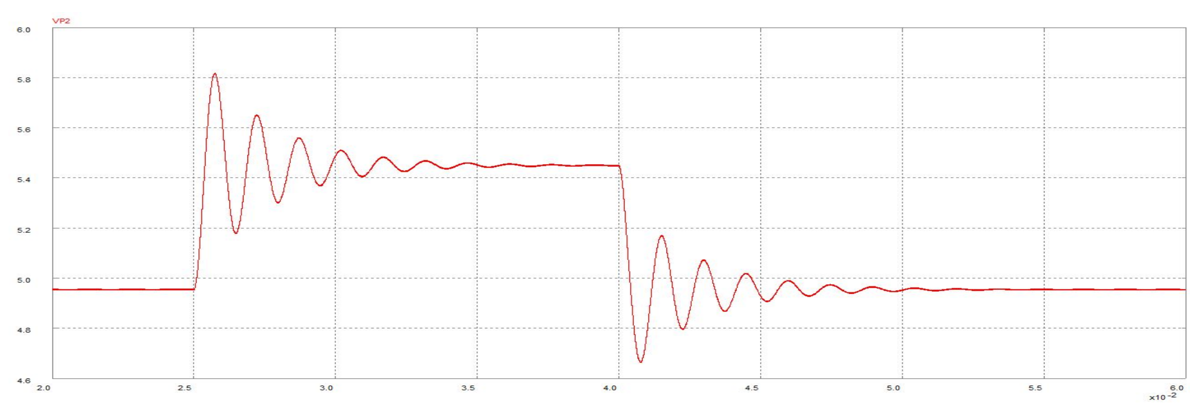


The figure above shows the output voltage (VP2) - (Top), the diode voltage (VP1) - (Middle), and the switch current (IP1) - (Bottom).

Average output voltage	4.954 V
Peak-to-peak output voltage (ripple)	3.44 mV
Peak-to-peak diode voltage	10 V
Peak inductor current	254 mA
Frequency of waveforms (all same freq)	40 kHz
Duty ratio	50 %

The duty ratio is set by the modulator in the circuit. The modulator has a sawtooth generator that is set by the Vpk and the Period. The sawtooth generator peak voltage of 5 V is compared to the voltage from the V2 supply of 2.5 V. The modulator output starts by being off while the voltage from the sawtooth generator ramps up. As the voltage from the sawtooth generator crosses 2.5 V, the output of the modulator turns on until the voltage from the sawtooth generator drops back down to 0 V.

Task 3:



The figure above is used in determining K_{vg}, Δv, and SSE for task 3.

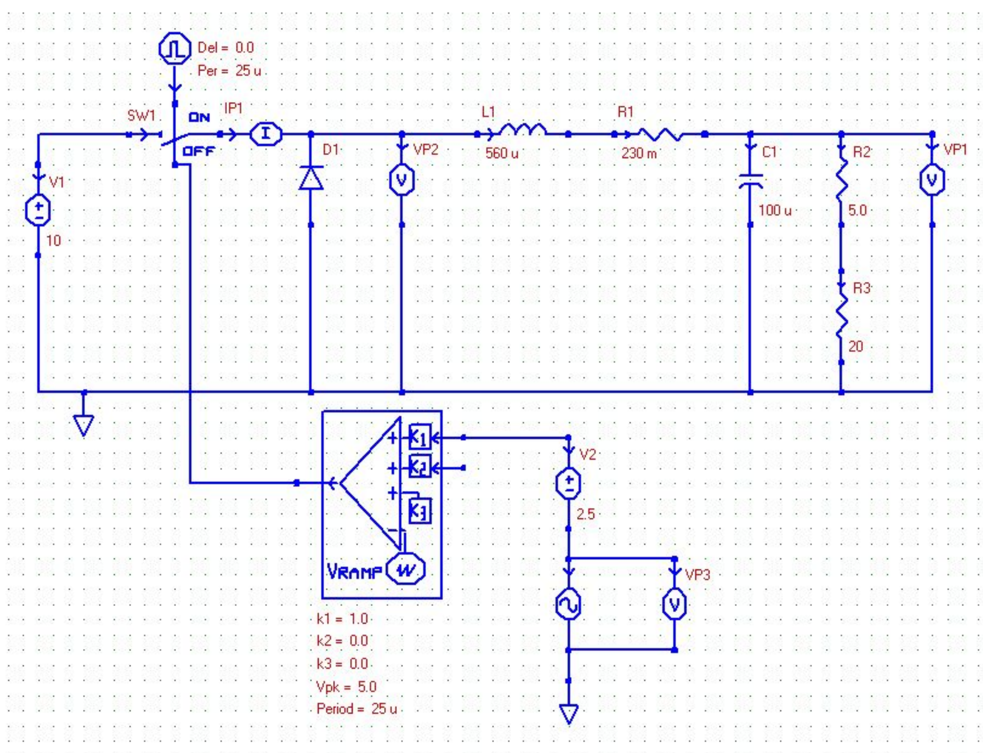
$K_{vg} = \frac{\Delta c}{\Delta v} = \frac{c_{final} - c_0}{v_{final} - v_0}$

