Converter Design

Assignment 3

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Submitted To:
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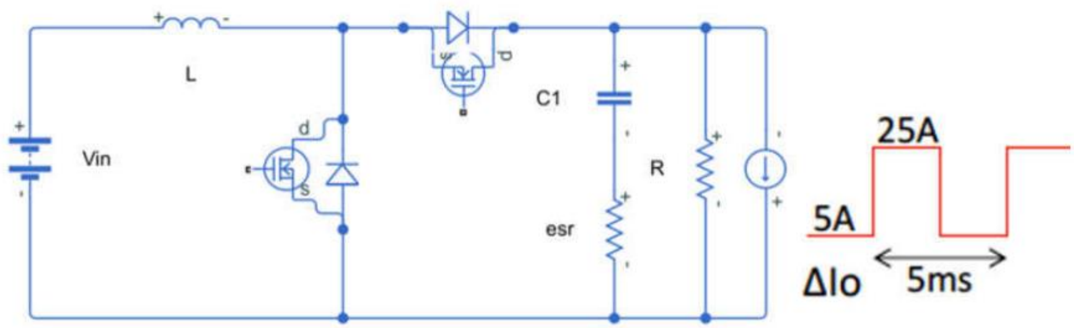
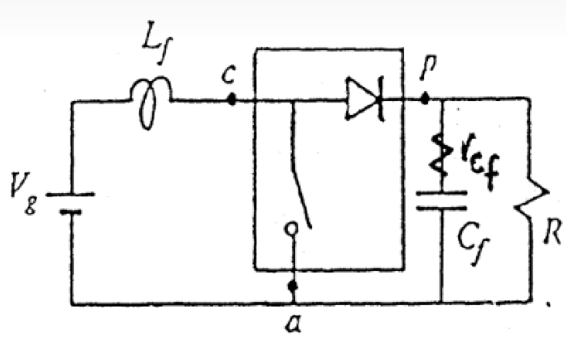
Q.1

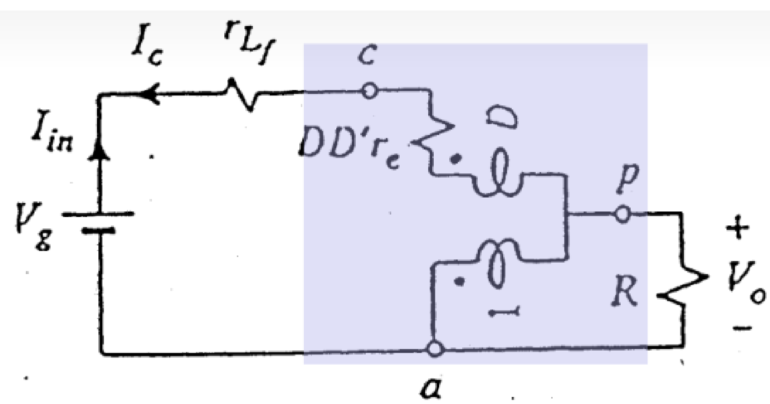
Bidirectoinal Boost converter is often used in renewable energy applications. It uses a synchronous rectifier (MOSFET) instead of the diode in the normal Boost topology. The two MOSFETs's gate signals are complementary. There is no DCM operation for this boost converter. The circuit diagram is illustrated below



The parameters of the above boost converter are:
Vin=10V, Vo=16V, L=100nH, R_L=0.5mΩ, R_c=4mΩ, C_o=660uF, R_o=120mΩ, fs= 1MHz; As shown in the graph, load transient current step ΔI_o=20A (from 25A to 5A) with period T_{load}=5ms.Load transient is assumed to be an ideal square waveform (50% duty cycle) with 0 rising and falling time. In this exercise, we assume S_1 and S_2 are ideal switches and neglect the dead-time between S_1 and S_2.

DC analysis





$V_{ap} = V_{ac} + V_{cp}$ $\quad$ $i_a = -I_L D$ $\quad$ $i_c = -I_L, i_p = I_o$

$$i_c = i_a - i_P = -I_L D - I_o = -I_L \qquad I_L = \frac{I_o}{D'} = \frac{V_o}{D'R}$$

$$V_{ac} = -V_g + I_L\, r_L\,, V_{ap} = -V_o \qquad V_{cp} = -V_o D + I_L\, DD' r_e$$

$$Z_p = \frac{R(R_c + \left(\frac{1}{SC}\right))}{R + R_c + (\frac{1}{SC})}$$

$$Z_p = \frac{R(SCR_c + 1)}{SCR_o + SCR_c + 1}$$

$$Z_o = -\frac{R_o(SCR_c + 1)}{SCR_o + SCR_c + 1} \,||\, \frac{(DD'R_e + R_L + sL)}{D'^2}$$

$$Z_o = \frac{-(DD'R_e + R_L + sL)R(R_cCs + 1)}{D'^2R(R_cCs + 1) + (DD'R_e + R_L + sL)RCs + (DD'R_e + R_L + sL)(R_cCs + 1)}$$

$$Z_o = \frac{-(DD'R_e + R_L + sL)R(R_cCs + 1)}{D'^2R(R_cCs + 1) + (DD'R_e + R_L + sL)RCs + (DD'R_e + R_L + sL)(R_cCs + 1)}$$

$$Z_o = \frac{-(DD'R_e + R_L + sL)R(R_cCs + 1)}{D'^2RR_cCs + D'^2R + (DD'R_e + R_L + sL)(C(R + R_c)s + 1)}$$

$$Z_o = \frac{-(DD'R_e + R_L + sL)R(R_cCs + 1)}{\big(LC(R + R_c)\big)s^2 + \big((DD'R_e + R_L)(CR + CR_c) + L + D'^2RR_cC\big)s + (D'^2R + R_L + DD'R_e)}$$

$$Z_o = \frac{-R\,\frac{(DD'R_e + R_L)}{D'^2}}{R + \frac{(R_L + DD'R_e)}{D'^2}} \frac{\left(1 + \frac{sL}{DD'R_e + R_L}\right)(R_cCs + 1)}{\frac{LC(R + R_c)}{D'^2R + R_L + DD'R_e}s^2 + \frac{D'^2RCR_c + L + (DD'R_e + R_L)(CR + CR_c)}{D'^2R + R_L + DD'R_e}\; s + 1}$$

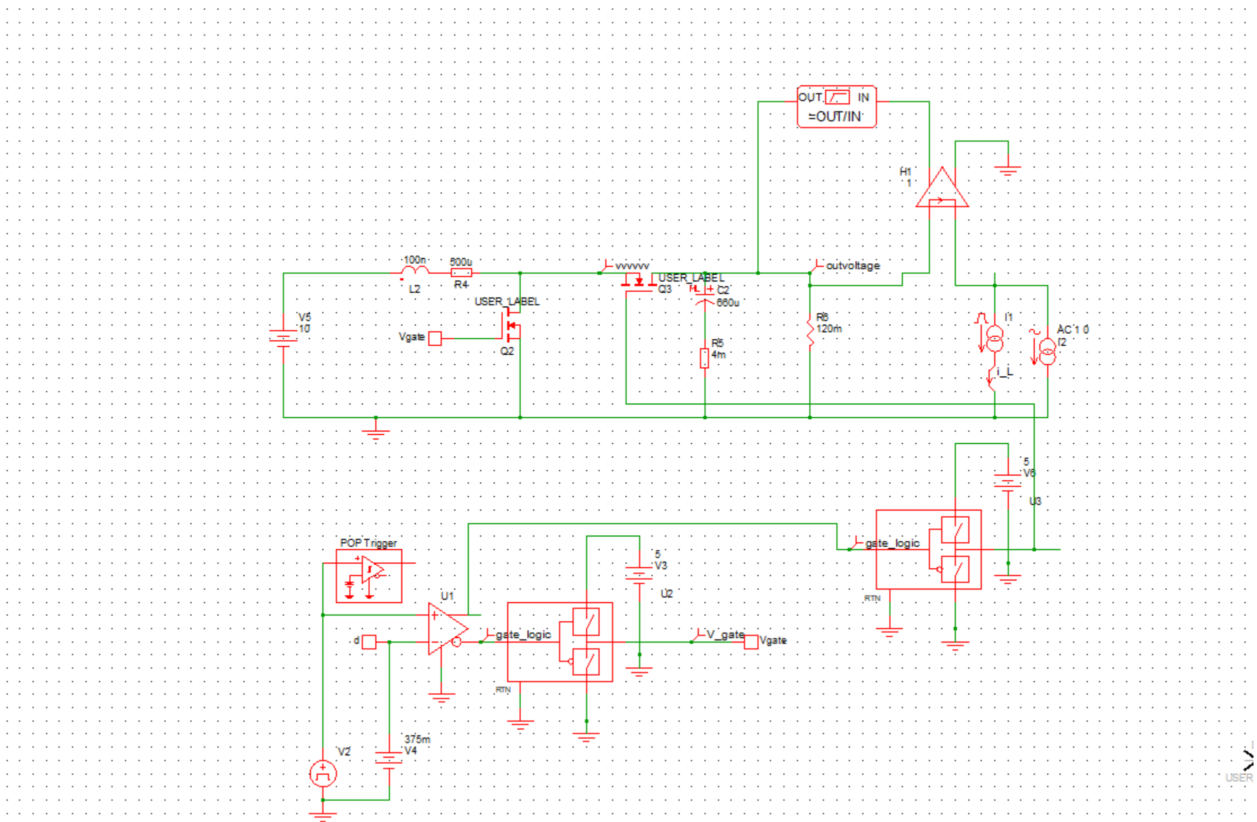
$$\boldsymbol{Z_o = -R_o \frac{(1 + \frac{s}{\omega_{zo}})\left(1 + \frac{s}{\omega_{esr}}\right)}{1 + \frac{s}{Q\omega_o} + \frac{s^2}{\omega_o^2}}}$$

