

**MIDDLE EAST TECHNICAL UNIVERSITY  
DEPARTMENT OF ELECTRICAL AND ELECTRONICAL  
ENGINEERING  
EE 464 HOMEWORK 3**

**Compensator Design for Buck Converter**

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**GitHub Page:** <https://github.com/erdemcanaz/EE464-HW3>

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## Introduction

In this homework, compensator design will be analyzed deeply. First, the concepts of bode plots, control-to-output, corner frequency type of fundamentals will be discussed. Then 2 different compensators will be designed considering given buck converter parameters. Finally, the circuits will be simulated in LT-spice environment and results will be discussed.

### Question 1:

*Explain the meaning of input-to-output transfer function and control-to-output transfer function in words.*

In this context, the input-to-output transfer function refers to the relationship between the input voltage (i.e.  $V_{in}$ ) and the output voltage (i.e.  $V_{out}$ ). On the other hand, the control-to-output transfer function describes the relationship between the control signal (i.e. duty cycle) and the output voltage  $V_{out}$ .

## Question 2:

Obtain the bode plot for control-to-output transfer function of buck converter with and without ESR ( $r_C$ ) on single graph on MATLAB. How do nonidealities affect the characteristic? Comment on phase margin & gain margin.

- $L = 8 \mu H$ ,
- $C = 8 \mu F$ ,
- $r_C = 15 \text{ mohm}$
- $V_{IN} = 5 \text{ V}$
- $V_o = 3.3 \text{ V}$
- $I_o = 4 \text{ A}$
- $f_{sw} = 250 \text{ kHz}$
- $V_{ref} = 1.2 \text{ V}$
- $V_{osc} = 1.8 \text{ V}$

$$G_p(s) = \frac{V_{out}}{d}(s) = \frac{R_{Load}(C_o \cdot ESR \cdot s + 1)}{L_o C_o \cdot s^2(R_{Load} + ESR) + s \cdot (L_o + R_{Load} \cdot C_o \cdot ESR) + R_{Load}} V_{in}$$

The bode plot of the given control-to-output transfer function  $G_p(s)$  of the buck converter with and without the ESR can be found in Fig. 1. The MATLAB script used can be found in Appendix I.

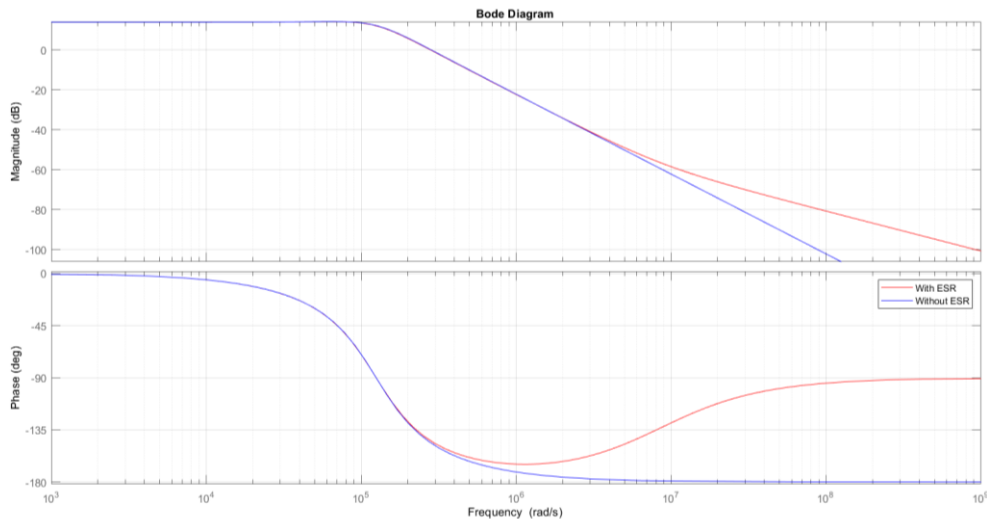


Figure 1 The bode plot of the control-to-output transfer function of the buck converter with and without the ESR

**The main differences between circuits with/without the ESR is, a zero is introduced at around  $10^7 \text{ rad/s}$ .** It causes a change in the slope of the magnitude and phase angle behaviors. Lets say magnitude  $G$  is;  $G = 20 \log_{10} |G_p(s)|$ .  $G_p(s)$  is of the form

$$G_p(s) = \frac{(s + z_1) \cdots (s + z_n)}{(s + p_1) \cdots (s + p_n)}$$

We may replace  $s$  with  $(jw)$

$$G_p(jw) = \frac{(jw + z_1) \cdots (jw + z_n)}{(jw + p_1) \cdots (jw + p_n)}$$

$$G_p(jw) = \left( \frac{z_1 \cdots z_n}{p_1 \cdots p_n} \right) \cdot \frac{(j \frac{w}{z_1} + 1) \cdots (j \frac{w}{z_n} + 1)}{(j \frac{w}{p_1} + 1) \cdots (j \frac{w}{p_n} + 1)}$$

Then  $|G_p(s)|$  can be found as;

$$|G_p(jw)| = \left( \frac{z_1 \cdots z_n}{p_1 \cdots p_n} \right) \frac{\left| j \frac{w}{z_1} + 1 \right| \cdots \left| j \frac{w}{z_n} + 1 \right|}{\left| \left( j \frac{w}{p_1} + 1 \right) \right| \cdots \left| j \frac{w}{p_n} + 1 \right|}$$

$$|G_p(jw)| = G_{DC} \frac{\left| j \frac{w}{z_1} + 1 \right| \cdots \left| j \frac{w}{z_n} + 1 \right|}{\left| \left( j \frac{w}{p_1} + 1 \right) \right| \cdots \left| j \frac{w}{p_n} + 1 \right|}$$

$$G = 20 \left( \log_{10} G_{DC} + \log_{10} \left| j \frac{w}{z_1} + 1 \right| + \cdots + \log_{10} \left| j \frac{w}{z_n} + 1 \right| \right) \\ - 20 \left( \log_{10} \left| j \frac{w}{p_1} + 1 \right| + \cdots + \log_{10} \left| j \frac{w}{p_n} + 1 \right| \right)$$

We can assume the modulus of a complex number can be approximated solely as either real or complex part provided one is much greater magnitude wise (i.e. 10 times). Then the contribution of zero introduced due to ESR can be written as.

$$\text{Contribution of ESR to Gain} = +20 \cdot \left( \log_{10} \left| j \frac{w}{z_{ESR}} + 1 \right| \right)$$

It can be further simplified as;

$$\text{Contribution of ESR to Gain} \approx \begin{cases} 20 \cdot (\log_{10} |1|) = 0, & w \ll z_{ESR} \\ 20 \log_{10} \left| \frac{w}{z_{ESR}} \right|, & w \gg z_{ESR} \end{cases}$$

It is obvious that the contribution is zero until  $w \gg z_{ESR}$ . Then it contributes 20dB per decade. Resulting in -40dB/dec slope to become -20dB/dec. For the phase discussion, one can simply consider any complex number as a complex exponential. Knowing real numbers are of the form  $Ae^0$  and complex ones are  $Ae^i$ , we can simplify ESR contribution to phase as follows;

$$\text{Contribution of ESR to phase} \approx \begin{cases} 0^\circ, & w \ll z_{ESR} \\ 90^\circ, & w \gg z_{ESR} \end{cases}$$

Both of gain and phase discussions are well seen in the Fig. 1.

Using MATLAB's built-in function, gain margins are calculated as infinity for both and phase margins are calculated as  $35.49^\circ$  and  $33.46^\circ$  for with and without ESR cases respectively.

The Difference in the phase margins is due to introduced zero has a positive contribution to phase even when  $w \ll z_{ESR}$ .