$K_{vg} = \frac{5.45\ V - 4.95\ V}{1\ V} = 0.5$

show formula for SSE

The maximum peak-to-peak output voltage deviation is 1.15 V and the steady state error is 0.5 V

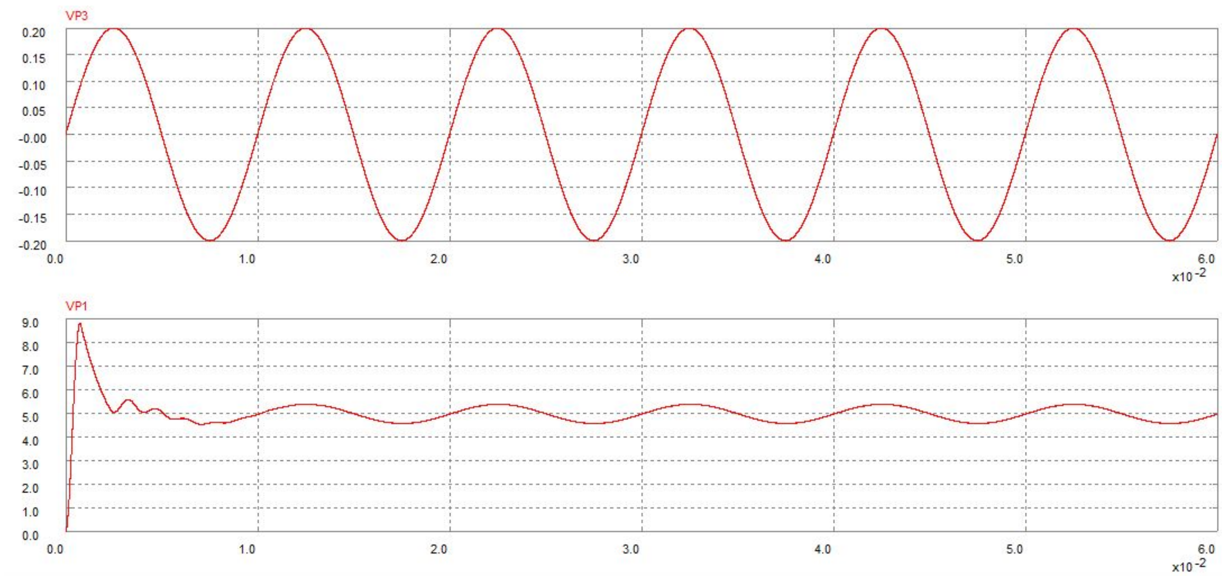
Task 4:



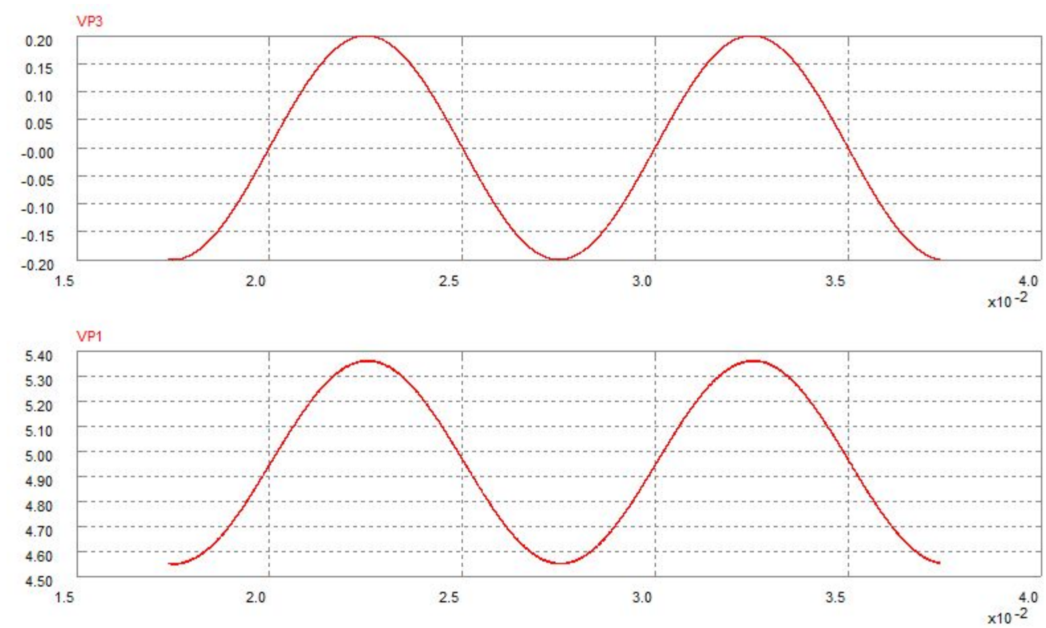
PECS schematic for task 4

Solving for filter corner frequency:

$$Fc = \frac{1}{2\pi\sqrt{LC}} \Rightarrow \frac{1}{2\pi\sqrt{(560x10^{-6})(100x10^{-6})}} = 673\ Hz$$



Plot of VP3 and VP1



Peak-to-peak voltage	
VP3	0.4V
VP1	~~0.8V~~ 0.81V

- VP3 and VP1 are in-phase.