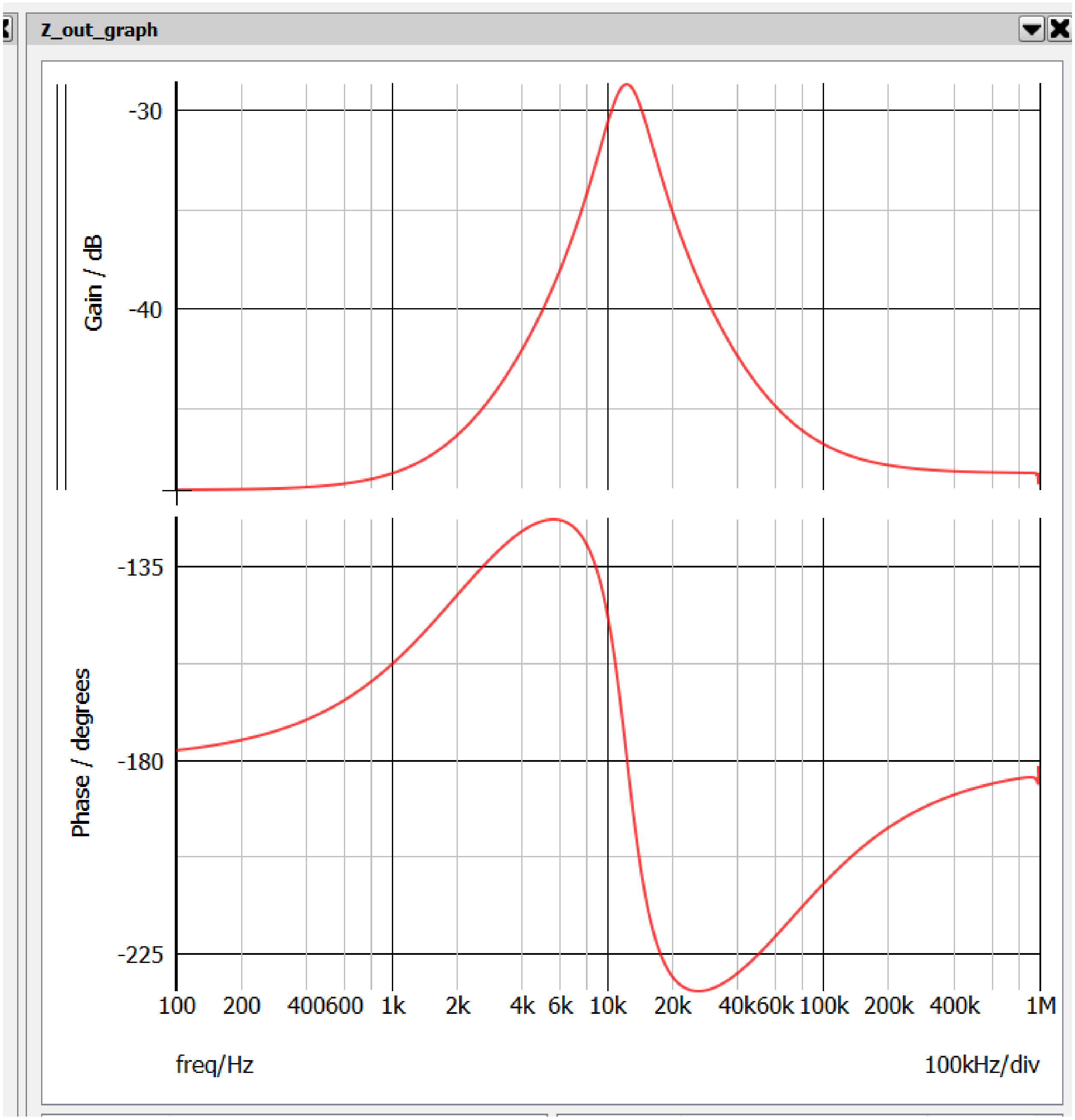
$$\boldsymbol{\omega_o = \frac{D'}{\sqrt{LC}} \sqrt{\frac{1 + \frac{r_L}{D'^2R} + \frac{Dr_e}{D'R}}{1 + \frac{r_c}{R}}}}$$

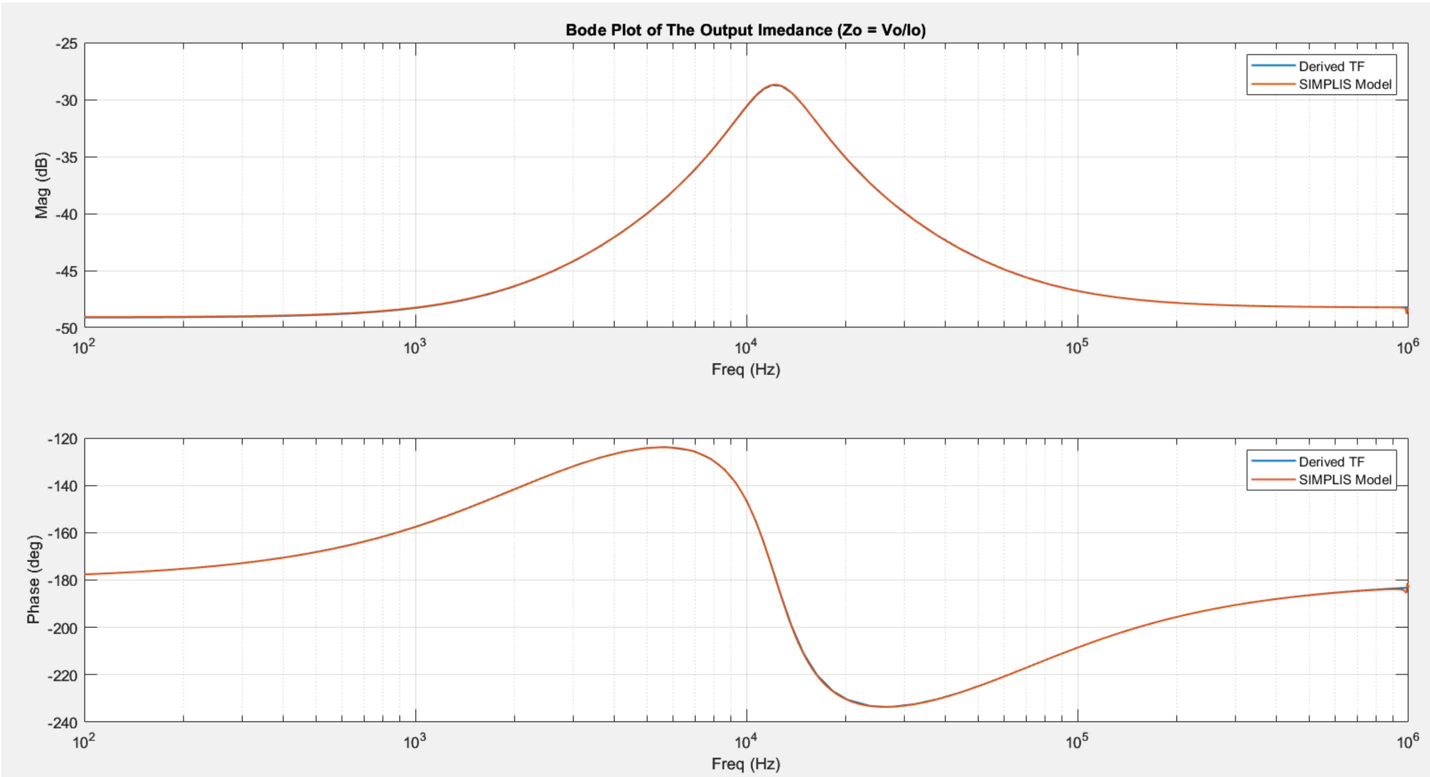
$$\boldsymbol{Q = \frac{\omega_o}{\frac{D'^2Rr_c}{L(R + r_c)} + \frac{1}{C(R + r_c)} + \frac{(DD'r_e + r_L)}{L}}}$$

$$R_o = R || \frac{(DD' r_e + r_L)}{D'^2} \qquad \omega_{zo} = \frac{(DD' r_e + r_L)}{L} \qquad \omega_{esr} = \frac{1}{R_c C}$$

Simplis model




Z_out_graph
Gain / dB
-30
-40
Phase / degrees
-135
-180
-225
100
200
400600
1k
2k
4k
6k
10k
20k
40k60k
100k
200k
400k
1M
freq/Hz
100kHz/div



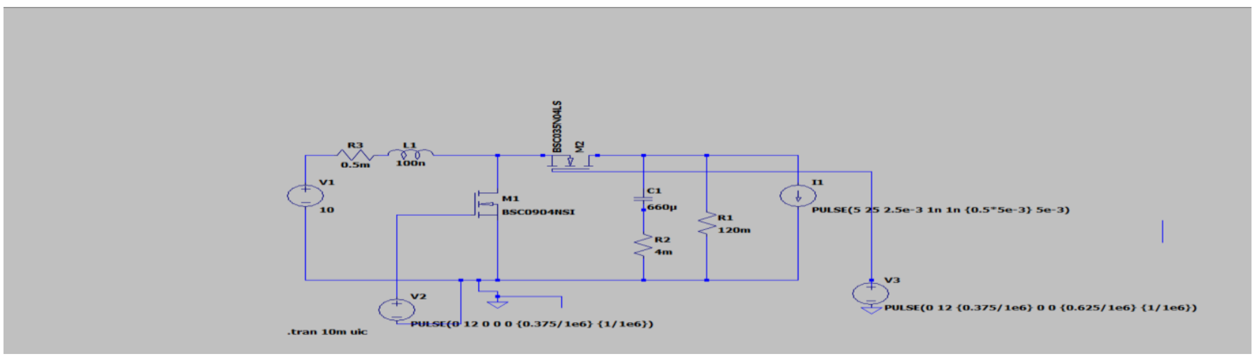
/MATLAB Drive/converters assignement 3/bode_boost.m

```
clear
clc
s=tf('s');

BB_data = xlsread('Z_out_boost.xlsx');

freq_1 = BB_data(:,1);
Gain_1 = BB_data(:,2);
phase_1 = BB_data(:,3);
Vin=10; %input voltage
Vo=16; %Output Voltage
L=100e-9; %Inductance
C=660e-6; %Capacitance
Rc=4e-3; %ESR
R=120e-3; %Load resistance
%Re=(R*(Rc+(1/(s*C))))/(R+(Rc+(1/(s*C))));
Re=(R*Rc)/(R+Rc);
RL=0.5e-3;
Fs=10^6; %Switching frequency
D=0.375; %Duty
D_=1-D;
w={100*2*pi,10^6*2*pi}; %Frequency limit of Bode plot
Gzo=-(R*((RL+Re*D*D_)/(D_)^2))/(R+((RL+Re*D*D_)/(D_)^2));
Num_zo=-((s^2)*(C*L*Rc/(RL+Re*D*D_))+s*(C*Rc+(L/(RL+Re*D*D_)))+1) ;
Den_zo= (s^2)*(C*L*(R+Rc)/((D_^2)*R+RL+Re*D*D_))+s*(L+(C*R+C*Rc)*(RL+Re*D*D_)+(D_^2)*R*Rc*C)/((D_^2)*R+RL+Re*D*D_)+1;
Zo=Gzo*Num_zo/Den_zo ;
w0=((Re*D*D_)+RL)/L;

[mag,phase,wout]= bode(Zo,w);
```

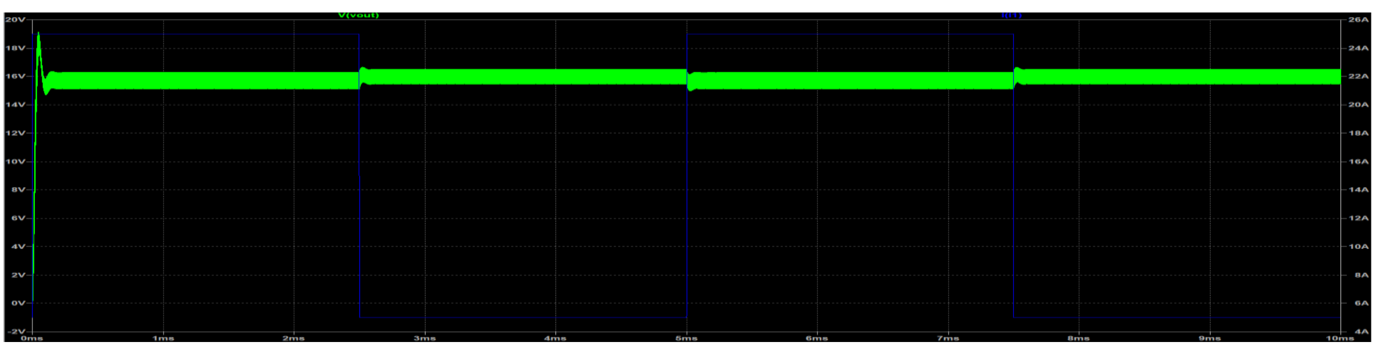
TLAB Drive/converters assignement 3/bode_boost.m

```
f_zo=wout/(2*pi);
figure(1);
subplot(2,1,1)
semilogx(f_zo,20*log10(mag_zo),freq_1,Gain_1,'LineWidth',1.2);
xlabel('Frequency (Hz)');
ylabel('Magnitude (dB)');
title('Bode Plot of The Control to Output ( GZo = Vo / Io )');
legend('Transfer Function','SIMPLIS Model');

subplot(2,1,2)
semilogx(f_zo,ph_zo-180,freq_1,phase_1,'LineWidth',1.2);
xlabel('Frequency (Hz)');
ylabel('Phase (deg)');
legend('Transfer Function','SIMPLIS Model');
grid on;
```