### Question 3:

*Identify the pole and zero frequencies for non-ideal buck converter. List them from lower to higher including switching frequency.*

The compact form of the  $G_{p,ESR}(s)$  is

$$G_{p,ESR}(s) = \frac{4.95 \cdot 10^{-7}s + 4.125}{5.376 \cdot 10^{-11}s^2 + 8.099 \cdot 10^{-6}s + 0.825}$$

The root that make numerator zero is

$$z_1 = -8.3 \cdot 10^6$$

Whereas roots that make denominator zero are

$$p_1 = (-7.533 + j9.835) \cdot 10^4$$

$$p_2 = (-7.533 - j9.835) \cdot 10^4$$

The frequencies of zeros and poles than found to be

$$f_{z_1} = 8.3 \cdot 10^6 \text{ rad/s}$$

$$f_{p_1} = |p_1| = 1.24 \cdot 10^5 \text{ rad/s}$$

$$f_{p_2} = |p_2| = 1.24 \cdot 10^5 \text{ rad/s}$$

The switching frequency is

$$f_{sw} = 250\text{kHz} = 1.57 \cdot 10^6 \text{ rad/s}$$

Then;

$$f_{p_1} = f_{p_2} < f_{sw} < f_{z_1}$$

One can use below formulas for the frequency of the poles and zeros directly<sup>[1]</sup>.

$$f_p = \frac{1}{\sqrt{L_o C_o}} = 1.25 \cdot 10^5 \text{ rad/s}$$

$$f_z = \frac{1}{R_c C_o} = 8.3 \cdot 10^6 \text{ rad/s}$$

You need to design two different compensators for this application and then you will compare. You can choose different crossover frequencies for two compensators or you can design two compensators with different phase-gain margins having same crossover frequency. It is advised you to apply different options and observe the bode plots and performances. At the end you need to report two of the options and compare performances. Final designs should be stable. An example of a compensator is given in Fig. 2.

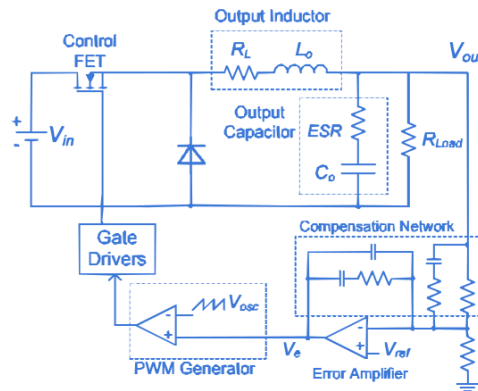


Figure 2 - Simplified circuit diagram of a buck converter with a voltage mode error-amplifier

#### Question 4:

What does a crossover frequency mean? What is the typical limit for a crossover frequency? Select a crossover frequency for your application, give your reasoning.

In the application note<sup>[1]</sup> the term “crossover frequency,” also known as the “bandwidth of the loop,” is defined as the point where the gain of the system (i.e. closed loop) equals 0 dB (unity gain). The selection of the crossover frequency is influenced by two factors: the desired response speed to transient changes and the need for effective filtering of switching noise. A higher crossover frequency leads to a faster response, while a lower crossover frequency results in better noise filtering. These two parameters inherently involve a tradeoff; improving one typically compromises the other. It is recommended that the crossover frequency be set between 1/10 to 1/5 of the switching frequency for practical applications. Since the switching frequency is 250kHz, one can choose closed-loop crossover frequency of the buck converter as

$$f_{cross} = \frac{1}{7.5} 250kHz = 33.3kHz$$



## Question 5:

*There are different types of compensator such as Type-I, Type-II, Type-III A or B. Pick the most suitable one for your design. Give your reasoning.*

Referring to the application notes<sup>[1][2]</sup> I will use Type-III A&B compensators for my design. With higher component count, it is given that type-III is a more generalized compensator that can be used with less consideration on capacitor types or characteristic frequencies etc.. Also, it's transient response is told to be relatively fast.

**Type I:** Simple compensator with a single pole. The topology can be seen in Fig. 3. It is discussed that this type is bad at transient response. Which can be also seen in the bode plot since the slope is -20dB/Dec starting from  $\omega = 0$ . At higher frequencies, the attenuation is too high.

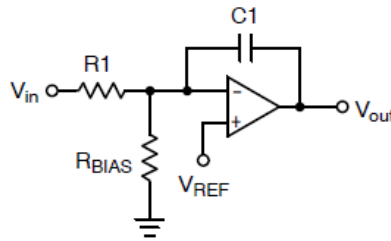


Figure 3 Type I compensator

$$\frac{V_{out}}{V_{in}}(s) = \frac{1}{R_1 C_1 s}$$

$$R_{BIAS} = \frac{V_{REF} R_1}{V_{in} - V_{REF}}$$

The bode plot of the Type-I compensator is given in Fig. 4 for  $R = 50k\Omega$  and  $C = 8\mu F$

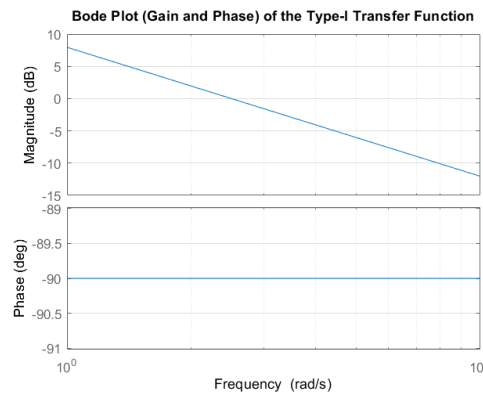


Figure 4 Type I compensator bode plot for  $R=50k\Omega$  and  $C=8\mu F$

**Type II:** Compensator with a zero-pole pair. The topology can be seen in Fig. 5.

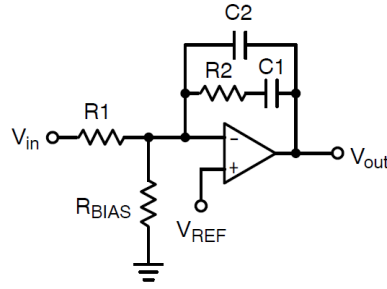


Figure 5 Type-II compensator

$$\frac{V_{out}}{V_{in}}(s) \approx \frac{1 + R_2 C_1 s}{R_1 s C_1 (R_2 C_2 s + 1)}$$

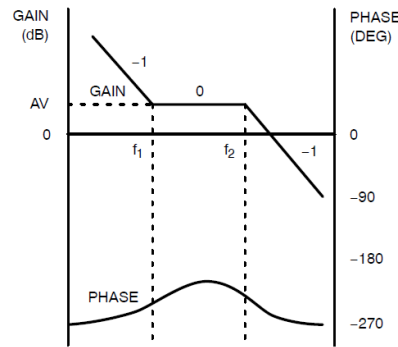


Figure 6 Type-II compensator typical bode plot

The variables can be found by the following formulas;

$$R_{BIAS} = \frac{V_{REF} R_1}{V_{in} - V_{REF}}$$

$$A_V = \frac{R_2}{R_1}$$

$$f_1 = \frac{1}{2\pi R_2 C_1}$$

$$f_2 = \frac{C_1 + C_2}{2\pi R_2 C_1 C_2} \approx \frac{C_2}{2\pi R_2 C_2} \text{ if } C_2 \gg C_1$$

**Type III:** Suggested for a comprehensive solution ensuring unconditional stability with any type of output capacitors and a broad range of ESR values. There are 2 types of type-III

compensator. Type A is used when the capacitor ESR is not negligible (i.e. zero is introduced at lower frequencies);

$$f_p < f_{cross} < f_z < \frac{f_{sw}}{2}$$

And Type B is used when the EST is negligible (i.e. zero is introduced at higher frequencies) ;

$$f_p < f_{cross} < \frac{f_{sw}}{2} < f_z$$

The circuit diagram of type-III compensator is given in Fig. 7.