Solving for K_{vd} :

$$G_{PWM} = \frac{1}{Vm}$$

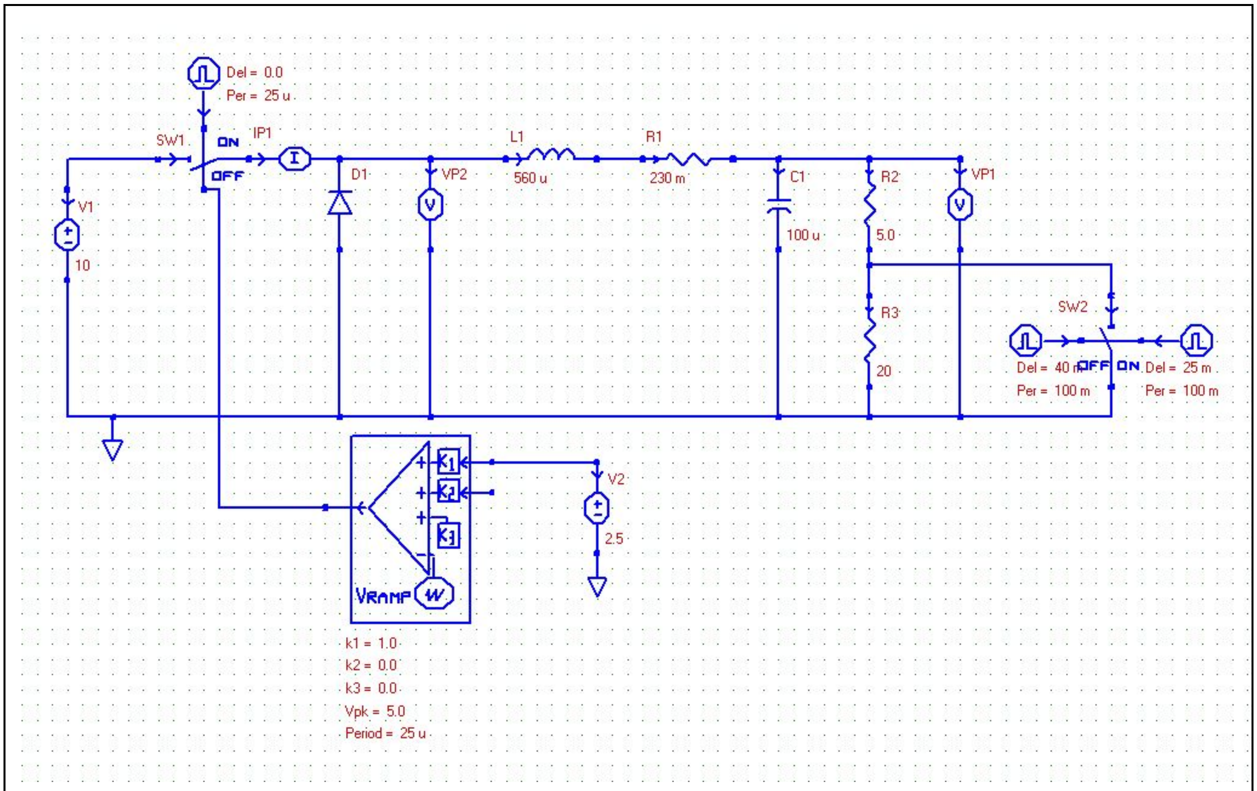
$$\widehat{Vc} = Vm$$

$$G_{LPF} \approx 1$$

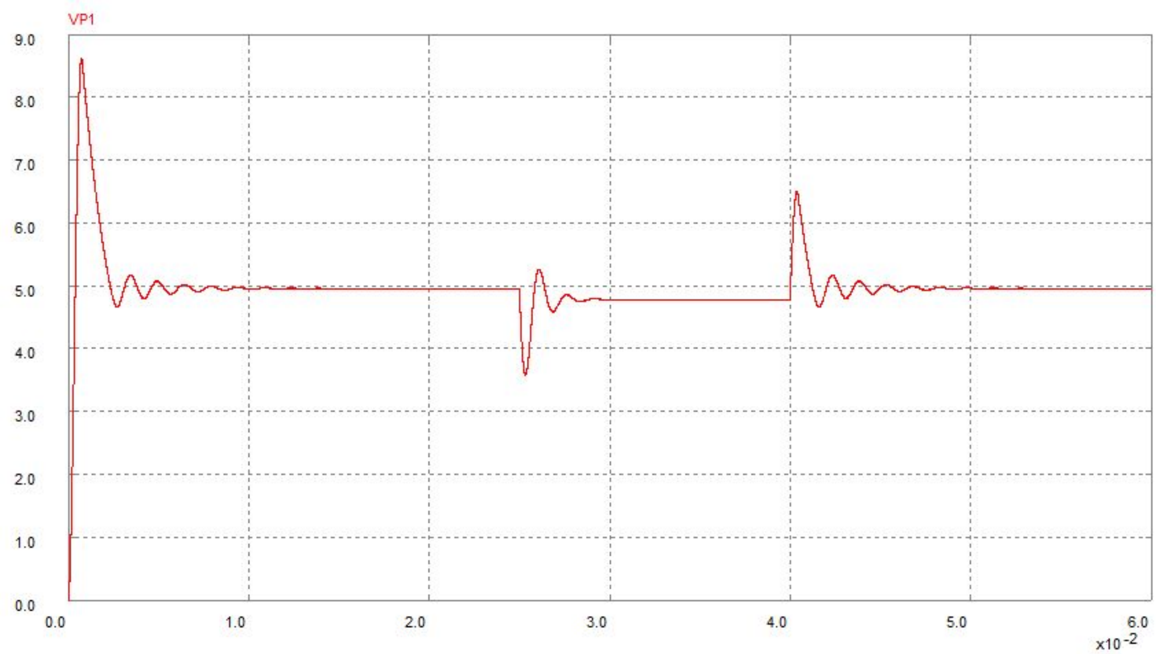
$$\frac{\hat{v}}{\hat{vc}} = \frac{1}{Vm} \cdot K_{vd} G_{LPF} \Rightarrow \frac{0.8}{0.4} = \frac{1}{5} \cdot K_{vd}(1)$$

