

PSPice™ based Laboratory USER MANUAL

Department of Electrical and Computer Engineering
University of Minnesota

Lab Manual version 2008

[Copyright © 2003, Adapted with permission from “Power Electronics Modeling Simplified using PSPice™ (Release 9)”: <http://www.mnpere.com>]

In this laboratory, the Reference Textbook is the following: “First Course in Power Electronics” by Ned Mohan, published by MNPERE (www.MNPERE.com), year 2007 edition.

The original PSpice Schematics referred in this Laboratory Manual are provided on a CD accompanying the reference textbook above.

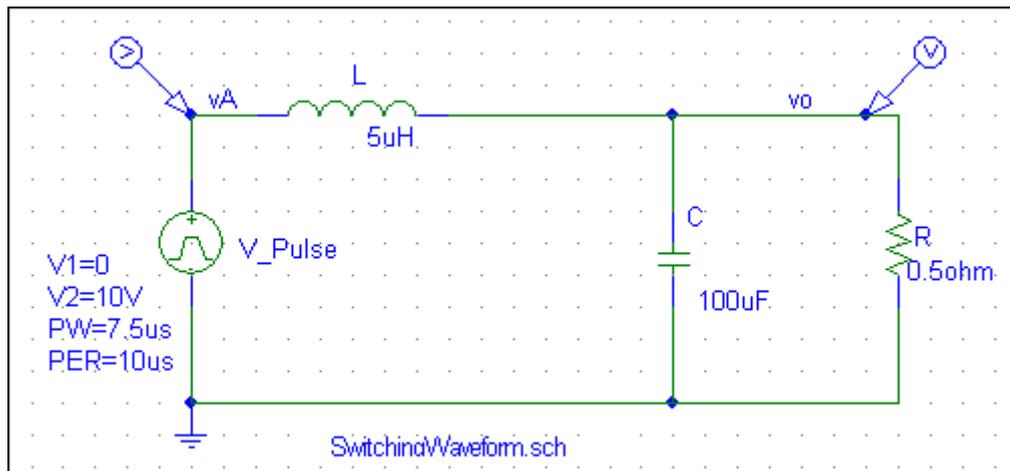
PSPICE POWER ELECTRONICS LAB

CONTENTS

1. Pulse-Width-Modulation (PWM) and Filter Characteristics
2. Switching Characteristics of MOSFET and Diode in a Power-Pole
3. Frequency Characteristics of Capacitors
4. Step-Down (Buck) DC-DC Converters
5. Step-Up (Boost) DC-DC Converter
6. Step-Down/Up (Buck-Boost) DC-DC Converter in CCM
7. Comparison of the Dynamic Response of the Switching Model with the Average Model: Buck-Boost Converter in CCM
8. Step-Down/Up (Buck-Boost) DC-DC Converter in DCM
9. Comparison of the Dynamic Response of the Switching Model with the Average Model: Buck-Boost Converter in DCM and CCM
10. Frequency Response Analysis of a Buck Converter using an Averaged Model
11. Designing the Feedback Control for a Buck Converter using the Voltage-Mode Control
12. Frequency Response Analysis of Buck-Boost Converter using Averaged Model
13. Current Mode Control of Buck-Boost Converter with Slope Compensation
14. Comparison of Frequency Response of a Buck-Boost Converter in CCM and DCM
15. Single-Phase Diode-Bridge Rectifiers
16. Three-Phase Diode-Bridge Rectifiers
17. Power Factor Correction (PFC) Circuit
18. Flyback DC-DC Converter
19. Forward DC-DC Converters
20. Full-Bridge DC-DC Converters
21. Zero-Voltage-Switching in a Synchronous Buck Converter
22. Three Phase PWM Inverters
23. Average Model of Three-Phase PWM Inverter
24. Single-Phase Thyristor-Bridge Rectifier