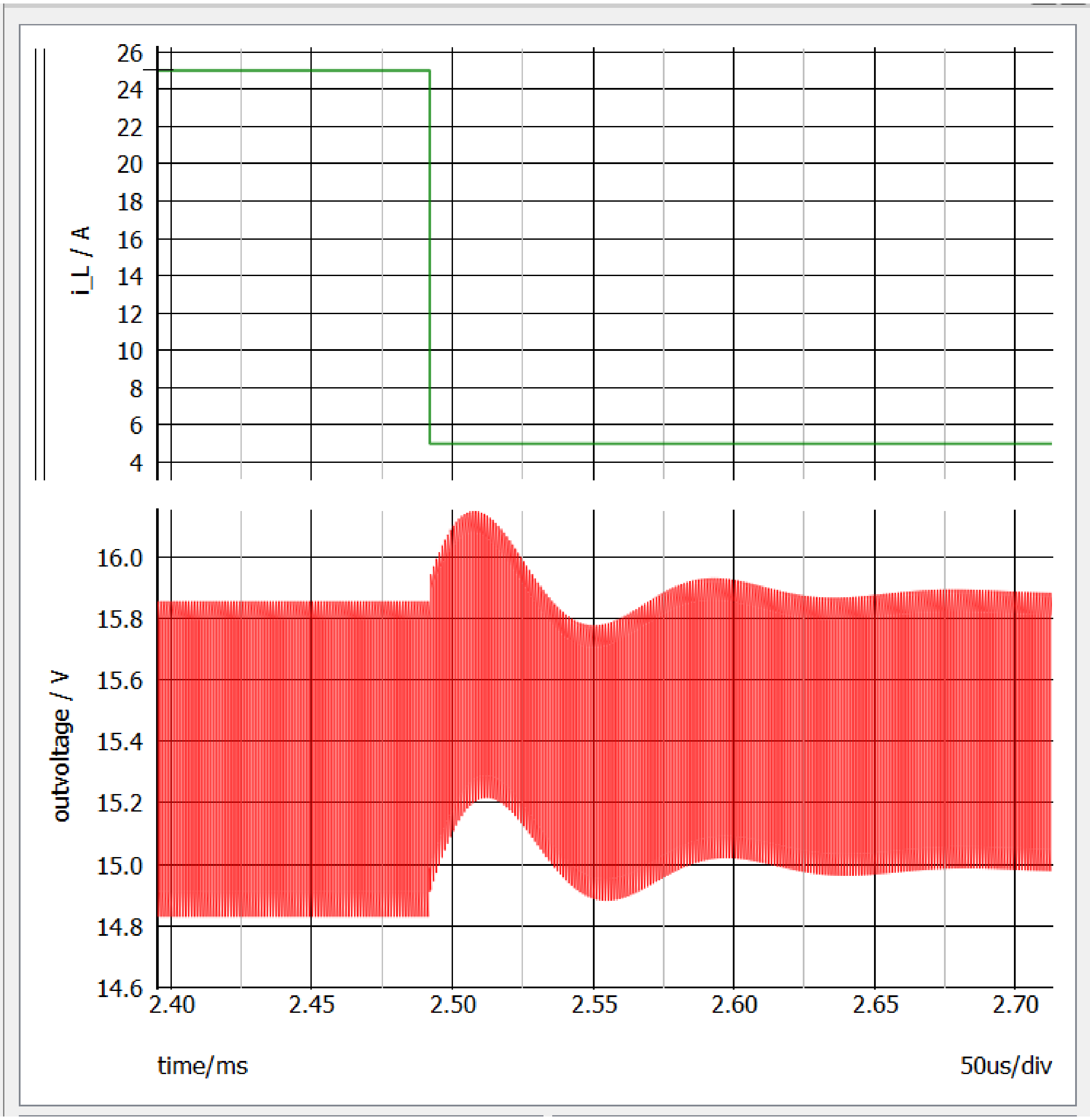
Ltspice model

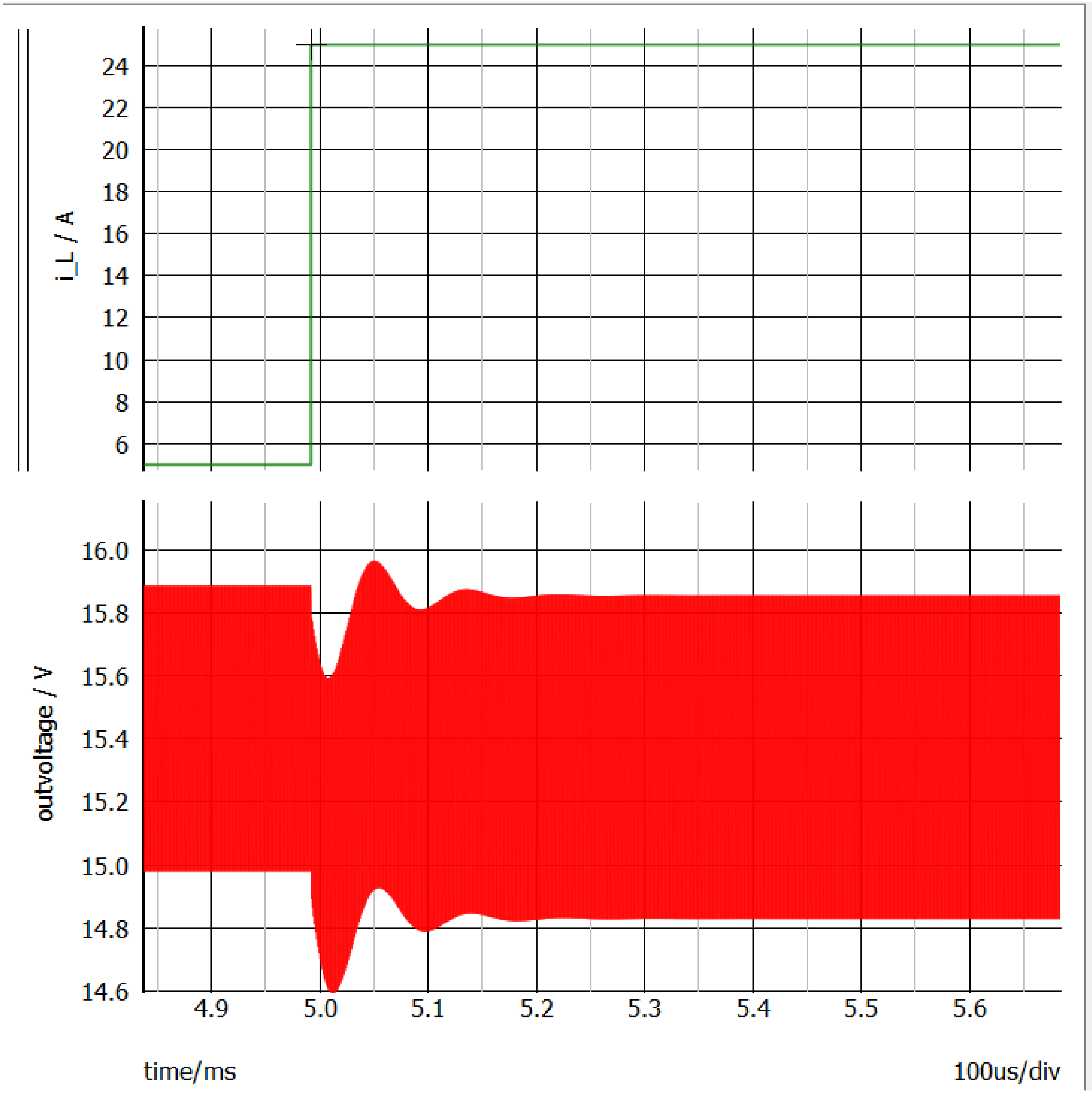


Transient response with Ltspice



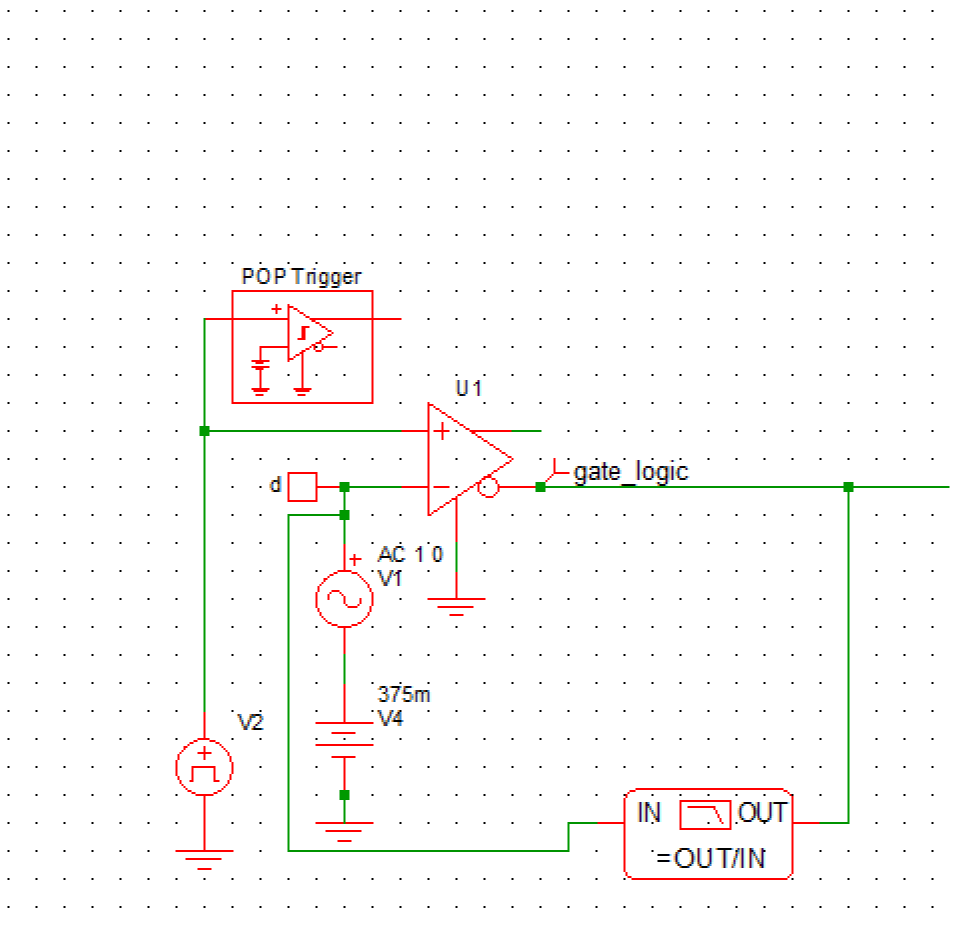
Transient response with Simplis


i_L / A
26
24
22
20
18
16
14
12
10
8
6
4
outvoltage / V
16.0
15.8
15.6
15.4
15.2
15.0
14.8
14.6
2.40
2.45
2.50
2.55
2.60
2.65
2.70
time/ms
50us/div