$K_{vd} = \cancel{10}$ 10.125

Task 5:



PECS schematic for task 5



Plot of VP1

Maximum peak-to-peak output voltage and steady state error:

$$\Delta V = 6.5 - 3.6 = 2.9V$$

$$SSE = 4.956 - 4.779 = 0.177V$$

Task 6a:

$$T(s) = -G_c(s)H(s)G_{vd}(s)G_{PWM}(s)$$

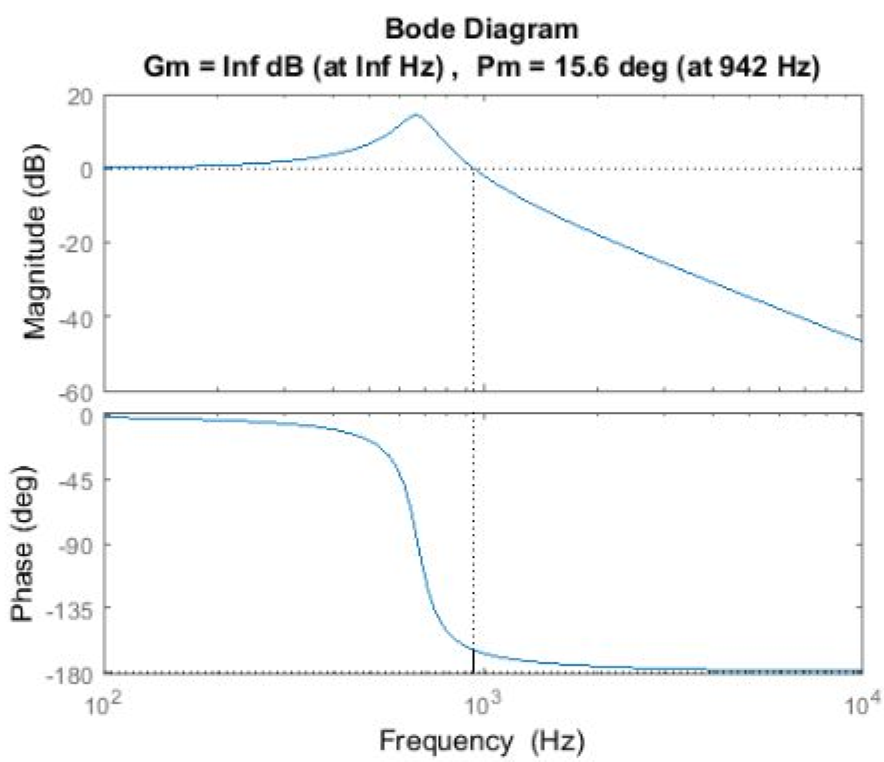
Using the previously found value K_{vd} and $G_{vd}(s) = K_{vd}G_{LPF}(s)$. We get the following:

$$T(s) = \frac{-1}{CLs^2+(Cr_L+\frac{L}{R})s+1}$$

```
s = tf('s');
% LCR Low Pass Filter Component Values
C = 100e-06;
R = 25;
r = 230e-03;
L = 560e-06;
% Gain Loop Function
G_loop = 1/(C*L*s^2+(C*r+(L/R))*s+1);

figure(1)
margin(G_loop)
h = gcr;
h.AxesGrid.Xunits = 'Hz'; % display the frequency in Hz
h.AxesGrid.TitleStyle.FontSize=12; % increase font size
h.AxesGrid.XLabelStyle.FontSize=12; % for readability
h.AxesGrid.YLabelStyle.FontSize=12;
```

Loop Gain Bode Diagram Code



The above shows an infinite gain margin, a phase margin of 15.6 degrees, unity gain frequency at 942 Hz , and the phase never crosses -180 degrees, establishing a stable system.

Task 6b:

Using the previously found K_{vg} .