Lab Experiment – 1

Pulse-Width-Modulation (PWM) and Filter Characteristics



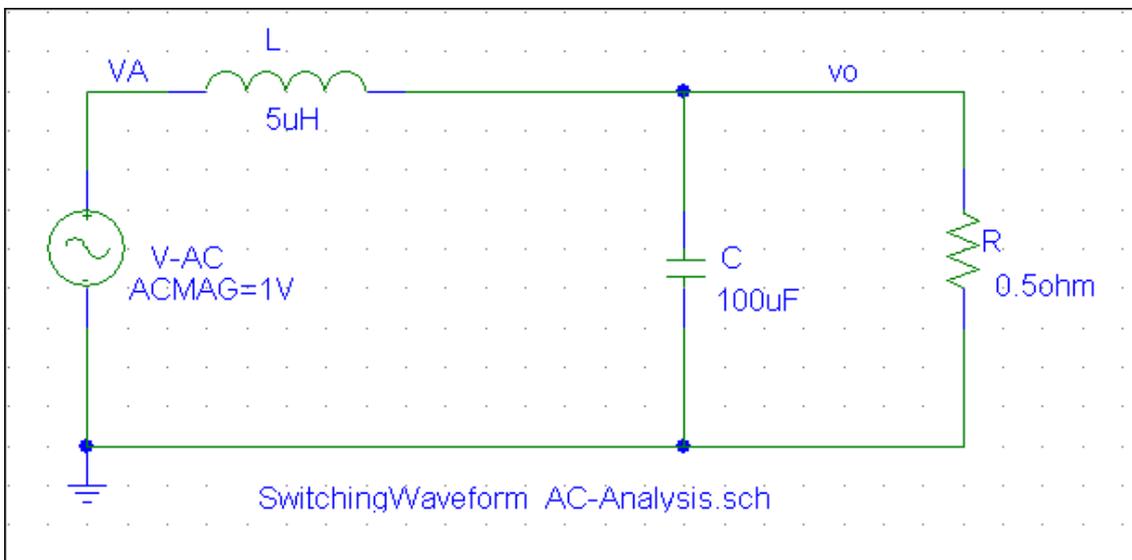
Objective:

This exercise shows $v_o(t) \approx V_o$, which is equal to the average of the switching-frequency input voltage $v_A(t)$, provided the L-C resonance frequency of the low-pass filter is significantly lower than the switching-frequency f_s .

Exercises:

- 1) Plot the input voltage v_A and the output voltage v_o for the last 10 switching cycles where v_o waveform has reached its steady state.
- 2) How does V_o relate to the average of v_A ?
- 3) From the simulation window, under View, look at the Output file for the Fourier components of v_A and v_o . Are the averages of the two the same? How does the fundamental frequency in the input voltage relate to its switching frequency? In this circuit, what is the ratio of the switching frequency to the L-C resonance frequency? What is the attenuation of the fundamental-frequency component by the filter at the switching frequency?

- 4) In the original schematic, change the pulse width (PW) of the input source to $6\mu s$ and repeat parts 1-3.
- 5) In the original schematic, change the switching frequency of the input voltage to 20 kHz (keeping the duty-cycle the same as in the original schematic). Make sure to increase the simulation time and change the Center Frequency in the Fourier Analysis. Repeat parts 1-3.
- 6) In the original schematic, change the pulse width (PW) of the input source to $5\mu s$ (50% duty-ratio). Calculate the amplitude of the fundamental frequency component in v_A and compare with the Fourier results in the simulation.