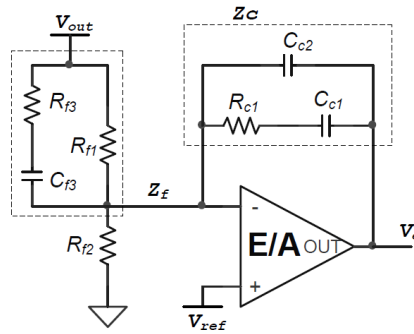


Figure 7 Type-III compensator

The transfer function  $H(s)$  that maps  $V_{out}$  to  $V_e$  is given by;

$$H(s) = - \frac{(1 + s \cdot R_{c1} \cdot C_{c1}) \cdot [1 + s \cdot C_{f3} \cdot (R_{f1} + R_{f3})]}{s \cdot R_{f1} \cdot (C_{c1} + C_{c2}) \cdot [1 + s \cdot R_{c1} \cdot (\frac{C_{c1} \cdot C_{c2}}{C_{c1} + C_{c2}})] \cdot (1 + s \cdot R_{f3} \cdot C_{f3})}$$

Which can be simplified to (under the assumption of  $C_{c2} \ll C_{c1}$ )

$$H(s) \approx - \frac{(1 + R_{c1} \cdot C_{c1} \cdot s) \cdot [1 + s \cdot C_{f3} \cdot (R_{f1} + R_{f3})]}{s \cdot R_{f1} \cdot C_{c1} \cdot (R_{c1} \cdot C_{c2} \cdot s + 1) \cdot (1 + s \cdot R_{f3} \cdot C_{f3})}$$

This response has 2 zeros and 3 poles. Their location in Hertz can be found by the following formulas;

$$F_{z1} = \frac{1}{2\pi \cdot R_{c1} \cdot C_{c1}}$$

$$F_{z2} = \frac{1}{2\pi \cdot C_{f3} \cdot (R_{f1} + R_{f3})}$$

$$F_{p1} = 0$$

$$F_{p2} = \frac{1}{2\pi \cdot C_{f3} \cdot R_{f3}}$$

$$F_{p3} = \frac{1}{2\pi \cdot R_{c1} \cdot C_{c2}}$$

## Question 6:

*Calculate the values of the circuit components for your each compensator. Round up or down the component ratings to the available ratings. For example, 4.68 nF turns into 4.7 nF.*

The parameter names are shown in Fig.7. For those parameters;

Type III-A:

**One should note that with given ESR value of 15mOhm, Type A is not suitable. Thus assume capacitor ESR is 0.2Ohm which is not far away from practical capacitor ESR values. Then  $f_z$  can be calculated as;**

$$f_z = 100kHz$$

With this modification, the type-III-A frequency condition is satisfied. Then using the application note<sup>[1]</sup> we can place poles and zeros of this compensator.

$$f_p = 1.25 \cdot 10^5 \text{ rad/s} = 20kHz$$

$$f_{cross} = 2.1 \cdot 10^5 \text{ rad/s} = 33.3kHz$$

$$f_z = 8.3 \cdot 10^6 \text{ rad/s} = 100kHz$$

$$f_{sw} = 1.57 \cdot 10^6 \text{ rad/s} = 250kHz$$

Then;

$$F_{p1} = 0$$

$$F_{p3} = \frac{f_{sw}}{2} = 125kHz$$

$$F_{z2} = f_p = 20kHz$$

$$F_{p2} = f_z = 100kHz$$

$$F_{z1} = 0.75F_{z2} = 15kHz$$

Then the component values to achieve this pole-zero locations are;

$$C_{f3} = 2.2nF \text{ (Good Start)}$$

$$R_{f3} = \frac{1}{2\pi \cdot C_{f3} F_{p2}} = \frac{1}{2\pi \cdot 2.2nF \cdot (100kHz)} = 720\Omega$$

$$R_{f1} = \frac{1}{2\pi \cdot C_{f3} \cdot F_{z2}} - R_{f3} = \frac{1}{2\pi \cdot 2.2nF \cdot (20kHz)} - 720 = 2.9k\Omega$$

$$R_{f2} = \frac{R_{f1} V_{ref}}{V_{out} - V_{ref}} = \frac{(2.9k\Omega)(1.2V)}{(3.3V - 1.2V)} = 1.66k\Omega$$

$$R_{C1} = \frac{2\pi f_z L_o C_o V_{osc}}{V_{in} C_{f3}} = \frac{2\pi(100kHz)(8\mu H)(8\mu F)(1.8V)}{(5.0V)(2.2nF)} = 6.57k\Omega$$

$$C_{C1} = \frac{1}{2\pi \cdot R_{C1} \cdot F_{z1}} = \frac{1}{2\pi(6.57k\Omega)(15kHz)} = 1.61nF$$

$$C_{C2} = \frac{1}{2\pi \cdot R_{C1} \cdot F_{p3}} = \frac{1}{2\pi(6.57k\Omega)(125kHz)} = 0.2nF$$

Type-III (A) Component selection		
Component	Desired Value	Component links
$C_{f3}$	$2.2nF$	<a href="#">2.2nF</a>
$R_{f3}$	$720\Omega$	<a href="#">680 Ohm</a> + <a href="#">39 Ohm</a>
$R_{f1}$	$2.9k\Omega$	<a href="#">2.7 kOhm</a> + <a href="#">220 Ohm</a>
$R_{f2}$	$1.66k$	<a href="#">1.6 kOhm</a>
$R_{C1}$	$6.57k\Omega$	<a href="#">6.8 kOhm</a>
$C_{C1}$	$1.61nF$	<a href="#">1nF</a> + <a href="#">560pF</a>
$C_{C2}$	$0.2nF$	<a href="#">220pF</a>

### Type III-B:

At question 3,  $f_{cross}$ ,  $f_{sw}$ ,  $f_p$  and  $f_z$  are calculated as;

$$f_p = 1.25 \cdot 10^5 \text{ rad/s} = 20\text{kHz}$$

$$f_{cross} = 2.1 \cdot 10^5 \text{ rad/s} = 33.3\text{kHz}$$

$$f_{sw} = 1.57 \cdot 10^6 \text{ rad/s} = 250\text{kHz}$$

$$f_z = 8.3 \cdot 10^6 \text{ rad/s} = 1.326\text{MHz}$$

Which satisfies the type-III-B frequency condition. Then using the application note<sup>[1]</sup> we can place poles and zeros of this compensator.

$$F_{p1} = 0$$

$$F_{p3} = \frac{f_{sw}}{2} = 125 \cdot \text{kHz}$$

$$F_{z2} = f_{cross} \sqrt{\frac{1 - \sin(70^\circ)}{1 + \sin(70^\circ)}} = 940 \text{ Hz}$$

$$F_{p2} = f_{cross} \sqrt{\frac{1 + \sin(70^\circ)}{1 - \sin(70^\circ)}} = 1.19 \cdot 10^6 \text{ rad/s} = 190\text{kHz}$$

$$F_{z1} = 0.5F_{z2} = 470 \text{ Hz}$$

Then the component values to achieve this pole-zero locations are;

$$C_{f3} = 2.2\text{nF} \text{ (good start)}$$

$$R_{f3} = \frac{1}{2\pi \cdot 2.2\text{nF} \cdot (190\text{kHz})} = 380\Omega$$

$$R_{f1} = \frac{1}{2\pi \cdot 2.2\text{nF} \cdot (940\text{Hz})} - 380 = 76.96\text{k}\Omega$$

$$R_{f2} = \frac{(76.96\text{k}\Omega)(1.2\text{V})}{(3.3\text{V} - 1.2\text{V})} = 44\text{k}\Omega$$

$$R_{C1} = \frac{2\pi(33.33\text{kHz})(8\mu\text{H})(8\mu\text{F})(1.8\text{V})}{(1.2\text{V!})(2.2\text{nF})} = 9.139\text{k}\Omega$$

$$C_{c1} = \frac{1}{2\pi(9.139k\Omega)(470Hz)} = 37nF$$

$$C_{c2} = \frac{1}{2\pi(9.139k\Omega)(125kHz)} = 140pF$$

The component selection is as follows;