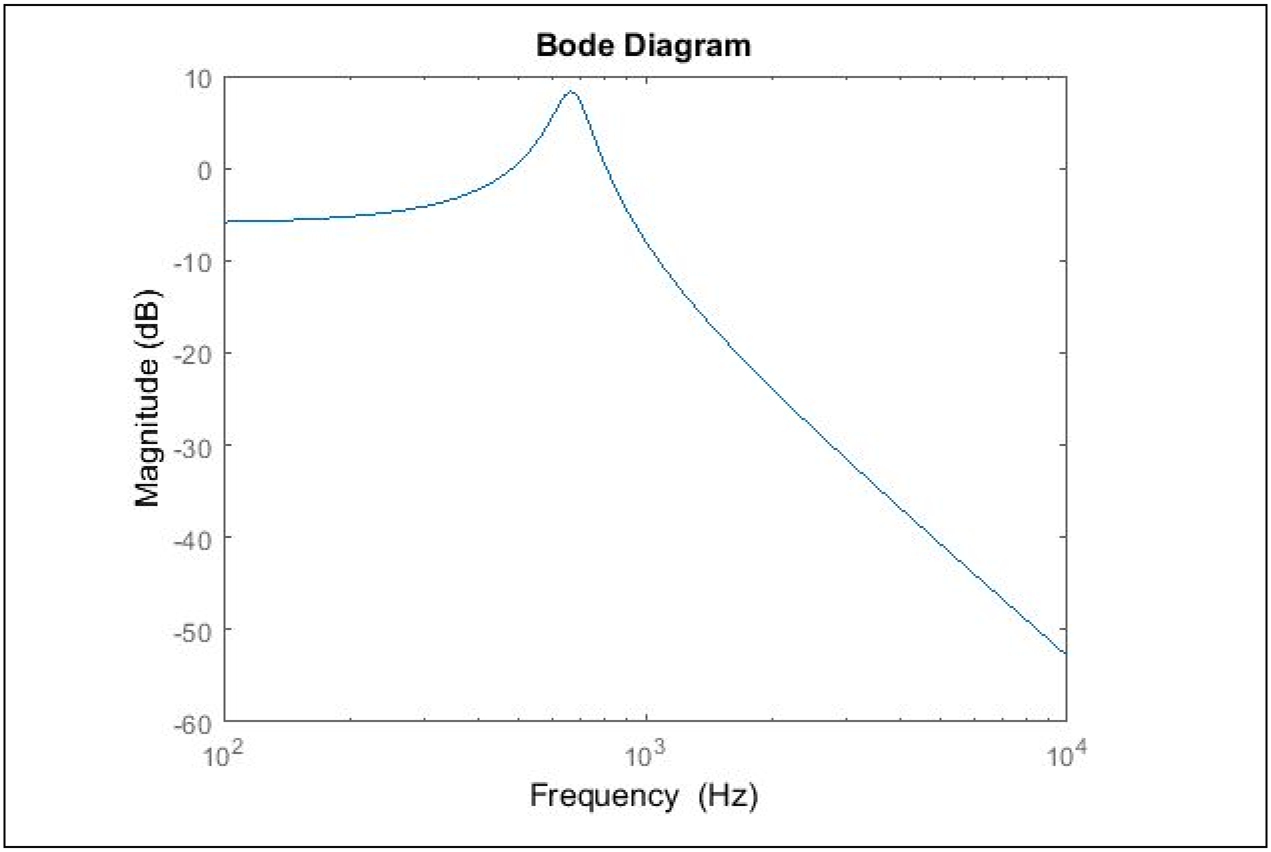
$$G_{vg}(s) \;=\; K_{vg}G_{LPF}(s) \;=\; \frac{.5}{CLs^2+(Cr_L+\frac{L}{R})s+1}$$

```
s = tf('s');
% LCR Low Pass Filter Component Values
C = 100e-06;
R = 25;
r = 230e-03;
L = 560e-06;
% Gain Transfer Function
G_vg = .5/(C*L*s^2+(C*r+(L/R))*s+1);

% Bode Magnitude Function
bodemag(G_vg);

% Convert frequency to Hz
h = gcr;
h.AxesGrid.Xunits = 'Hz'; % display the frequency in Hz
h.AxesGrid.TitleStyle.FontSize=12; % increase font size
h.AxesGrid.XLabelStyle.FontSize=12; % for readability
h.AxesGrid.YLabelStyle.FontSize=12;
```

Bode Magnitude Diagram Code



Task 6c:

$$-Z_{out} = (R + r_L) \parallel R \parallel \frac{1}{sC} = \frac{-r_L(1+\frac{sL}{r_L})}{CLs^2+(Cr_L+\frac{L}{R})s+\frac{(r_L+R)}{R}}$$