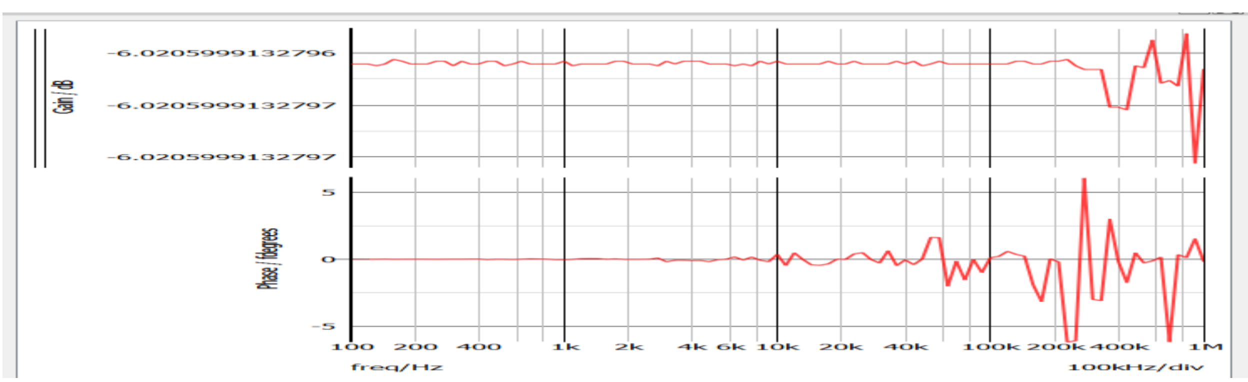
Q2

Finding $G_{PWM} = \frac{\widehat{v_c}}{\hat{d}}$



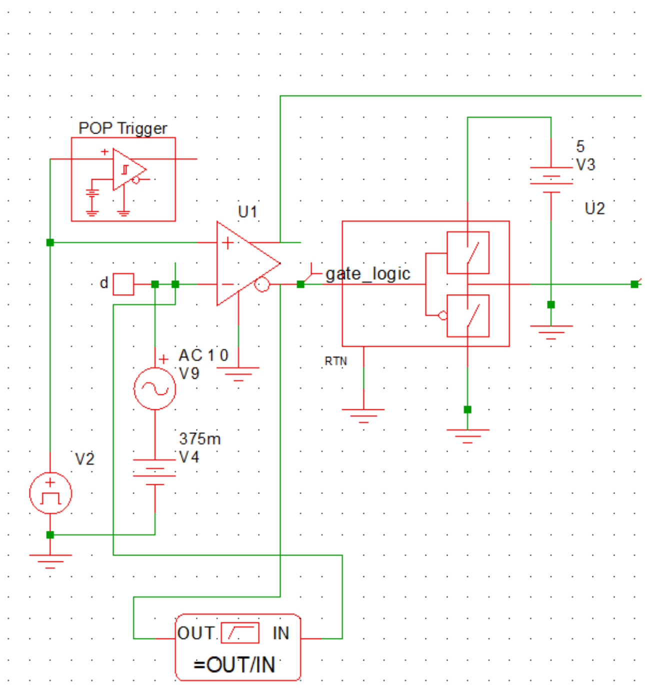
$@\ V_p = 10$

$$V_p = 10 \ \rightarrow \ |G_{PWMo}| = -6.3dB$$

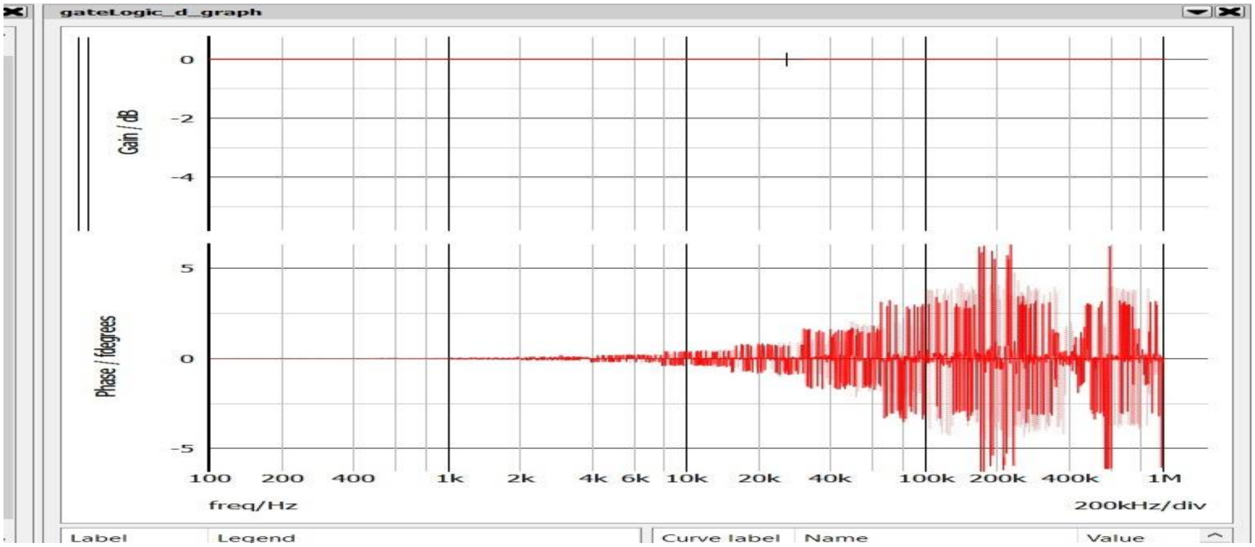


$@V_p = 1$

$|G_{PWMo}|$ =0 db



POP Trigger
U1
gate_logic
d
AC 1 0
V9
5
V3
U2
RTN
375m
V4
V2
OUT
IN
=OUT/IN



$$gain = \frac{dD}{dV_{ctrl}}$$

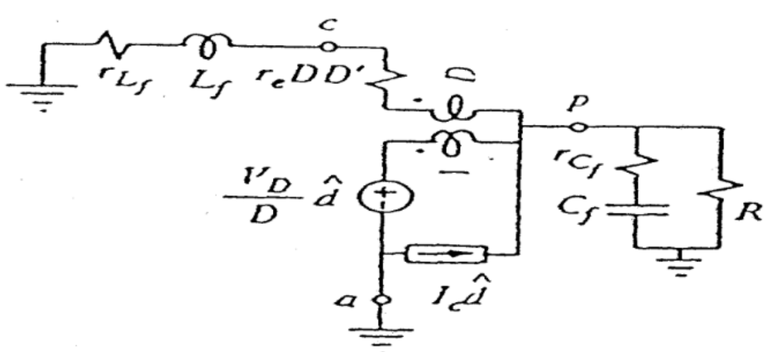
$$D = \frac{V_{ctrl}}{V_p}$$

$$\frac{dD}{dV_{ctrl}} = \frac{1}{V_p}$$

$$G_{pwm} = \frac{1}{V_p}$$

Q3 - a)

Obtaining control to output TF for controller design $G_{vd}(s) = \frac{\hat{v}_o(s)}{\hat{d}(s)}$ @ $\hat{V}_g = 0$



$$V_{ap} = V_{ac} + V_{cp}$$

$$\hat{\imath}_a = \hat{\imath}_c D \,, \hat{\imath}_p = \frac{\hat{v}_o}{R} + \frac{\hat{v}_o}{r_c + \frac{1}{sC}}$$

$$\hat{\imath}_c = \hat{\imath}_a + I_c \hat{d} - \hat{\imath}_P = \hat{\imath}_c D + I_c \hat{d} - \frac{\hat{v}_o}{R||\left(r_c + \frac{1}{sC}\right)}$$

$$\hat{\imath}_c = \frac{1}{D'}\left(I_c \hat{d} - \frac{\hat{v}_o}{R||\left(r_c + \frac{1}{sC}\right)}\right)$$

$$V_{ac} = -\hat{\imath}_c(r_L + sL), V_{ap} = -\hat{v}_o \,, V_{cp} = -\hat{v}_o D - \hat{\imath}_c\, DD' r_e + V_D \hat{d}$$

$$\hat{v}_o = \hat{\imath}_c(r_L + sL) + \hat{v}_o D + \hat{\imath}_c\, DD' r_e - V_D \hat{d}$$

$$\hat{v}_o D' = \hat{\imath}_c(r_L + DD' r_e + sL) - V_D \hat{d}$$

$$\hat{v}_o = \frac{1}{D'^2}\left(I_c \hat{d} - \frac{\hat{v}_o}{R||\left(r_c + \frac{1}{sC}\right)}\right)(r_L + DD' r_e + sL) - \frac{V_D}{D'}\hat{d}$$

$$\hat{v}_o\left(1 + \frac{(r_L + DD' r_e + sL)}{D'^2\left(R||\left(r_c + \frac{1}{sC}\right)\right)}\right) = \frac{1}{D'^2} I_c \hat{d}(r_L + DD' r_e + sL) - \frac{V_D}{D'}\hat{d}$$

$$V_D = -\hat{v}_o + I_c(D - D') r_e$$

$$\hat{v}_o\left(1 + \frac{(r_L + DD' r_e + sL)}{D'^2\left(R||\left(r_c + \frac{1}{sC}\right)\right)}\right) = \frac{1}{D'^2} I_c \hat{d}(r_L + DD' r_e + sL) - \frac{(-V_o + I_c(D - D') r_e)}{D'}\hat{d}$$

$$I_C = -I_L = -\frac{I_O}{D'} = -\frac{V_O}{RD'} = -\frac{V_g}{RD'^2}\frac{1}{1 + \frac{r_L}{D'^2 R} + \frac{D r_e}{D' R}} \text{, by using M converstion ratio}$$

$$\hat{v}_o\left(1 + \frac{(r_L + DD' r_e + sL)}{D'^2\left(R||\left(r_c + \frac{1}{sC}\right)\right)}\right) = \frac{1}{D'^2}\frac{V_O}{RD'}\left(-(r_L + DD' r_e + sL) + DD' r_e - D'^2 r_e\right)\hat{d} + \frac{V_o}{D'}\hat{d}$$

$$\hat{v}_o\left(\frac{D'^2\left(R||\left(r_c+\frac{1}{sC}\right)\right)+(r_L+DD'r_e+sL)}{D'^2\left(R||\left(r_c+\frac{1}{sC}\right)\right)}\right)=\frac{V_o}{D'}\left(\frac{1}{RD'^2}\left(-r_L-sL-D'^2r_e+RD'^2\right)\right)\hat{d}$$

$$\frac{\hat{v}_o}{\hat{d}}=\frac{V_oD'^2}{D'}\frac{\left(\frac{1}{RD'^2}\left(-r_L-sL-D'^2r_e+RD'^2\right)\right)\left(R||\left(r_c+\frac{1}{sC}\right)\right)}{D'^2\left(R||\left(r_c+\frac{1}{sC}\right)\right)+(r_L+DD'r_e+sL)}$$

$$\frac{\hat{v}_o}{\hat{d}}=\frac{V_o}{D'}\frac{\left(-r_L-sL-D'^2r_e+RD'^2\right)(r_cCs+1)}{D'^2Rr_cCs+D'^2R+(r_L+DD'r_e+sL)(C(R+r_c)s+1)}$$

$$\frac{\hat{v}_o}{\hat{d}}=\frac{V_o}{D'}\frac{\left((RD'^2-r_L-D'^2r_e)-sL\right)(r_cCs+1)}{\left(LC(R+r_c)\right)s^2+\left((DD'r_e+r_L)(CR+Cr_c)+L+D'^2Rr_cC\right)s+(D'^2R+r_L+DD'r_e)}$$

$$\frac{\hat{v}_o}{\hat{d}}=\frac{V_o}{D'(D'^2R+r_L+DD'r_e)}\frac{\left((RD'^2-r_L-D'^2r_e)-sL\right)(r_cCs+1)}{\frac{LC(R+r_c)}{D'^2R+r_L+DD'r_e}s^2+\frac{D'^2RCr_c+L+(DD'r_e+r_L)(CR+Cr_c)}{D'^2R+r_L+DD'r_e}s+1}$$

$$\frac{\hat{v}_o}{\hat{d}}=\frac{V_g\,RD'^2(RD'^2-r_L-D'^2r_e)}{D'^2\left(D'^2R+r_L+DD'r_e\right)^2}\frac{\left(1-\frac{sL}{RD'^2-r_L-D'^2r_e}\right)(r_cCs+1)}{\frac{LC(R+r_c)}{D'^2R+r_L+DD'r_e}s^2+\frac{D'^2RCr_c+L+(DD'r_e+r_L)(CR+Cr_c)}{D'^2R+r_L+DD'r_e}s+1}$$

$$\boldsymbol{\frac{\hat{v}_o(s)}{\hat{d}(s)}=K\,\frac{\left(1-\frac{s}{\omega_{rhp}}\right)\left(1+\frac{s}{\omega_{esr}}\right)}{1+\frac{s}{Q\omega_o}+\frac{s^2}{\omega_o^2}}}$$

$$\boldsymbol{K=\frac{V_g\,RD'^2(RD'^2-r_L-D'^2r_e)}{D'^2\left(D'^2R+r_L+DD'r_e\right)^2}}$$

$$\boldsymbol{\omega_{rhp}=\frac{\left(RD'^2-r_L-D'^2r_e\right)}{L}}$$

From control to output TF we can get

$$f_o = 12.22kHz \quad f_{esr} = 60kHz \quad f_{rhp} = 71kHz \quad Q = 1.8547$$

Designing a type-3 compensator for $f_c = 50kHz \pm 5kHz\,, \varphi_m \geq 60°\,, GM \geq 10dB$