Type-III (B) Component selection		
Component	Desired Value	Component links
$C_{f3}$	$2.2nF$	<a href="#">2.2nF</a>
$R_{f3}$	$380\Omega$	<a href="#">390 Ohm</a>
$R_{f1}$	$76.96k\Omega$	<a href="#">75 kOhm</a>
$R_{f2}$	$44k\Omega$	<a href="#">47kOhm</a>
$R_{c1}$	$9.139k\Omega$	<a href="#">10 kOhm</a>
$C_{c1}$	$37nF$	<a href="#">22nF</a> + <a href="#">10 nF</a> + <a href="#">4.7nF</a>
$C_{c2}$	$140pF$	<a href="#">100pf</a> + <a href="#">47pf</a>

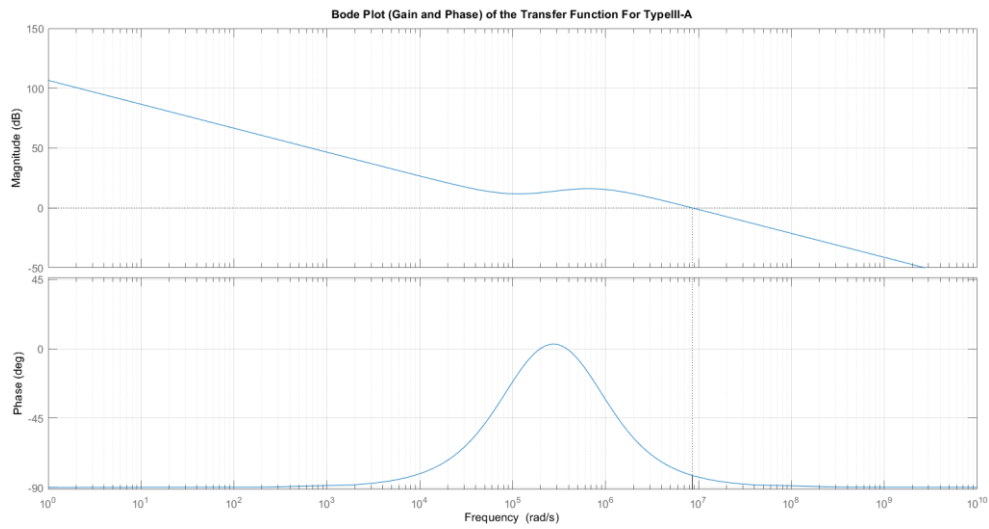
### Question 7:

*Obtain the bode plots of the loop transfer functions for each compensator design. Show and comment on phase margins. You do not need to simulate system for this step. Bode plots of MATLAB transfer functions are acceptable.*

$$H(s) \approx -\frac{(1 + R_{c1} \cdot C_{c1} \cdot s) \cdot [1 + s \cdot C_{f3} \cdot (R_{f1} + R_{f3})]}{s \cdot R_{f1} \cdot C_{c1} \cdot (R_{c1} \cdot C_{c2} \cdot s + 1) \cdot (1 + s \cdot R_{f3} \cdot C_{f3})}$$

The MATLAB script can be found in Appendix II.

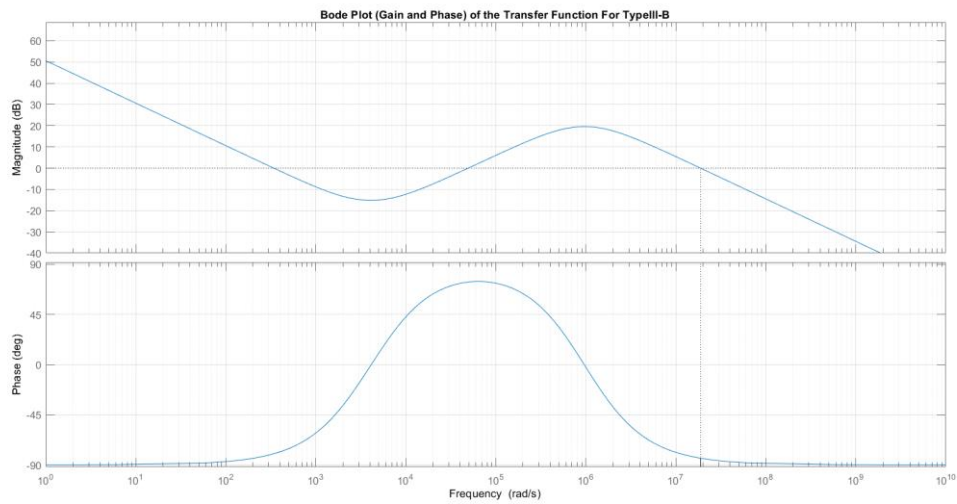
### Type III-A:



*Figure 8 Bode plot of the designed type-III-A compensator*

As shown in Fig 8. The phase margin is 97.3 degrees which is pretty safe phase margin.

### Type III-B:



*Figure 9 Bode plot of the designed type-III-B compensator*

As shown in Fig 9. The phase margin is 95.98 Degrees which is pretty safe phase margin.



## Question 8:

Give the transient waveform for output voltage, inductor current and duty cycle ( $0 < x < 1$ ) for each compensator design when load is switched from full to half. Explain what happens at that moment briefly.

At the switching instance, the average current of the inductor is twice that of the steady-state average current of the load. This surplus energy is transferred to the capacitor, causing a brief voltage spike. During this period, the duty cycle is zero. Subsequently, the average inductor current falls below the final steady-state average current. To compensate for this, the duty cycle is increased for a short duration. ***I am genuinely amazed at how effectively this controller operates in terms of transient and steady state response.***

Type III-A:

The simulated circuit is given in Fig. 10.

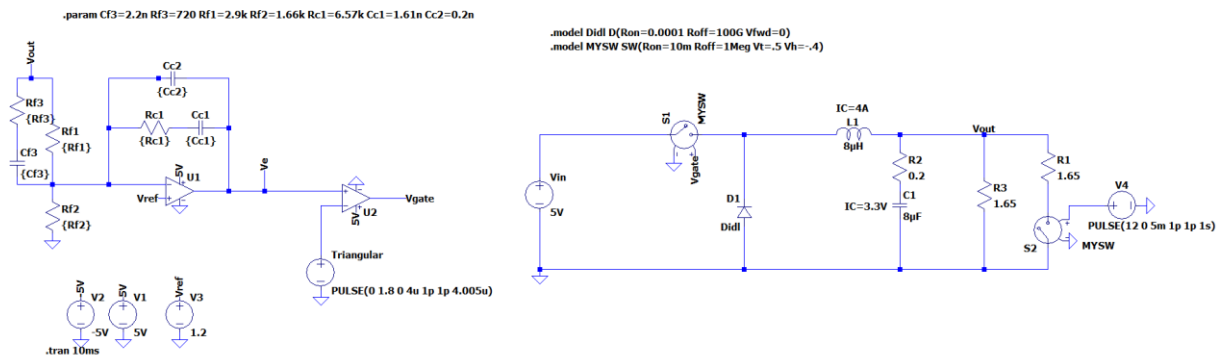


Figure 10: Type-III-A Compensator LTSpice Simulation for Transient Response to Load Change from Full to Half

Output voltage and inductor current at the switching instance is given in Fig. 11.

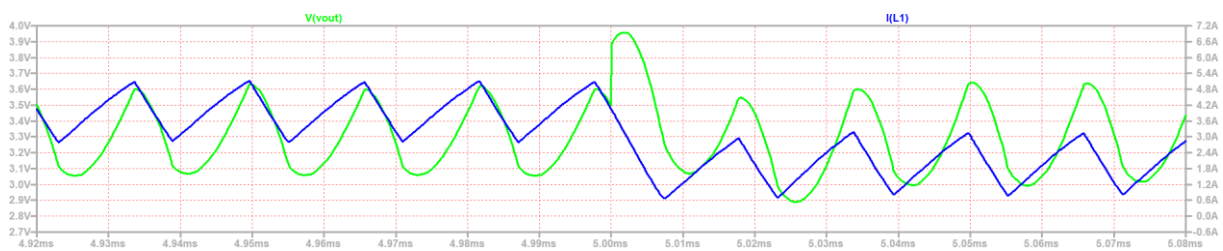


Figure 11: Type-III-A Compensator LTSpice Simulation Results - Inductor Current and Output Voltage During Transient Response to Load Change from Full to Half

Duty, triangular signal and error signal at the switching instance are given in Fig. 12.