Where $(r_L + R) \approx R$ when $r_L << R$, so that

$$-Z_{out} = \frac{-r_L(1+\frac{sL}{r_L})}{CLs^2+(Cr_L+\frac{L}{R})s+1}$$

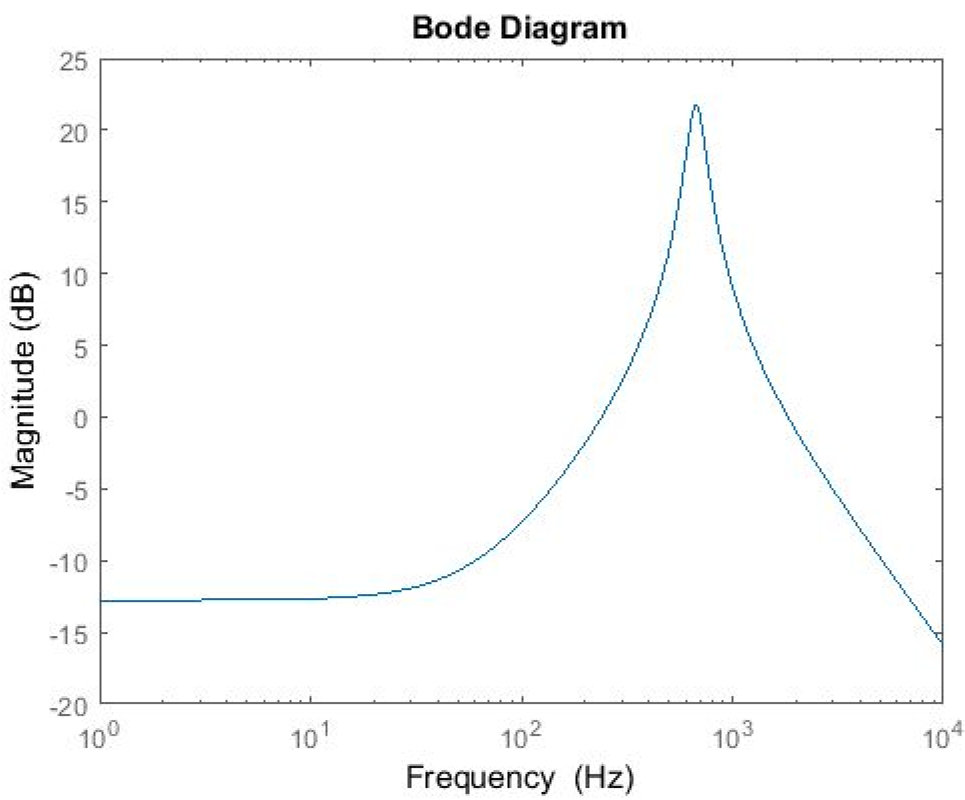
```
s = tf('s');
% LCR Low Pass Filter Component Values
C = 100e-06;
R = 25;
r = 230e-03;
L = 560e-06;

% Impedance Out Transfer Function
Z_out = -(r+s*L)/(C*L*s^2+(C*r+(L/R))*s+1);

% Bode Magnitude Function
bodemag(Z_out);

% Convert frequency to Hz
h = gcr;
h.AxesGrid.Xunits = 'Hz'; % display the frequency in Hz
h.AxesGrid.TitleStyle.FontSize=12; % increase font size
h.AxesGrid.XLabelStyle.FontSize=12; % for readability
h.AxesGrid.YLabelStyle.FontSize=12;
```

Impedance Bode Diagram Code



Task 6d:

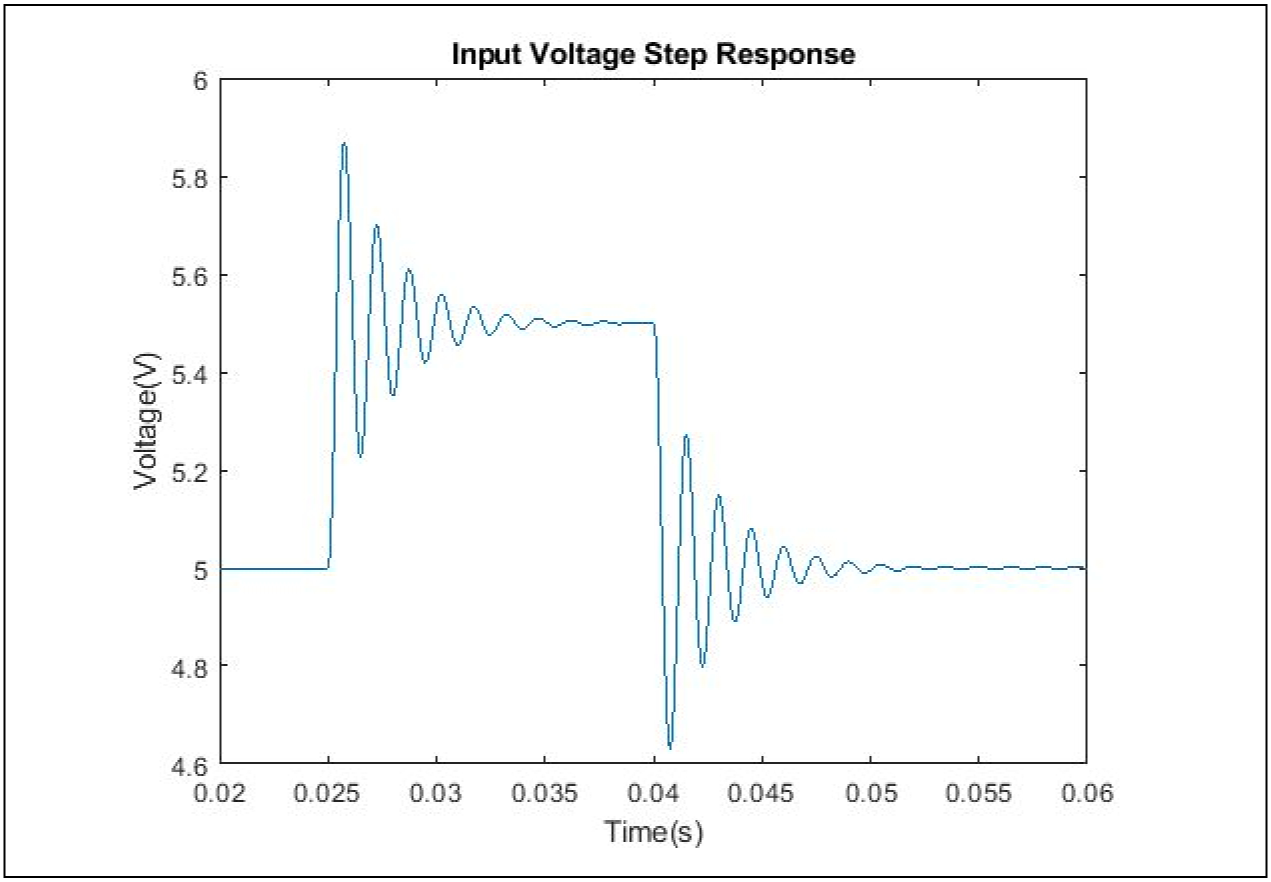
```
s = tf('s');
% LCR Low Pass Filter Component Values
C = 100e-06;
R = 25;
r = 230e-03;
L = 560e-06;

Vg = 10; % Input voltage
D = 0.5; % K_vg
V = D*Vg; % Steady state voltage

% Gain Transfer Function
G_vg = .5/(C*L*s^2+(C*r+(L/R))*s+1);

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(G_vg, u, t); % Simulate the step response
plot(t,y+V) % Add steady state voltage to the output and plot it
title('Input Voltage Step Response');
xlabel('Time(s)');
ylabel('Voltage(V)');
del_v = max(y) - min(y) % Peak-to-peak vo
SSE = y(ind(end)) % Steady state error
```