1- Choosing $f_{P1} = f_{esr} = 60kHz$

2- Choosing $f_{P2} = 10f_c = 500kHz$

3- For the phase margin

$$\varphi_m = 180 - tan^{-1}\left(\frac{f_c}{f_{P1}}\right) - tan^{-1}\left(\frac{f_c}{f_{P2}}\right) - 90 + tan^{-1}\left(\frac{f_c}{f_{esr}}\right) + tan^{-1}\left(\frac{f_c}{f_{Z1}}\right) + tan^{-1}\left(\frac{f_c}{f_{Z2}}\right) + tan^{-1}\left(\frac{f_c}{f_{rhp}}\right) - tan^{-1}\left(\frac{\frac{f_c}{Qf_o}}{1-\left(\frac{f_c}{f_o}\right)^2}\right) \geq 60°$$

Let $f_{Z1} = 5kHz \rightarrow \; f_{Z2} = 93kHz$

4- For gain margin

$|T| = 1 @ f_c \rightarrow 50kHz$

$$|T| = \frac{\sqrt{1+\left(\frac{f_c}{f_{Z1}}\right)^2} * \sqrt{1+\left(\frac{f_c}{f_{Z2}}\right)^2} * \sqrt{1+\left(\frac{f_c}{f_{rhp}}\right)^2}}{50 * 10^3 * 2\pi \sqrt{\left(1-\left(\frac{f_c}{f_o}\right)^2\right)^2 + \left(\frac{f_c}{f_o Q}\right)^2} * \sqrt{1+\left(\frac{f_c}{f_{P2}}\right)^2}} * V_g * FM * \omega_I = 1$$

$$\omega_I = 36000$$

According to design notes in the lecture

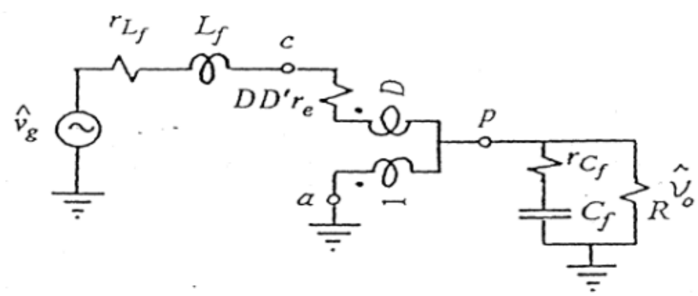
$$\omega_I = \frac{1}{R_1 C_1} \qquad \omega_{Z1} = \frac{1}{R_2 C_1} \qquad \omega_{Z2} = \frac{1}{R_1 C_2} \qquad \omega_{P1} = \frac{1}{R_3 C_2} \qquad \omega_{P2} = \frac{1}{R_2 C_3}$$

$$R_1 = 10K\Omega \quad R_2 = 13.8K\Omega \quad R_3 = 15.5K\Omega$$

$$C_1 = 2.7pF \quad C_2 = 171pF \quad C_3 = 23pF$$

continue with obtaining $\mathrm{G_{vg}}(\mathrm{s}) = \frac{\hat{\boldsymbol{v}}_{\boldsymbol{o}}(\mathbf{s})}{\hat{\boldsymbol{V}}_{\boldsymbol{g}}(\mathbf{s})}$, $\mathrm{G_{vd}}(\mathrm{s}) = \frac{\hat{\boldsymbol{v}}_{\boldsymbol{o}}(\mathbf{s})}{\hat{\boldsymbol{d}}(\mathbf{s})}$

$$\mathrm{G_{vg}}(\mathrm{s}) = \mathrm{M}\frac{\hat{\boldsymbol{v}}_{\boldsymbol{o}}(\mathbf{s})}{\hat{\boldsymbol{V}}_{\boldsymbol{g}}(\mathbf{s})} \text{ When } \hat{I}_o = \hat{d} = 0$$



Circuit Model

$$\mathrm{V_{ap}} = \mathrm{V_{ac}} + \mathrm{V_{cp}}$$

$$\mathrm{i_a} = \hat{\mathrm{i}}_\mathrm{c}\mathrm{D}\,, \mathrm{i_p} = \frac{\hat{\mathrm{v}}_\mathrm{o}}{\mathrm{R}} + \frac{\hat{\mathrm{v}}_\mathrm{o}}{\mathrm{r_c} + \frac{1}{\mathrm{sC}}}$$

$$\mathrm{i_c} = \mathrm{i_a} - \mathrm{i_P} = \hat{\mathrm{i}}_\mathrm{c}\mathrm{D} - \left(\frac{\hat{\mathrm{v}}_\mathrm{o}}{\mathrm{R}} + \frac{\hat{\mathrm{v}}_\mathrm{o}}{\mathrm{r_c} + \frac{1}{\mathrm{sC}}}\right)$$

$$\mathrm{i_c} = -\frac{\hat{\mathrm{v}}_\mathrm{o}}{\mathrm{D'}}\left(\frac{1}{\mathrm{R}} + \frac{1}{\mathrm{r_c} + \frac{1}{\mathrm{sC}}}\right)$$

$$\mathrm{V_{ac}} = -\hat{\mathrm{v}}_\mathrm{g} - \hat{\mathrm{i}}_\mathrm{c}(\mathrm{r_L} + \mathrm{sL}), \mathrm{V_{ap}} = -\hat{\mathrm{v}}_\mathrm{o}\,, \mathrm{V_{cp}} = -\hat{\mathrm{v}}_\mathrm{o}\mathrm{D} - \hat{\mathrm{i}}_\mathrm{c}\ \mathrm{DD'r_e}$$

$$\hat{\mathrm{v}}_\mathrm{o} = \hat{\mathrm{v}}_\mathrm{g} + \hat{\mathrm{i}}_\mathrm{c}(\mathrm{r_L} + \mathrm{sL}) + \hat{\mathrm{v}}_\mathrm{o}\mathrm{D} + \hat{\mathrm{i}}_\mathrm{c}\ \mathrm{DD'r_e}$$

$$\hat{v}_o D' = \hat{v}_g + \hat{i}_c\big((r_L + sL) + DD' r_e\big)$$

$$\hat{v}_o D' \left(\frac{D'^2 R r_c + \frac{D'^2 R}{sC} + \left(\left(r_c + \frac{1}{sC} + R\right)(r_L + sL + DD' r_e)\right)}{D'^2 R r_c + \frac{D'^2 R}{sC}} \right) = \hat{v}_g$$

$$\frac{\hat{v}_o}{\hat{v}_g} = \frac{1}{D'} \left(\frac{D'^2 R r_c + \frac{D'^2 R}{sC}}{D'^2 R r_c + \frac{D'^2 R}{sC} + \left(\left(r_c + \frac{1}{sC} + R\right)(r_L + sL + DD' r_e)\right)} \right)$$

$$\frac{\hat{v}_o}{\hat{v}_g} = \frac{D'^2 R}{D'} \left(\frac{C r_c s + 1}{(CR + C r_c) L s^2 + (D'^2 R C r_c + L + (DD' r_e + r_L)(CR + C r_c)) s + (D'^2 R + r_L + DD' r_e)} \right)$$

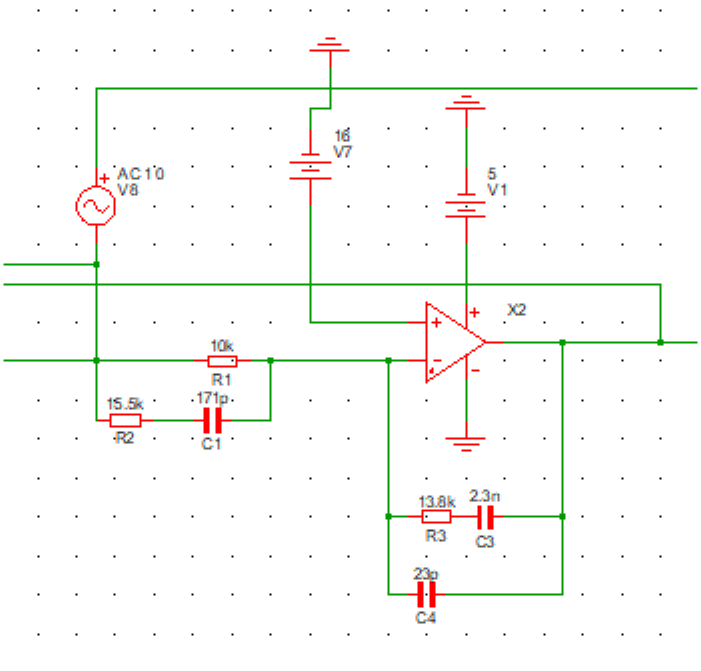
$$\frac{\hat{v}_o}{\hat{v}_g} = \frac{1}{D'\left(1 + \frac{r_L}{D'^2 R} + \frac{D r_e}{D' R}\right)} \left(\frac{C r_c s + 1}{\frac{(CR + C r_c) L}{D'^2 R + r_L + DD' r_e} s^2 + \frac{D'^2 R C r_c + L + (DD' r_e + r_L)(CR + C r_c)}{D'^2 R + r_L + DD' r_e} s + 1} \right)$$

$$\frac{\hat{v}_o(s)}{\hat{v}_g(s)} = M \frac{1 + \frac{s}{\omega_{esr}}}{1 + \frac{s}{Q\omega_o} + \frac{s^2}{\omega_o^2}}$$