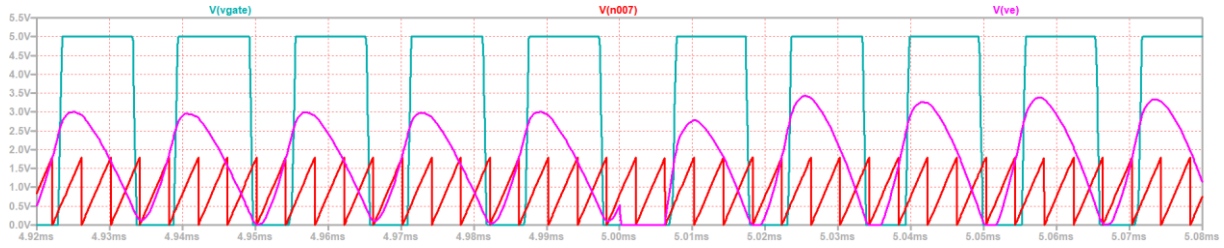


Figure 12 type-III-A compensator LT-spice simulation results of gate signal, triangular signal and error signal for transient response when load is switched from full to half

**One should note that this output voltage has very low voltage regulation. After checking what is wrong, I realized that the used OP-AMP has very low slew rate for this purpose. After increasing bandwidth and slew while providing a negative rail, I have observed better results as shown in Fig. X and Y**

Output voltage and inductor current at the switching instance is given in Fig. 13. when more ideal op-amp model is used

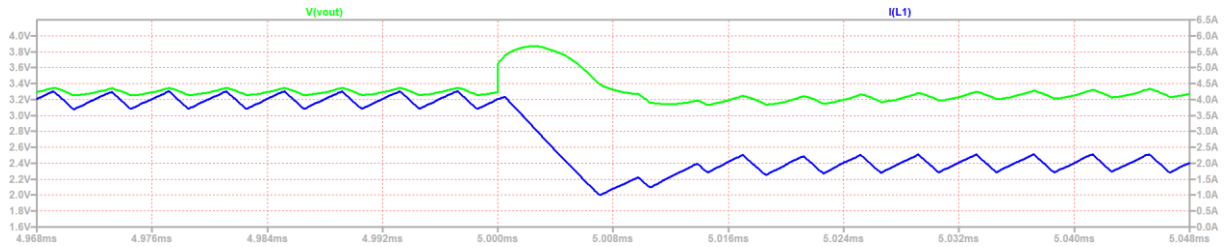


Figure 13: Type-III-A Compensator LT-Spice Simulation Results - Inductor Current and Output Voltage During Transient Response to Load Change from Full to Half with More Ideal Op-Amp Using Negative Rail

Duty, triangular signal and error signal at the switching instance are given in Fig. 14. when more ideal op-amp model is used

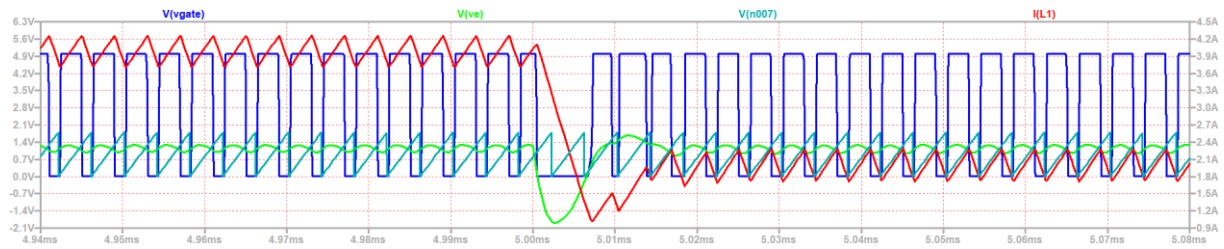


Figure 14: Type-III-A Compensator LT-Spice Simulation Results - Gate Signal, Triangular Signal, and Error Signal During Transient Response to Load Change from Full to Half with More Ideal Op-Amp Using Negative Rail

### Type III-B:

The simulated circuit is given in Fig. 15.

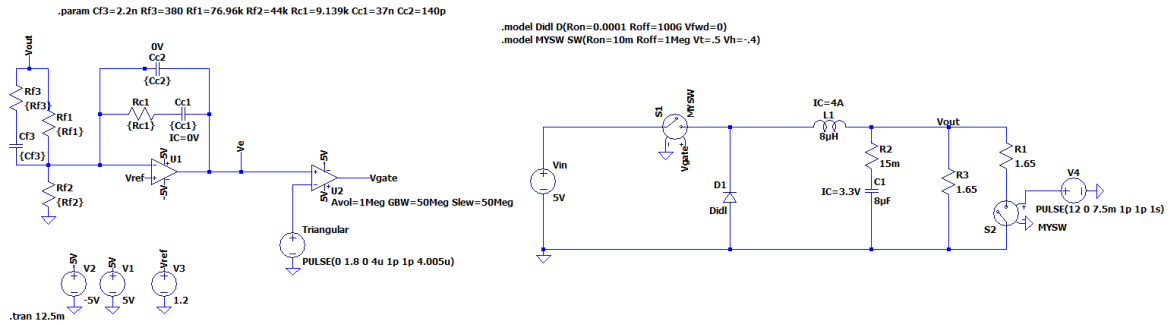


Figure 15: Type-III-B Compensator LT-Spice Simulation for Transient Response to Load Change from Full to Half

Output voltage and inductor current at the switching instance is given in Fig. 16.

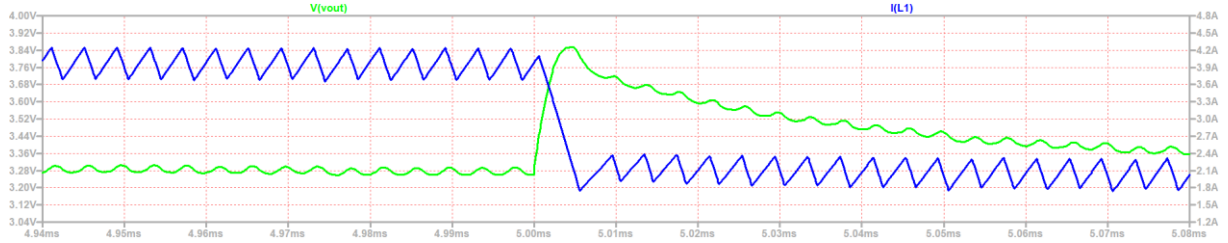


Figure 16: Type-III-B Compensator LT-Spice Simulation Results - Inductor Current and Output Voltage During Transient Response to Load Change from Full to Half with More Ideal Op-Amp Using Negative Rail

Duty, triangular signal and error signal at the switching instance are given in Fig. 17.

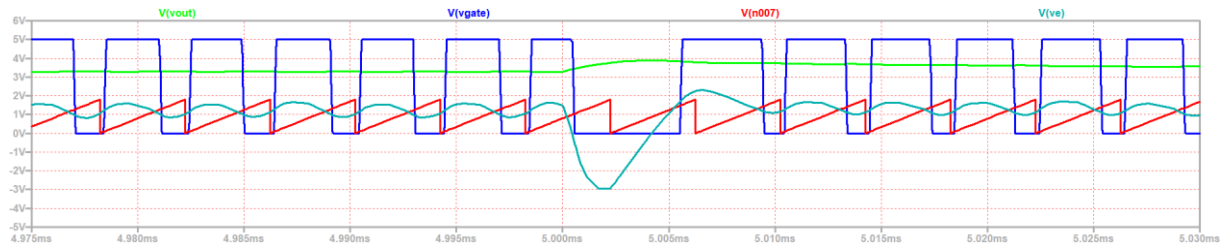


Figure 17: Type-III-B Compensator LT-Spice Simulation Results - Gate Signal, Triangular Signal, and Error Signal During Transient Response to Load Change from Full to Half with More Ideal Op-Amp Using Negative Rail

## Question 9:

Give the transient waveform for output voltage, inductor current and duty cycle ( $0 < x < 1$ ) for each compensator design when load is switched from half to full. Explain what happens at that moment briefly.