Input Voltage Step Response Code




```
del_v =

    1.2367


SSE =

    0.4988
```

Deviation Voltage and Steady State Error

Task 6e:

$$-Z_{out} = \frac{-r_L(1+\frac{sL}{r_L})}{CLs^2+(Cr_L+\frac{L}{R})s+1}$$

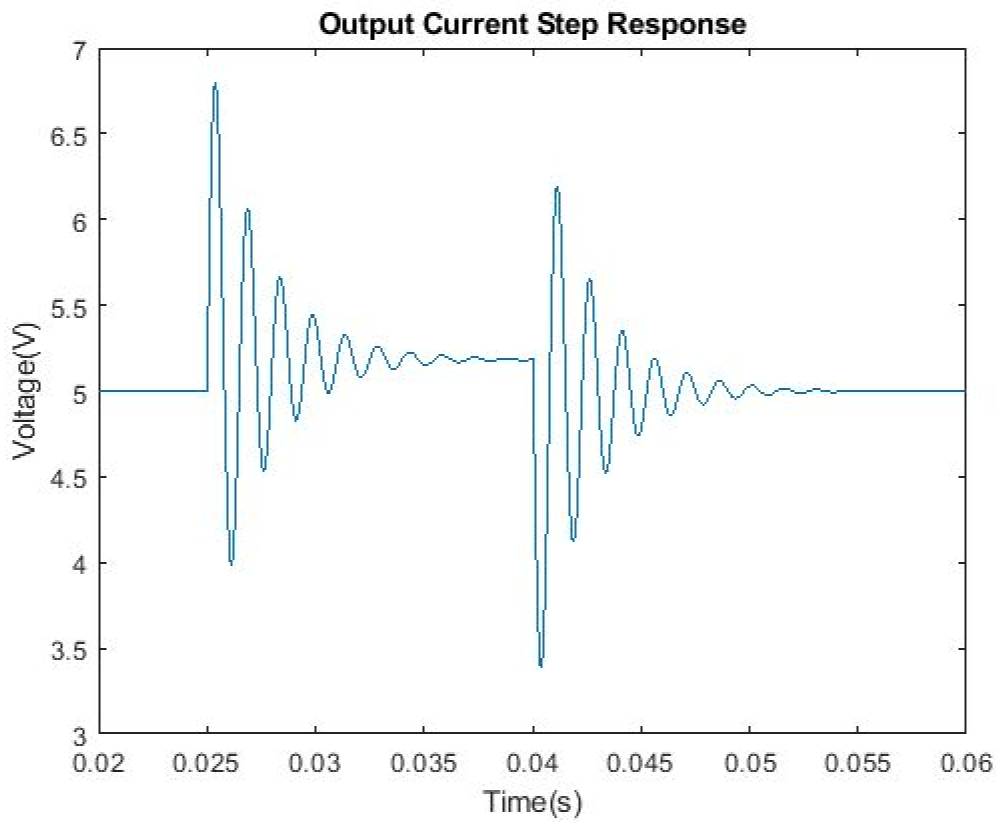
```
s = tf('s');
% LCR Low Pass Filter Component Values
C = 100e-06;
R = 25;
r = 230e-03;
L = 560e-06;

Vg = 10; % Input voltage
D = 0.5; % K_vg
V = D*Vg; % Steady state voltage

% Impedance Out Transfer Function
Z_out = -(r+s*L)/(C*L*s^2+(C*r+(L/R))*s+1);

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(1)
y = lsim(-Z_out, u, t);
plot(t,y+V)
title('Output Current Step Response');
xlabel('Time(s)');
ylabel('Voltage(V)');
del_v = max(y) - min(y)
SSE = y(ind(end))
```