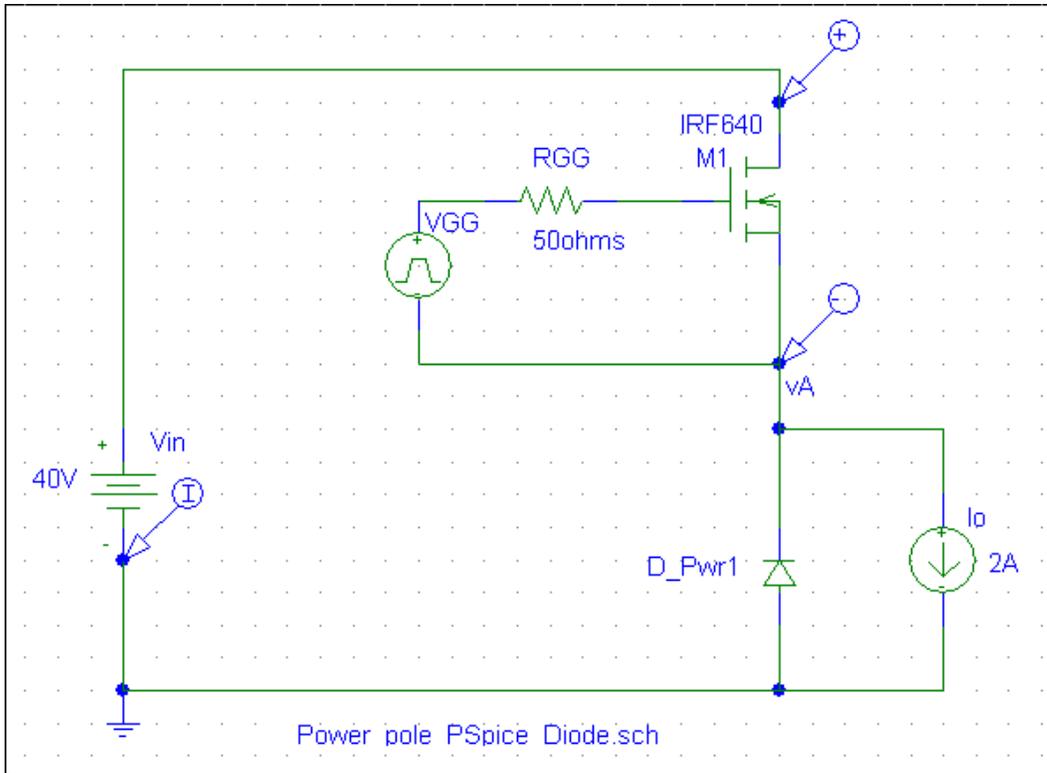


- 7) Using the schematic above for the ac, plot the transfer function $V_o(s)/V_A(s)$. Does the frequency at which the transfer-function gain is peaking coincide with the L-C resonance frequency?
- 8) Calculate the attenuation of the fundamental-frequency component by the filter. How does it compare with that obtained by the Fourier analysis in part 3?

Reference: Chapter 1

Lab Experiment – 2

Switching Characteristics of MOSFET and Diode in a Power-Pole



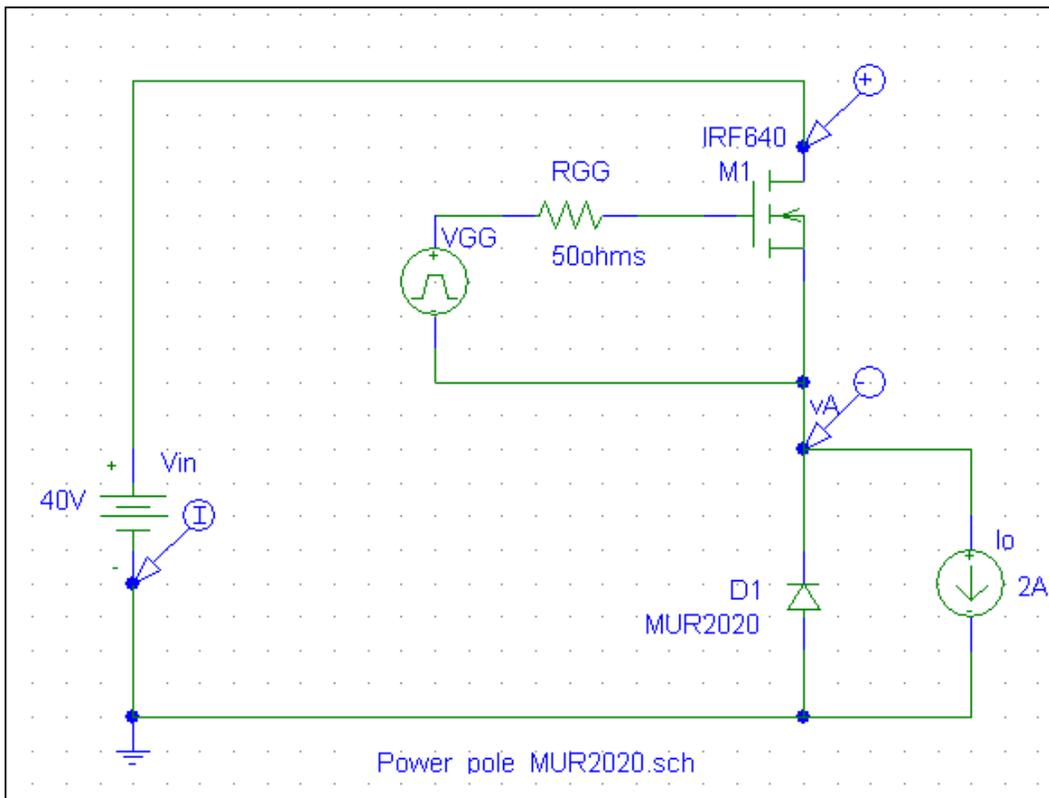
Objective:

This exercise shows the switching waveforms, switching times and the power losses associated with actual MOSFETs and Diodes.

Exercises:

- 1) In the schematic above, the switching power-pole in the circuit of Fig. 2-5a of the reference textbook consists of a MOSFET IRF640 and a diode in the PSpice Library with $R_s = 1m\Omega$. Obtain the turn-on switching characteristics as shown in Fig. 2-5c.

- 2) Measure $t_{d(on)}$, t_{ri} and t_{fv} in the turn-on switching characteristics.
- 3) Measure $v_{GS(th)}$ and $v_{GS(I_o)}$. Compare these with the datasheet for the IRF640.
- 4) Using Eq. 2-3, estimate the average switching power loss during the turn-on.
- 5) Obtain the turn-off switching characteristics as shown in Fig. 2-7c.
- 6) Measure $t_{d(off)}$, t_{rv} and t_{fi} in the turn-on switching characteristics.
- 7) Using Eq. 2-3, calculate the average switching power loss during the turn-on.

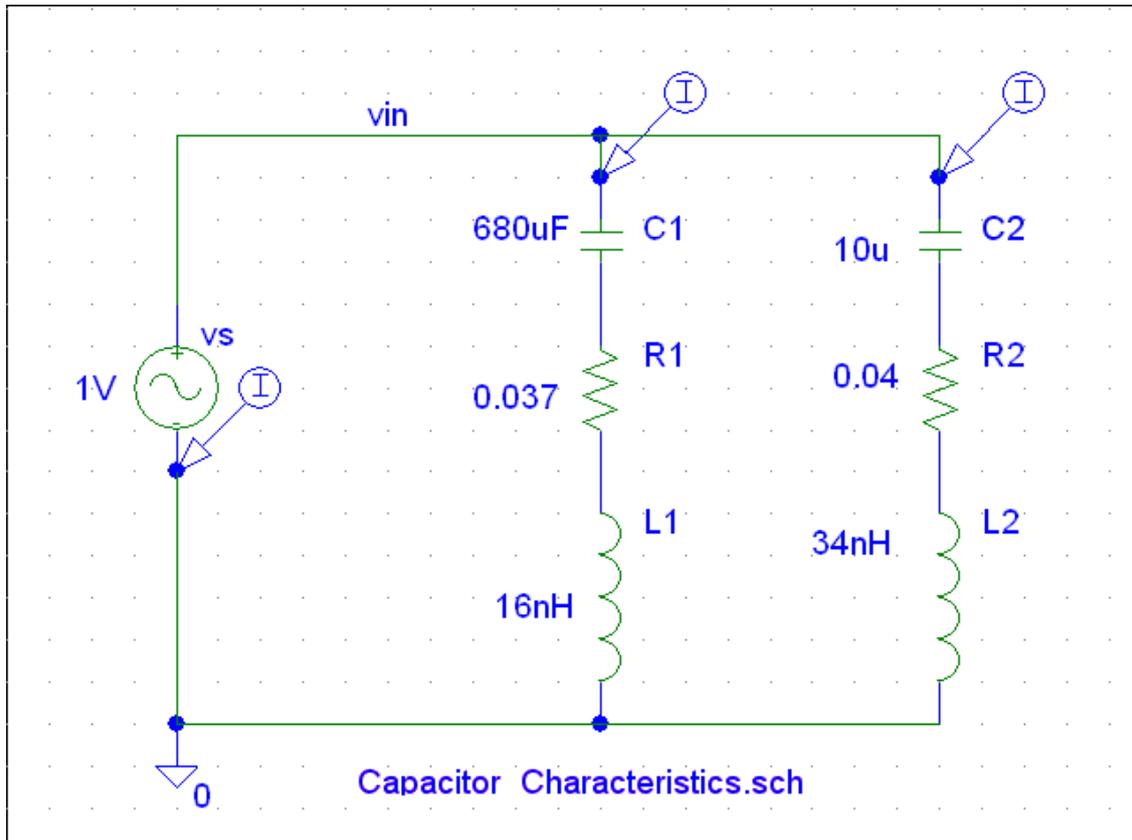


- 8) The schematic above has a diode MUR200. Obtain the turn-on switching characteristics as shown in Fig. 2A-2.