The discussion is exactly the same as in question 8, with the exception that an energy deficit in the inductor is observed rather than a surplus. Additionally, for a short duration, the duty cycle exceeds the steady-state value. Following this, the duty cycle falls below the steady-state value because the inductor current is greater than the steady-state value. During this transition period, output voltage is dropped first then maintained at steady state.

### Type III-A:

The simulated circuit is given in Fig. 18.

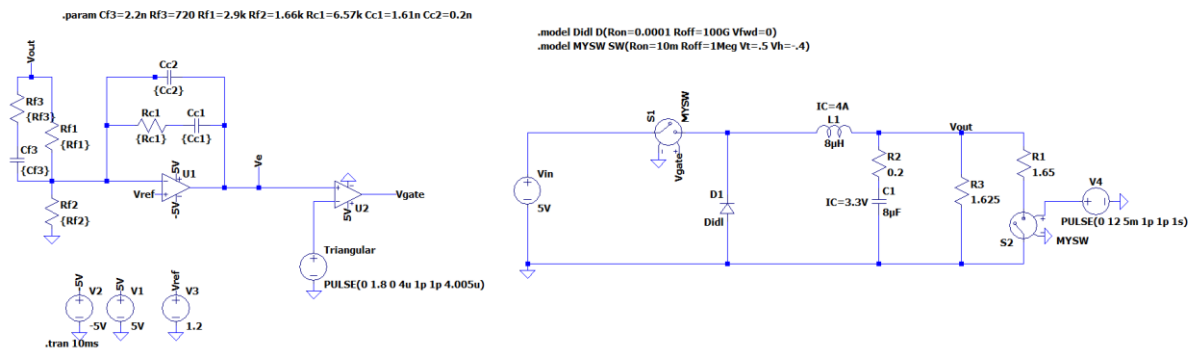


Figure 18: Type-III-A Compensator LT-Spice Simulation for Transient Response to Load Change from Half to Full

Output voltage and inductor current at the switching instance is given in Fig. 19.

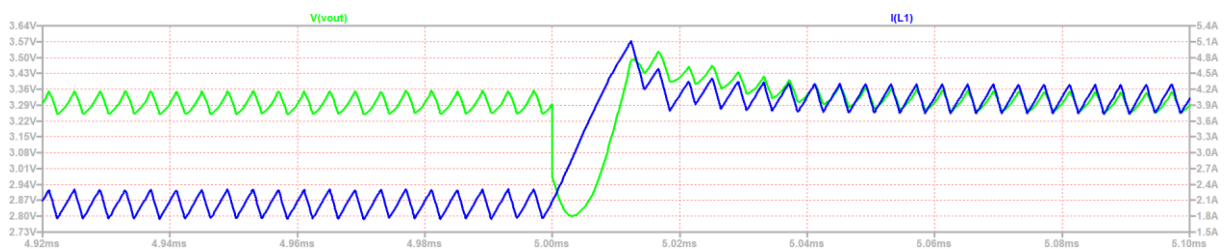


Figure 19: Type-III-A Compensator LT-Spice Simulation Results - Inductor Current and Output Voltage During Transient Response to Load Change from Half to Full with More Ideal Op-Amp Using Negative Rail

Duty, triangular signal and error signal at the switching instance are given in Fig. 20.

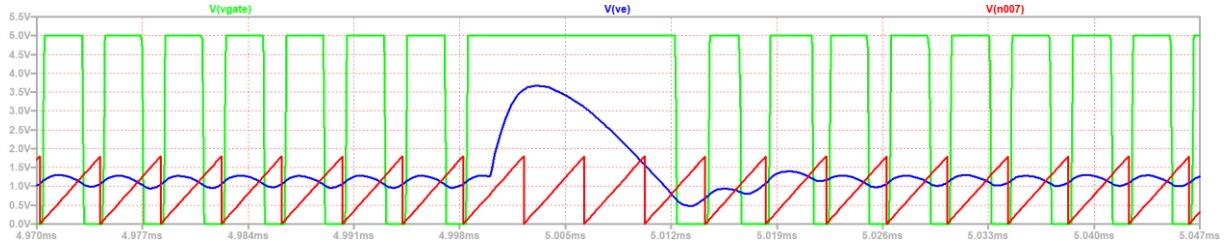


Figure 20: Type-III-A Compensator LT-Spice Simulation Results - Gate Signal, Triangular Signal, and Error Signal During Transient Response to Load Change from Half to Full with More Ideal Op-Amp Using Negative Rail

### Type III-B:

The simulated circuit is given in Fig. 21.

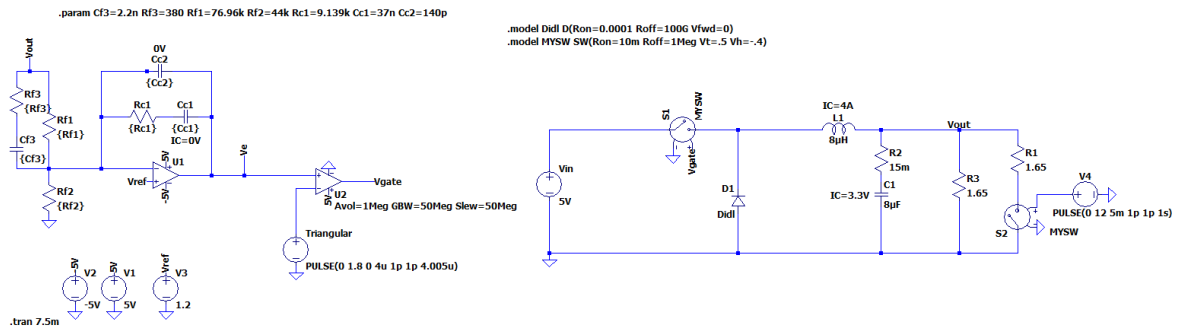


Figure 21: Type-III-B Compensator LT-Spice Simulation for Transient Response to Load Change from Half to Full

Output voltage and inductor current at the switching instance is given in Fig. 22.

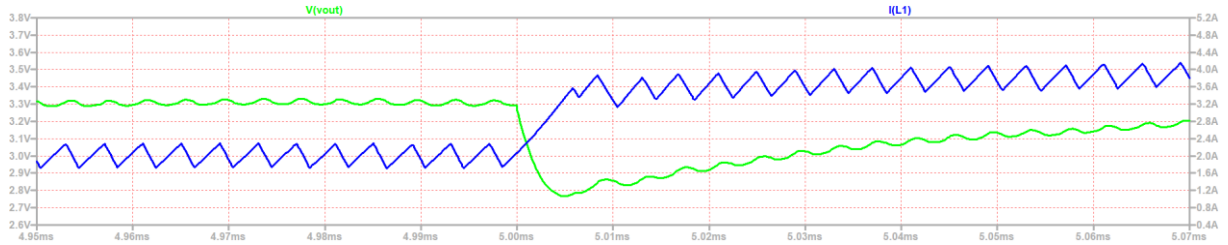


Figure 22: Type-III-B Compensator LT-Spice Simulation Results - Inductor Current and Output Voltage During Transient Response to Load Change from Half to Full with More Ideal Op-Amp Using Negative Rail

Duty, triangular signal and error signal at the switching instance are given in Fig. 23

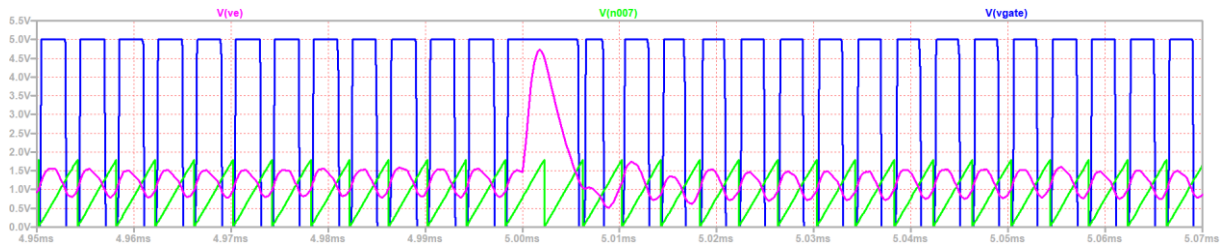


Figure 23: Type-III-B Compensator LT-Spice Simulation Results - Gate Signal, Triangular Signal, and Error Signal During Transient Response to Load Change from Half to Full with More Ideal Op-Amp Using Negative Rail

## Question 10:

Give the transient waveform for output voltage, inductor current, input voltage and duty cycle ( $0 < x < 1$ ) for each compensator design when input voltage drops to 4 V as a step change. Explain what happens at that moment briefly. Does your compensator still helps to regulate output voltage?