Output Current Step Response Code




```
del_v =

    3.4141


SSE =

    0.1843
```

Deviation Voltage and Steady State Error

Results:

Transfer function DC gains:

	From PECS	From model: Symbolic	From model: Symbolic Evaluated
K_{VG}	0.5	D	0.5
K_{VD}	~~10~~ 10.125	V_G	10

Margins and associated frequencies:

Gain Margin	Phase Crossover Frequency	Phase Margin	Gain Crossover Frequency
Infinite	~~Never~~ infinite	15.6	942

Step response characteristics table:

	PECS	Matlab	
Vg step:	~~0.5~~	~~0.5~~	1.15 and 1.24
Vg step SSE:	498mV	498mV	
i_{out}:	~~1946mV~~	~~176mV~~	2.92V and 3.41V
i_{Out}: SSE	174mV	184mV	

Comparison of results for V and Iout changes:

It may be due to the fact that the model we use in Matlab takes the assumption that r_L+R=R where in the PECS simulation it includes r_L in all of the calculations. Some additional artifacts may arise in the fact we are adding a large signal step after simulation to the output of matlab. Matlab simplifaction of switching

Simple symbolic expression for SSE for a step in v:

Error = R(s)-C(s)

C(s)=R(s)T(s)

$$T(s) = \frac{D}{1+(\frac{s}{\omega_0 Q})+(\frac{s}{\omega_0})^{2}}$$

$$R(s)= \frac{1}{s}$$

Error = $R(s)(1 - T(s)$

$$= \frac{Qs^2+\omega_0 s-(D-1)Q\omega_0^2}{Qs^2+\omega_0 s+Q\omega_0^2}$$

When $s \to 0$
SSE =1-D

Lab 3 Grading Sheet

1. Task 1:
   (i) Your PECS schematic ______ /1
   (ii) Start-up transient plot ______ /1
   (iii) Steady state output voltage value ______ /1
2. Task 2:
   (i) Plot of output voltage, diode voltage and switch current in proper format /3
   (ii) Average output voltage value ______ /1
   (iii) Peak-to-peak output voltage ripple value ______ /1
   (iv) Peak-to-peak diode voltage value ______ /1
   (v) Peak inductor current ______ /1
   (vi) Switching frequency ______ /1
   (vii) Duty ratio ______ /1
   (viii) Explanation of how duty ratio is set ______ /2
3. Task 3:
   (i) Simulation plot ______ /1
   (ii) K_{vg} ______ /2
   (iii) Δv ______ /1
   (iv) SSE ______ /1
4. Task 4:
   (i) Your PECS schematic ______ /1
   (ii) Filter corner frequency in Hz. ______ /1
   (iii) Plot of VP3 and VP1 in proper format ______ /1
   (iv) Peak-to-peak of VP3 and of VP1 ______ /2
   (v) In-phase or out of phase? ______ /1
   (vi) K_{vd} ______ 1 ______ /2
5. Task 5
   (i) Your PECS schematic ______ /1
   (ii) Simulation plot of VP1 ______ /1
   (iii) Δv ______ /1
   (iv) SSE ______ /1
6. Task 6a:
   (i) Loop gain transfer function ______ /2
   (ii) Your complete MATLAB code ______ /1
   (iii) Matlab plot ______ /1

(iv) Unity gain and phase crossover frequencies, phase and gain margins values /2

7. Task 6b:
   - (i) G_{vd} transfer function ____ /2
   - (ii) Your Matlab code ____ /1
   - (iii) Your Matlab plot ____ /1
8. Task 6c:
   - (i) $-Z_{out}$ transfer function ____ /2
   - (ii) Your Matlab code ____ /1
   - (iii) Your Matlab plot ____ /1
9. Task 6d:
   - (i) Your complete Matlab code ____ /1
   - (ii) Matlab plot ____ /1
   - (iii) Δv ____ /1
   - (iv) SSE ____ /1
10. Task 6e:
   - (i) Z_{out}transfer function ____ /1
   - (ii) Your Matlab code ____ /1
   - (iii) Your Matlab plot ____ /1
   - (iv) Δv ____ /1
   - (v) SSE ____ /1
11. Results (summary):
   - (i) Transfer function DC gains' table ____ 2.5 ____ /3
   - (ii) Margins and associated frequencies table ____ 1.5 ____ /2
   - (iii) Step response characteristics table ____ 1 ____ /2
   - (iv) Comparison of results for $\Delta v$and i_{out} changes ____ 1 ____ /2
   - (v) Simple symbolic expression for SSE for a step in Δv ____ 1 ____ /2

Report: ____ /5

Total: ____ 65 ____ /70