- 9) Measure $t_{d(on)}$, t_{ri} , t_{rr} and t_{fv} in the turn-on switching characteristics.
- 10) What is I_{RRM} ?
- 11) Estimate the average switching power loss during the turn-on using the equation in the Appendix of Chapter 2.

Reference: Chapter 2

Lab Experiment – 3

Frequency Characteristics of Capacitors



Objective:

Observe that capacitors begin to behave as inductors beyond their respective resonance frequencies. Their proper selection and combination of these capacitors are needed for filtering purposes. As in our power electronics hardware lab, C_1 is an electrolytic capacitor and C_2 is a polypropylene capacitor, both of which are presented along with their ESR and ESL.

Exercises:

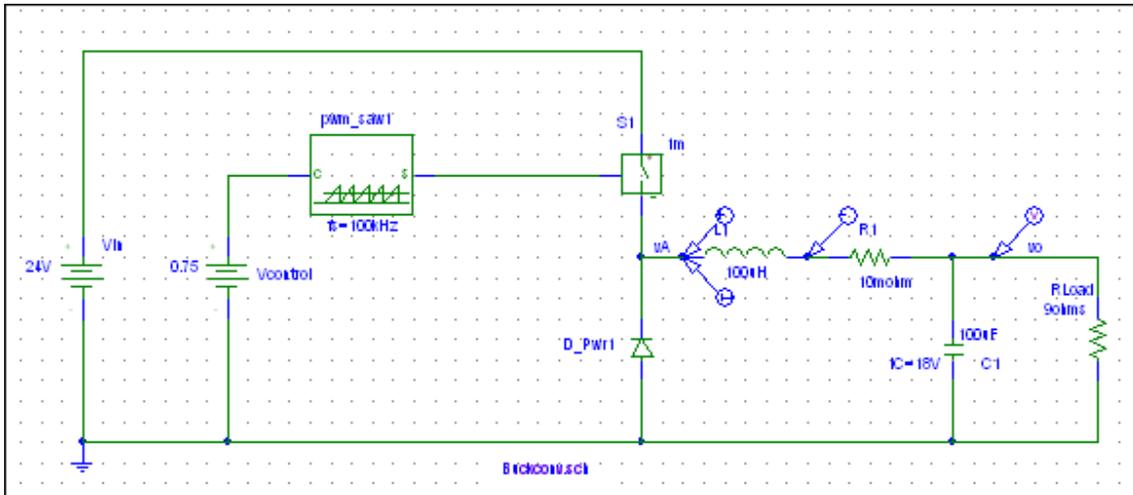
1. Obtain the frequency response of the admittances associated with C_1 and C_2 , and their parallel combination, in terms of their magnitude and the phase angles.
2. Obtain the resonance frequency for the two capacitors and their combination.

Hint: Look at the phase plot.