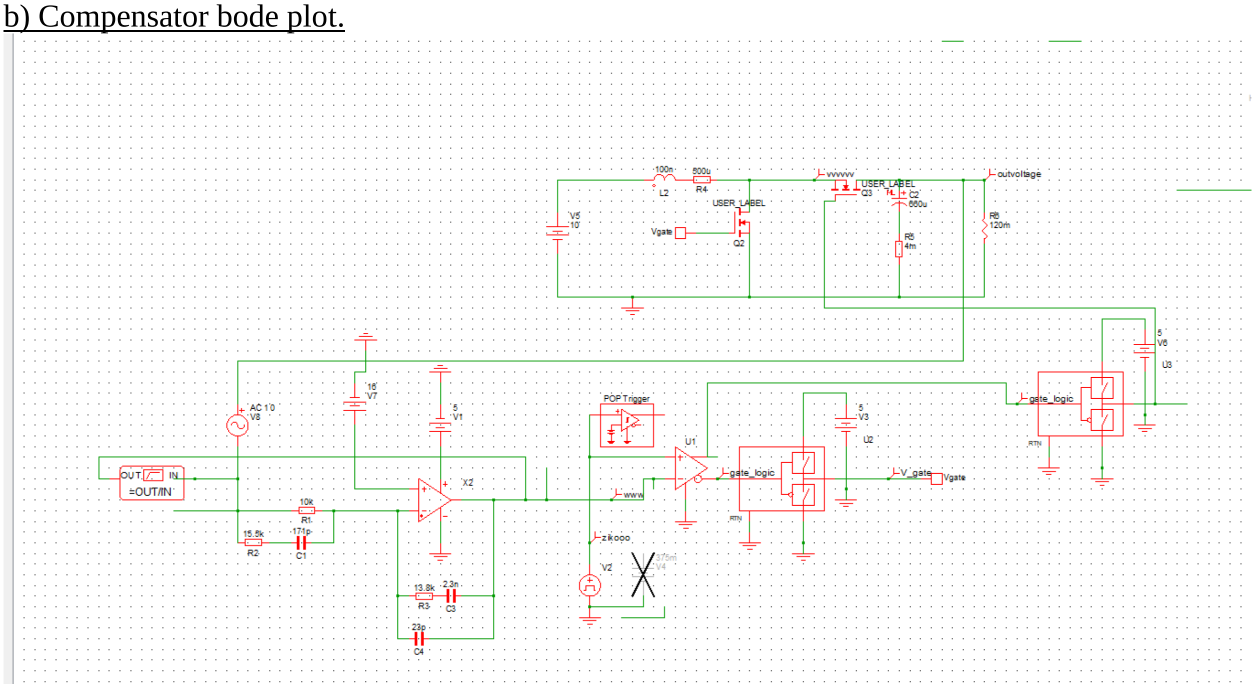
$$\omega_o = \sqrt{\frac{D'^2 R + r_L + DD' r_e}{LC(R + r_c)}} = \frac{D'}{\sqrt{LC}} \sqrt{\frac{1 + \frac{r_L}{D'^2 R} + \frac{D r_e}{D' R}}{1 + \frac{r_c}{R}}}$$

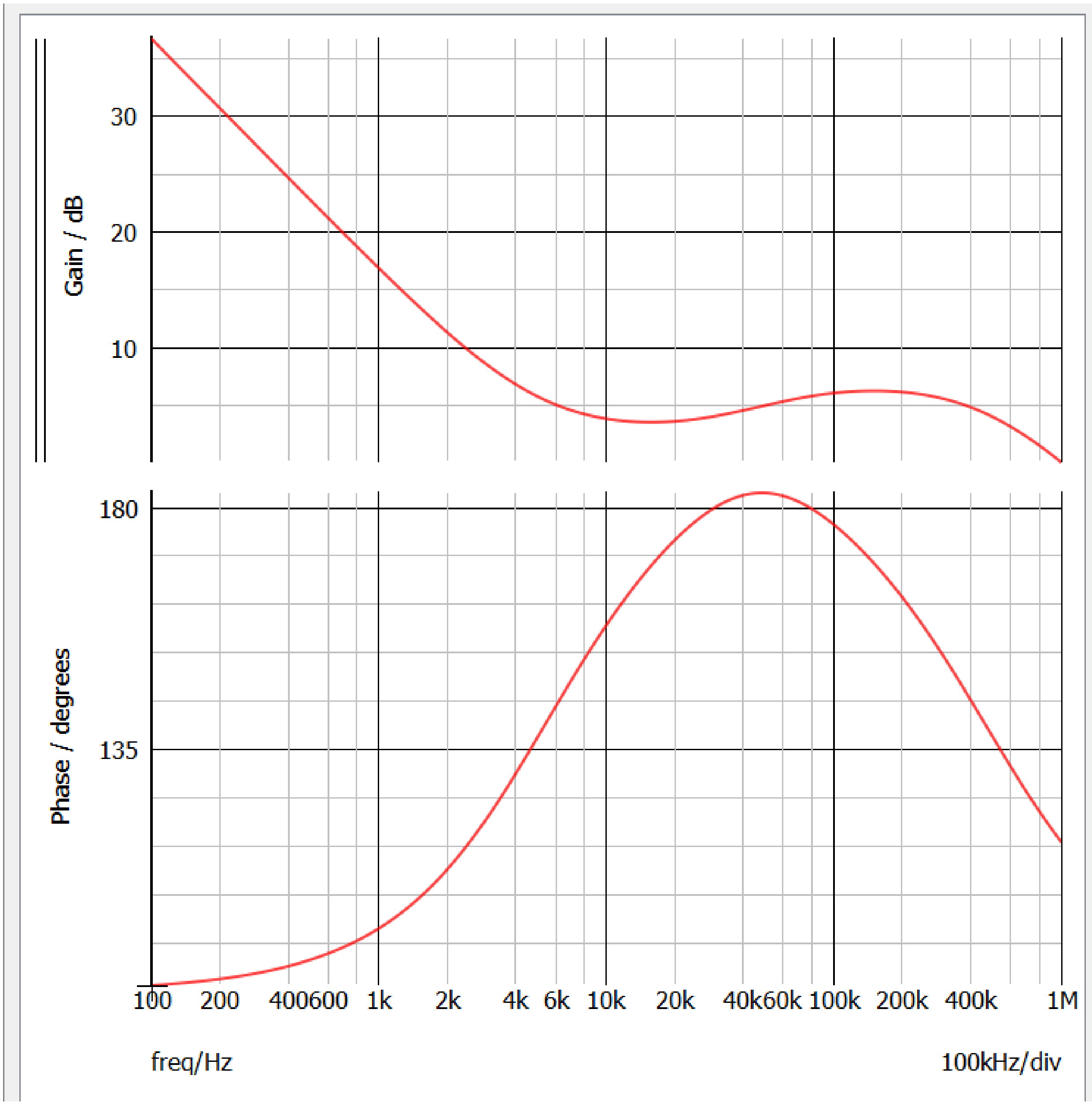
$$Q = \frac{\omega_o}{\frac{D'^2 R r_c}{L(R + r_c)} + \frac{1}{C(R + r_c)} + \frac{(DD' r_e + r_L)}{L}}, \quad \omega_{esr} = \frac{1}{r_c C}$$

Now we will obtain <u>Control to Output Transfer Function</u>

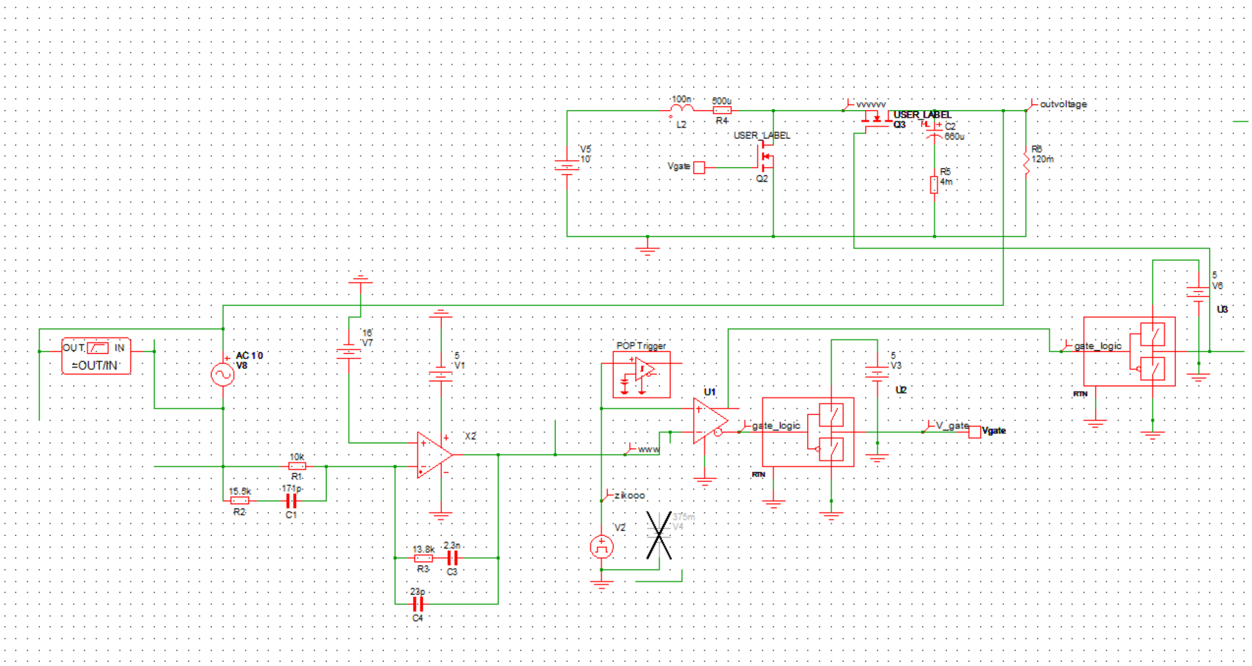


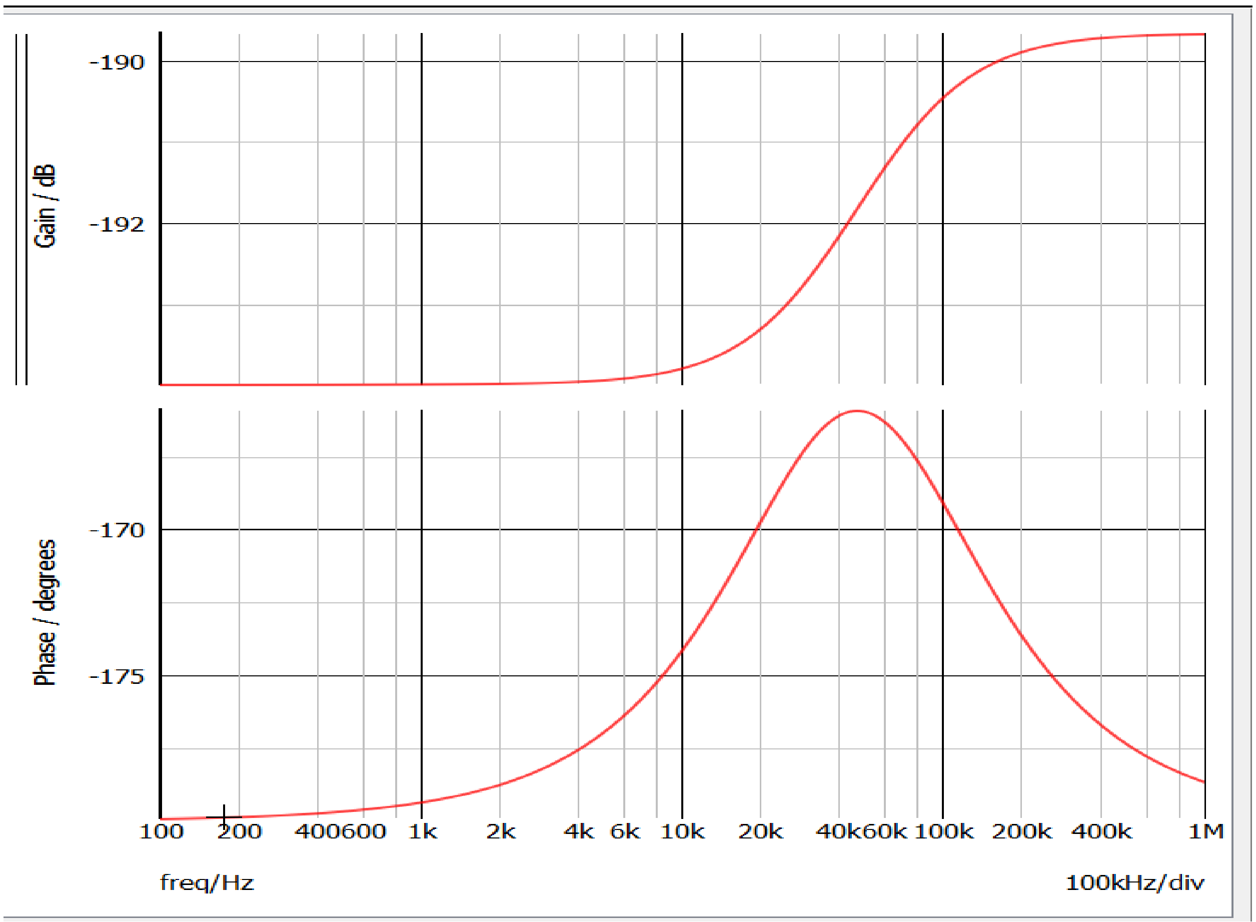
b) Compensator bode plot.