Noticing a very high settling time, I reviewed my calculations to identify components calculated using the input voltage  $V_{in}$  to further analyze the cause of high settling time. I discovered the mistake of the  $R_{C1}$  calculation of type-III-B, I. For the seek of meeting the deadline, I was unable to correct this error. Despite some incorrect calculations, the output voltage appears to converge to the desired value, so I will consider this a working controller. However, it should be noted that this calculation error was not the case for type-III-A and it has a way better convergence than the mistaken one. The compensators still help to regulate output voltage. This can also be seen by the increased duty as shown in Fig. 26.

### Type III-A:

The simulated circuit is given in Fig. 24.

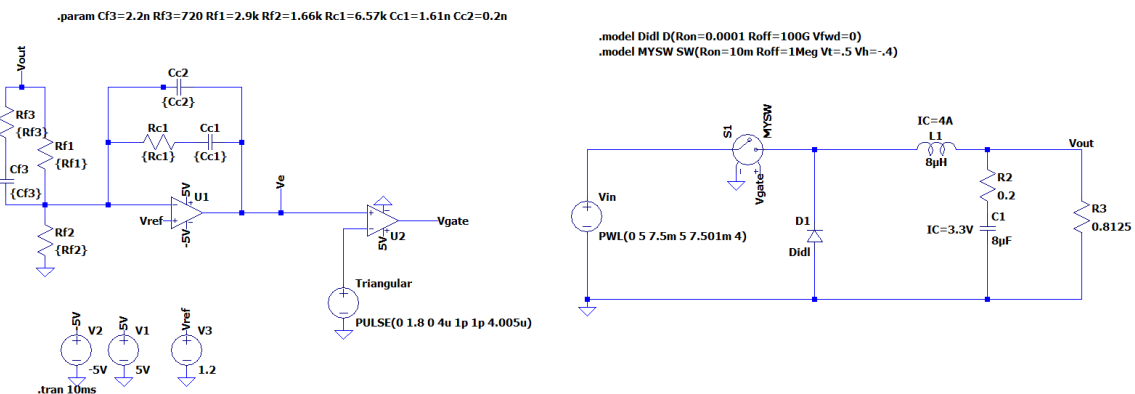


Figure 24: Type-III-A Compensator LT-Spice Simulation for Transient Response of Input Voltage Dropping to 4V

Output voltage and inductor current at the step instance is given in Fig. 25.

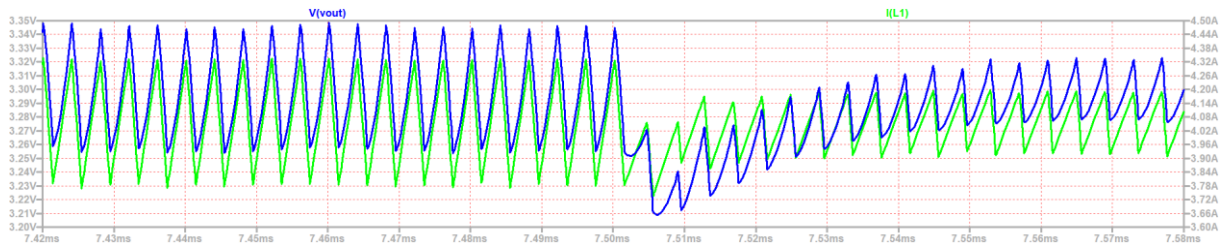


Figure 25: Type-III-A Compensator LT-Spice Simulation Results - Inductor Current and Output Voltage During Transient Response of Input Voltage Dropping to 4V with More Ideal Op-Amp Using Negative Rail

Input voltage and Duty is given in Fig 26.

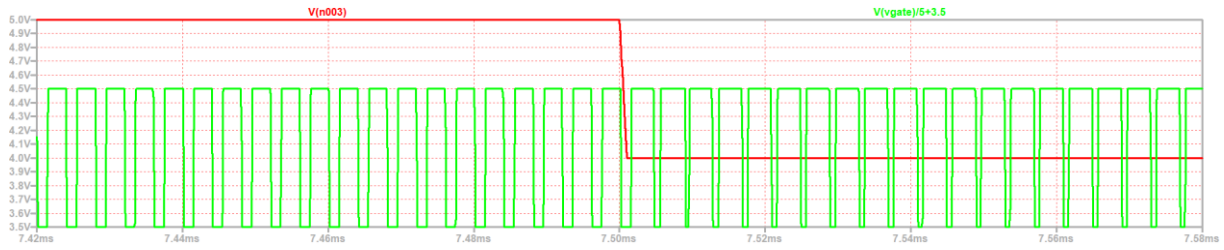


Figure 26: Type-III-A Compensator LT-Spice Simulation Results – Input Voltage and Duty During Transient Response of Input Voltage Dropping to 4V with More Ideal Op-Amp Using Negative Rail

Type III-B:

The simulated circuit is given in Fig. 27.

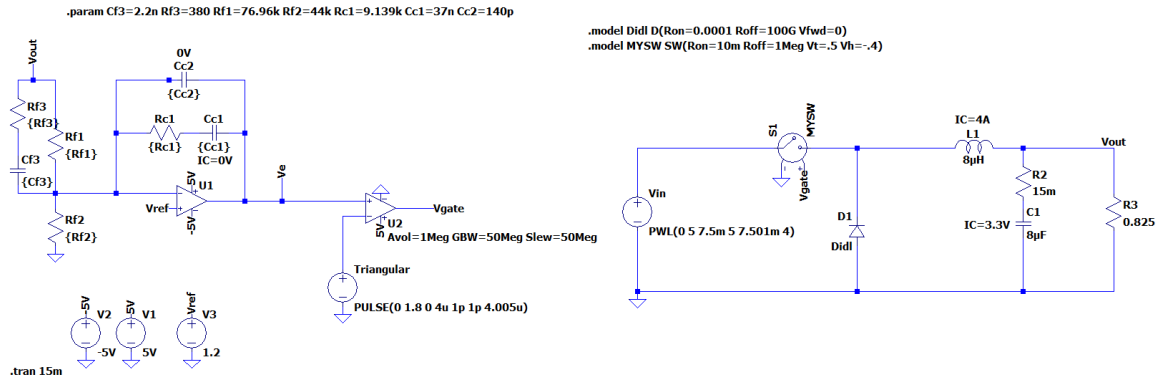


Figure 27: Type-III-B Compensator LT-Spice Simulation for Transient Response of Input Voltage Dropping to 4V

Output voltage and inductor current at the step instance is given in Fig. 28.