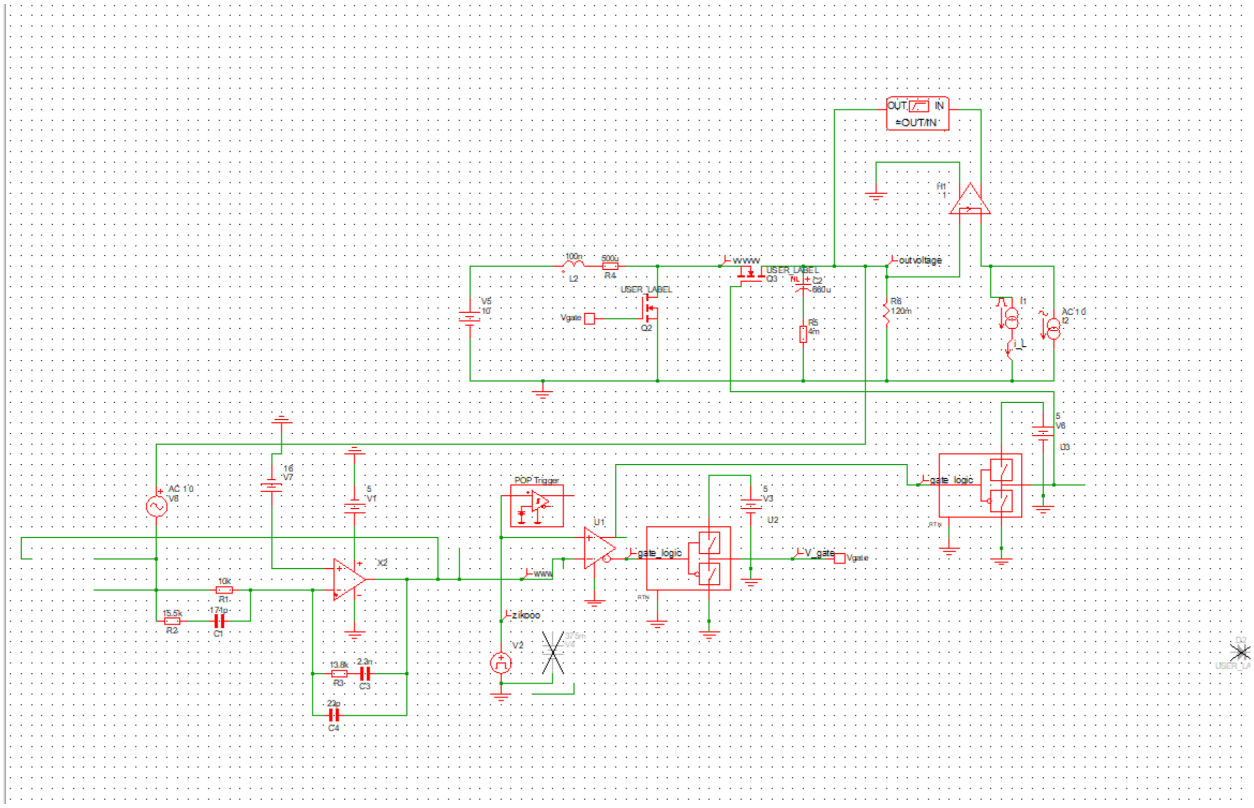


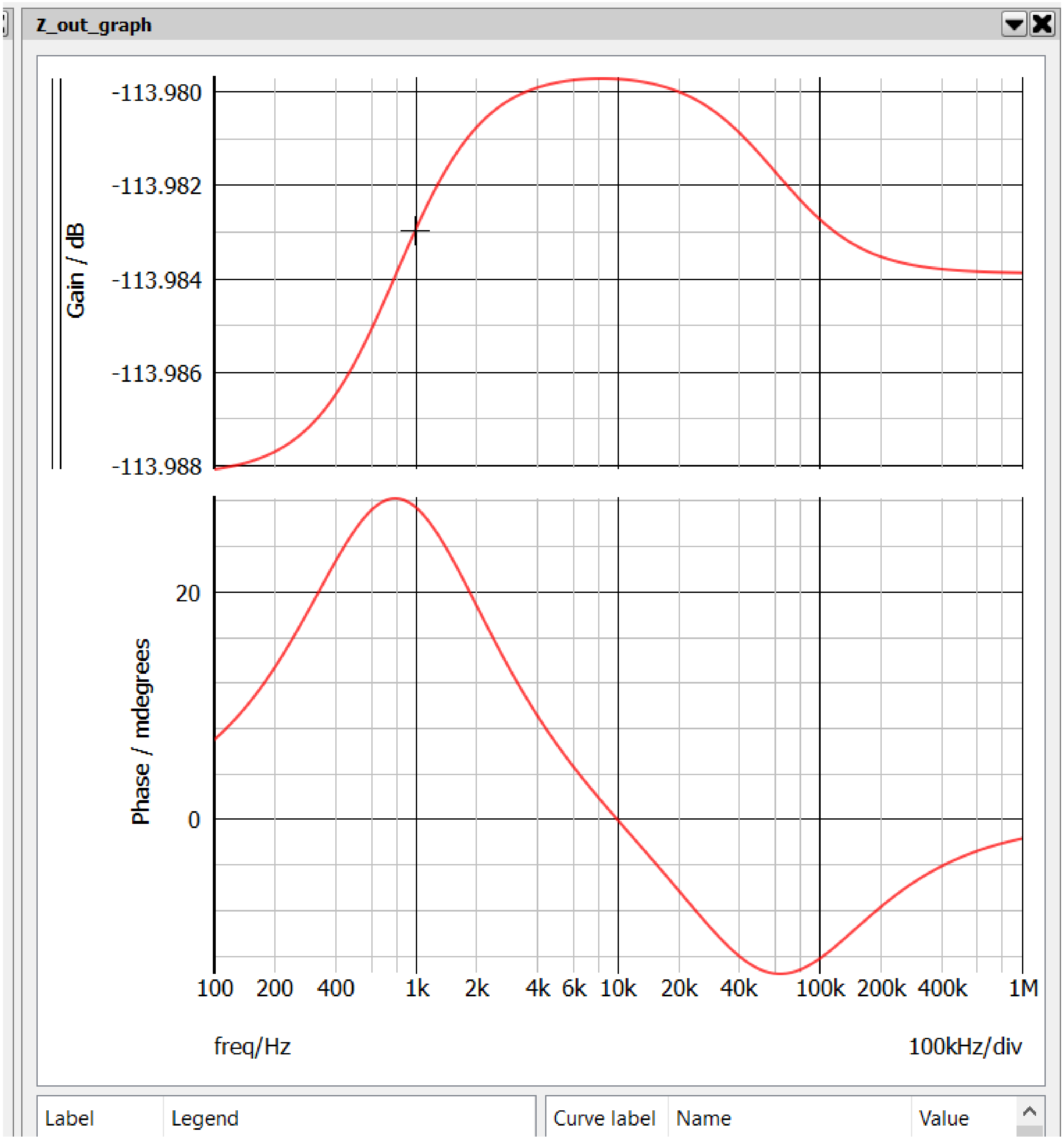
Loop gain bode plot


100n
L2
600u
R4
USER_LABEL
Q2
Vgate
V5
10
vvvvvv
USER_LABEL
Q3
C2
560u
R5
4m
R6
120m
outvoltage
OUT IN
=OUT/IN
AC 1 0
V8
16
V7
5
V1
X2
10k
R1
15.8k
R2
171p
C1
13.8k
R3
2.3n
C3
23p
C4
POP Trigger
U1
www
zikooo
V2
gate_logic
RTN
U2
5
V3
V_gate
Vgate
gate_logic
RTN
5
V6
U3

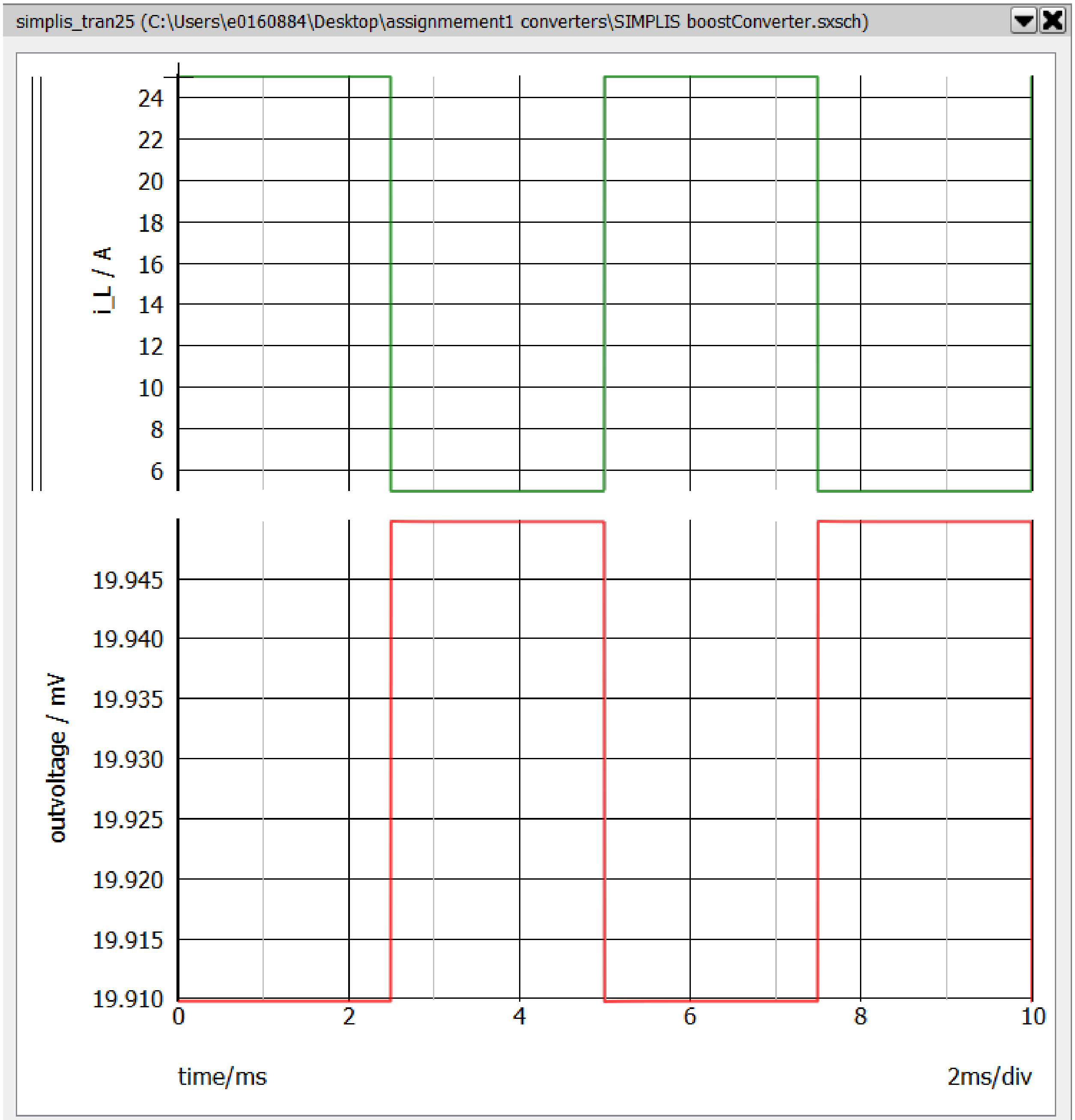

Gain / dB
-190
-192
Phase / degrees
-170
-175
100
200
400600
1k
2k
4k
6k
10k
20k
40k60k
100k
200k
400k
1M
freq/Hz
100kHz/div

C- Closed loop response of output impedance

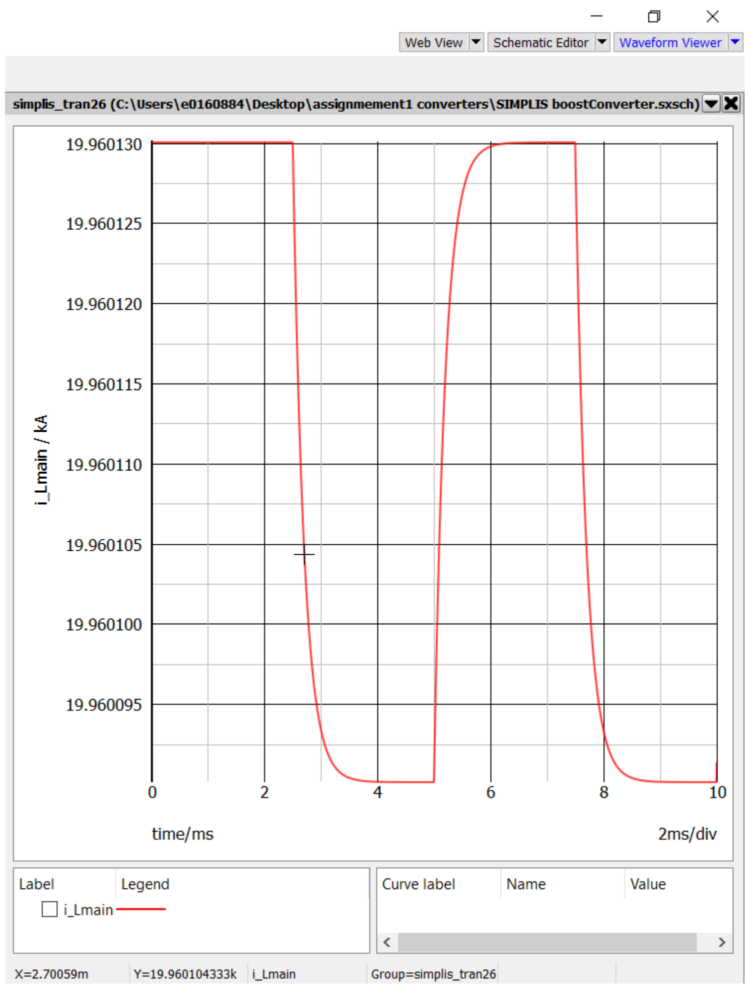




The controller failed to achieve the desired PM and GM because the location of the zeros as the compensator added an ustable zero which has a frequecny higher than the cutoff frequency and near to the RHP zero and phase margin wouldn't be achieved and the controller hits -180 as a rule of thumb the gain cross over frequency should be lower than $\frac{W_{rhp}}{5}$

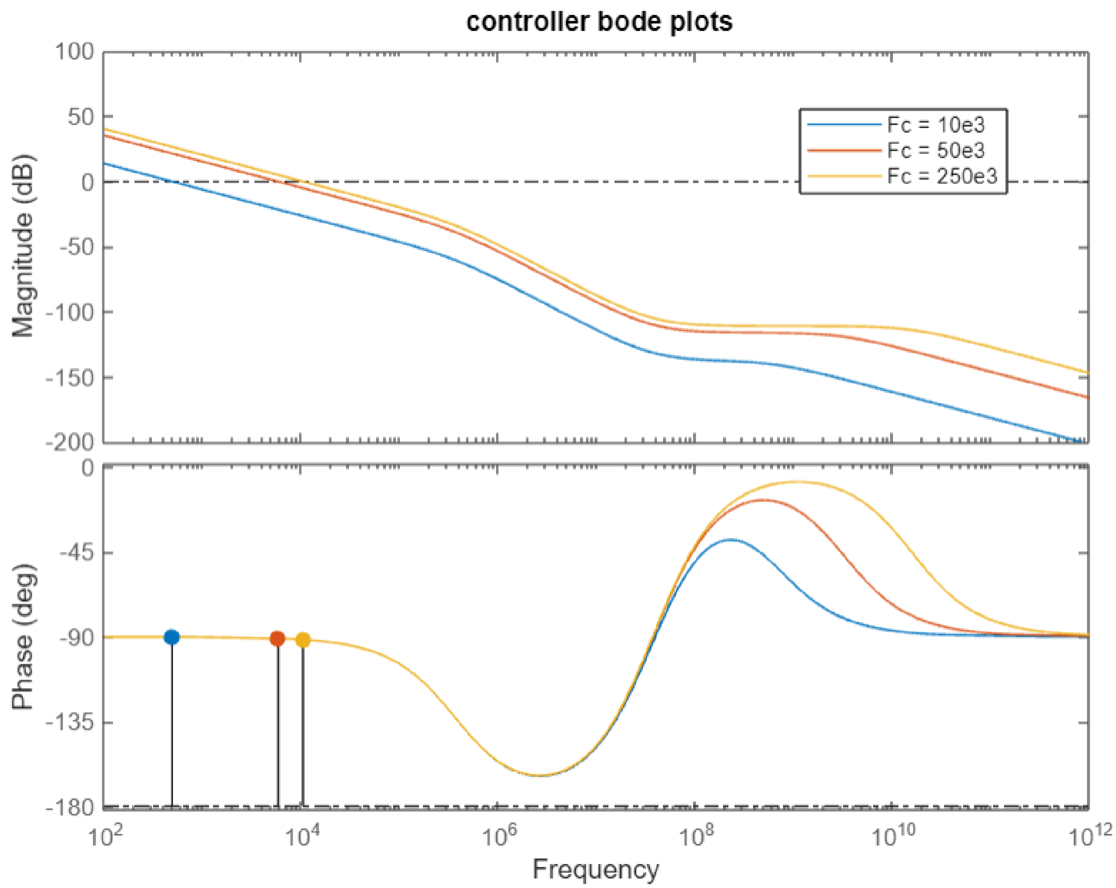


As also resulted from this the high inductor current due to higher duty ratio so it's also mandatory to apply saturation before the PWM modulator

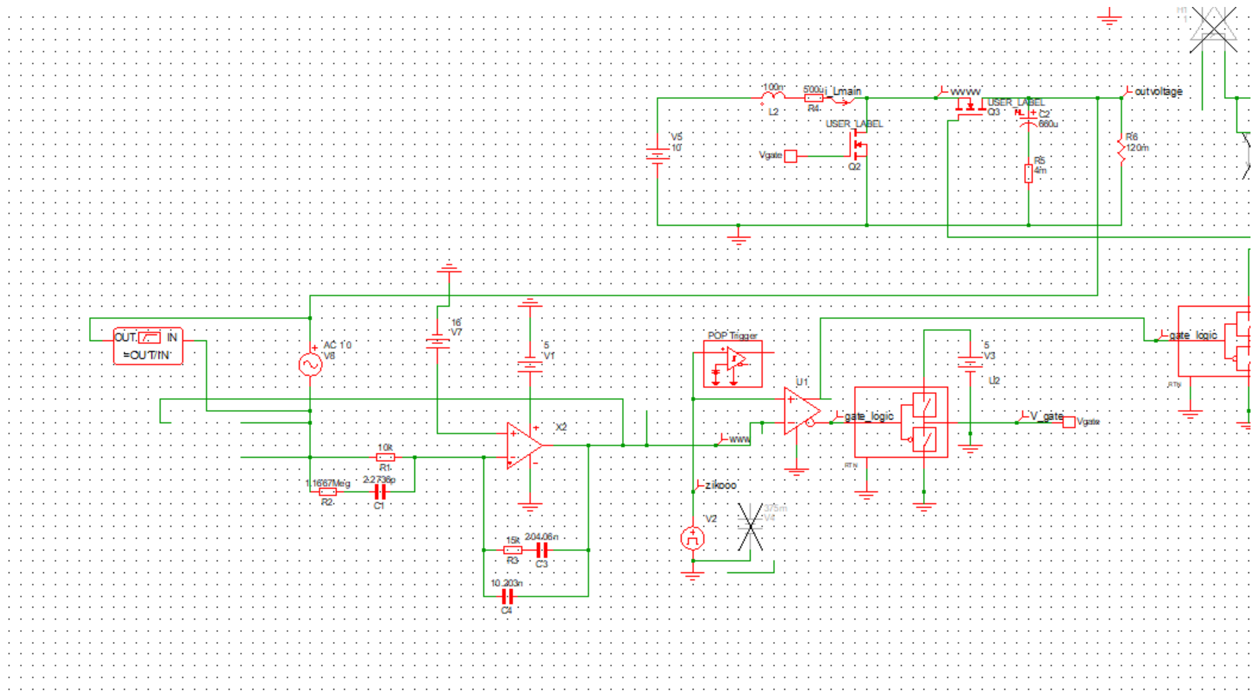


The controller failed to compensate and achieve target voltage.

Q4)



controller bode plots
Magnitude (dB)
Phase (deg)
Frequency
Fc = 10e3
Fc = 50e3
Fc = 250e3
100
50
0
-50
-100
-150
-200
-45
-90
-135
-180
10^2
10^4
10^6
10^8
10^{10}
10^{12}



Increasing the bandwidth by Increasing the integrator gain and decreasing the first zero fz1 and the second zero Fz2 away from Fo.

High DC gain will lead to higher bandwidth but poor PM and the same thing for the pwm modulator gain.

The bandwidth is also limited by the RHP zero as $\boldsymbol{\omega_{rhp}} = \frac{\left(\boldsymbol{RD'^2 - r_L - D'^2 r_e}\right)}{\boldsymbol{L}}$

when the load current is high , the R will be small which means $\boldsymbol{\omega_{rhp}}$

Will be smaller and near to the imaginary axis which will leads to undershoot effect.

ω_{ESR} has insufficient effect on BW.

```
sw = [10e3 50e3 250e3];


s = tf('s');
for i = 1 : length(sw)
fc = sw(i);
fz1 = 5e3;
fz2 = 7e3;
frhp = 71e3;
fo = 12e3;
q = 1.8547;
fp2 = 10*fc;
R1 = 10e3;




Wz1=fz1*(10^3)*2*pi;
Wz2=fz2*(10^3)*2*pi;
Wp1=60*(10^3)*2*pi;
Wp2=10*fc*(10^3)*2*pi;



x1 = sqrt(1 + (fc/fz1)^2);
x2 = sqrt(1 + (fc/fz2)^2);
x3 = sqrt(1 + (fc/frhp)^2);
x4 = sqrt((1 - (fc/fo)^2)^2 + (fc/(fo*q)^2));
```

_AB Drive/converters assignement 3/Q4.m

```
T = 10*(x1 * x2 * x3)/(x4 * x5 * 2*pi*fc);

Wi = 1/T;

C1 = 1/(R1*Wi);
R2 = 1/(C1*Wz1);
C2 = 1/(R1*Wz2);
R3 = 1/(C2*Wp1);
C3 = 1/(R2*Wp2);

A=(Wi/s)*(1+s/Wz1)*(1+s/Wz2)/((1+s/Wp1)*(1+s/Wp2));

bode(A)
title(' controller bode plots');
legend ('Fc = 10e3','Fc = 50e3','Fc = 250e3')
hold on

end
```