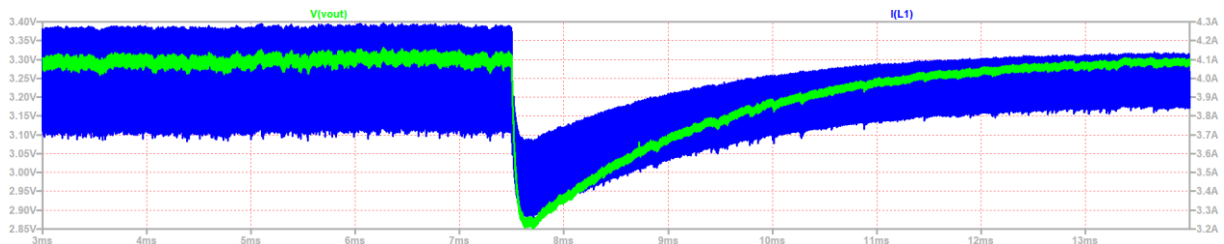


Figure 28: Type-III-B Compensator LT-Spice Simulation Results - Inductor Current and Output Voltage During Transient Response of Input Voltage Dropping to 4V with More Ideal Op-Amp Using Negative Rail

Input voltage and Duty is given in Fig 29.

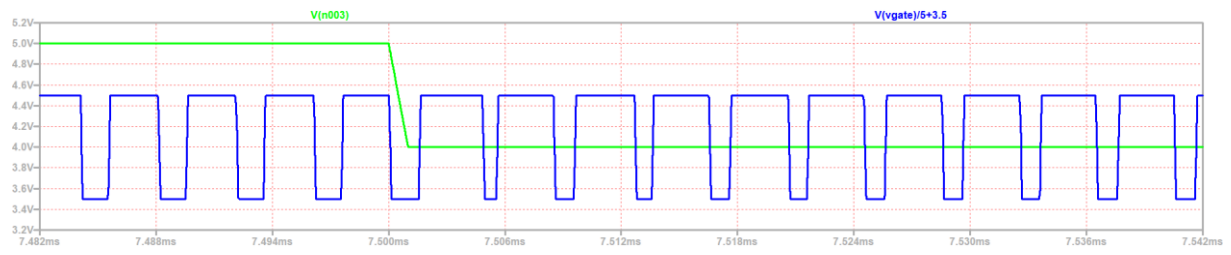


Figure 29: Type-III-B Compensator LT-Spice Simulation Results – Input Voltage and Duty During Transient Response of Input Voltage Dropping to 4V with More Ideal Op-Amp Using Negative Rail



### Question 11:

*Compare performance of the designs in terms of overshoot, settling time, oscillation etc. Do not forget to mention how the design parameters affect performance.*

I could not answer this question myself due to time constraint. Thus, I have used ChatGPT. It's response sounds noticeable and accurate.

*"Type-III (A) and Type-III (B) compensators differ in their handling of overshoot, settling time, and oscillations. Type-III (A) compensators generally provide a moderate level of overshoot and a quick settling time, with some minor oscillations, due to their balanced design aimed at fast response and stability. In contrast, Type-III (B) compensators are optimized for better damping, resulting in lower overshoot, shorter settling time, and minimal oscillations. This makes Type-III (B) compensators more suitable for applications requiring high precision and stability."*

*-ChatGPT*

## References

[1] A. Rahimi, P. Parto, and P. Asadi, “Compensator Design Procedure for Buck Converter with Voltage-Mode Error-Amplifier.” Available: <https://www.infineon.com/dgdl/an-1162.pdf?fileId=5546d462533600a40153559a8e17111a>. [Accessed: May 19, 2024]

[2] W.H Lei, T.K. Man, “A General Approach for Optimizing Dynamic Response for Buck Converter” Available: <http://www.cpdee.ufmg.br/~troliveira/docs/aulas/fontes/AND8143-D.PDF>. [Accessed: May 24, 2024]

## Appendix I: The MATLAB script to plot bode plot for control-to-output transfer function of buck converter

```
clear
clearvars
clc

% Parameters
L_out = 8e-6;    % H
C_out = 8e-6;    % F
R_c = 15e-3;     % Ohm
V_in = 5;        % V
V_out = 3.3;     % V
I_out = 4;       % A
f_sw = 250e3;    % Hz
V_ref = 1.2;     % V
V_osc = 1.8;     % V

%determined variables
R_load = V_out/I_out; % Load resistance

% Transfer function with esr: G_p_with_ESR(s)
numerator_with_ESR = V_in*R_load * [C_out * R_c, 1];
denominator_with_ESR = [L_out * C_out * (R_load + R_c), (L_out + R_load * C_out * R_c), R_load];
G_p_with_ESR = tf(numerator_with_ESR, denominator_with_ESR);

% Transfer function without esr: G_p_without_ESR(s)
numerator_without_ESR = V_in*R_load * [0, 1];
denominator_without_ESR = [L_out * C_out * R_load, L_out, R_load];
G_p_without_ESR = tf(numerator_without_ESR, denominator_without_ESR);

% Plot Bode plots
figure;
bode(G_p_with_ESR, 'r', G_p_without_ESR, 'b');
legend('With ESR', 'Without ESR');
grid on;

% Display transfer functions as fractions
disp('Transfer function with ESR:');
G_p_with_ESR
disp('Transfer function without ESR:');
G_p_without_ESR

% Gain margin and phase margin
[Gm_with_ESR, Pm_with_ESR, Wcg_with_ESR, Wcp_with_ESR] = margin(G_p_with_ESR);
[Gm_without_ESR, Pm_without_ESR, Wcg_without_ESR, Wcp_without_ESR] = margin(G_p_without_ESR);

% Display margins
disp('With ESR:');
fprintf('Gain Margin: %.2f dB\n', 20*log10(Gm_with_ESR));
fprintf('Phase Margin: %.2f degrees\n', Pm_with_ESR);

disp('Without ESR:');
fprintf('Gain Margin: %.2f dB\n', 20*log10(Gm_without_ESR));
fprintf('Phase Margin: %.2f degrees\n', Pm_without_ESR);
```

## Appendix II: The MATLAB script to plot bode plot requested at question seven.

```
%Q7-Type III A & B bode plots
clear
clearvars
clc
close all

is_type_A = true;

if is_type_A
    %Values for TypeIII-A: R_f1, R_C1, R_f3, C_C1, C_C2, C_f3
    R_f1 = 2.9e3; % Replace with your specific value
    R_C1 = 6.57e3; % Replace with your specific value
    R_f3 = 720; % Replace with your specific value
    C_C1 = 1.61e-9; % Replace with your specific value
    C_C2 = 0.2e-9; % Replace with your specific value
    C_f3 = 2.2e-9; % Replace with your specific value
else
    % Values for TypeIII-B: R_f1, R_C1, R_f3, C_C1, C_C2, C_f3
    R_f1 = 79.96e3; % Replace with your specific value
    R_C1 = 9.139e3; % Replace with your specific value
    R_f3 = 380; % Replace with your specific value
    C_C1 = 37e-9; % Replace with your specific value
    C_C2 = 140e-12; % Replace with your specific value
    C_f3 = 2.2e-9; % Replace with your specific value
end

% Numerator coefficients
numerator = [R_C1 * C_C1 * C_f3 * (R_f1 + R_f3) , (R_C1 * C_C1 + C_f3 * (R_f1 + R_f3)), 1 ];

% Denominator coefficients
denominator = [R_f1 * R_C1 * C_C1 * C_C2 * R_f3 * C_f3, R_f1 * C_C1 * (R_C1 * C_C2 + R_f3 * C_f3), R_f1 * C_C1, 0];

% Transfer function
transfer_function = tf(numerator, denominator)

% Create the Bode plot and calculate margins
figure;
[~,~,wcg] = bode(transfer_function);
[GM, PM, Wcg, Wcp] = margin(transfer_function);

% Plot Bode plot with gain and phase margins
margin(transfer_function);
% Add title and grid for better readability
title('Bode Plot (Gain and Phase) of the Transfer Function For TypeIII-A');
grid on;

% Display gain and phase margins
disp(['Gain Margin (GM): ', num2str(20*log10(GM)), ' dB']);
disp(['Phase Margin (PM): ', num2str(PM), ' degrees']);
disp(['Gain Crossover Frequency (Wcg): ', num2str(Wcg), ' rad/s']);
disp(['Phase Crossover Frequency (Wcp): ', num2str(Wcp), ' rad/s']);
```