Reference: Chapter 2

Lab Experiment – 4

Step-Down (Buck) DC-DC Converters



Objective:

The objective of this experiment is to observe switching waveforms in a Buck Converter operating at a fixed duty-ratio and consisting of a near-ideal MOSFET and diode.

Exercises:

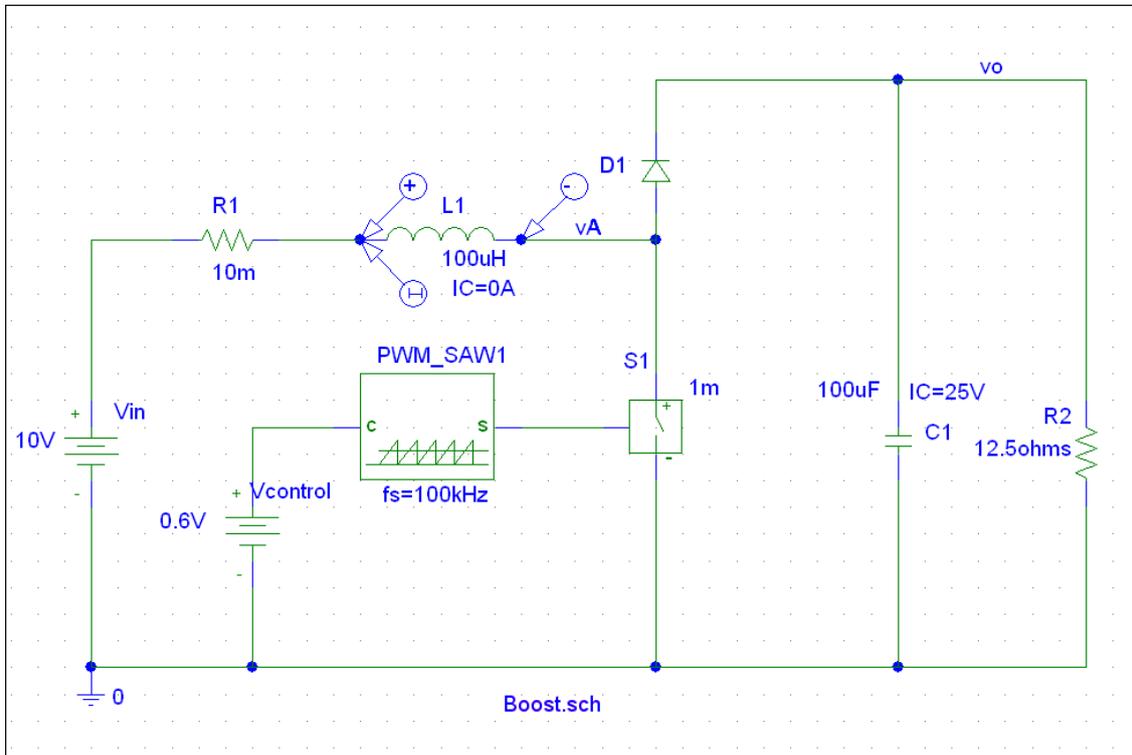
1. Plot the waveforms during the last 10 switching cycles for i_L , v_L and v_o .
2. Plot the average value of v_L .
3. Plot i_L and measure the peak-peak ripple Δi_L and compare it with Eq. 3-13.
4. Plot i_c waveform. What is the average of i_c . Compare the i_c waveform with the ripple in i_L .
5. Plot the input current waveform and calculate its average. Compare that to the value calculated from Eq. 3-16.
6. Calculate the inductance value of L , if Δi_L should be $1/3^{\text{rd}}$ of the load current. Verify the results by simulations.

7. Change the output power in this circuit to one-half its original value. Measure the peak-peak ripple Δi_L and compare it with that in Exercise 3. Comment on this comparison.
8. Calculate R_{crit} from Eq. 3-45 and verify whether the converter is operating on the boundary of CCM and DCM.

Reference: Chapter 3

Lab Experiment – 5

Step-Up (Boost) DC-DC Converter



Objective:

The objective of this experiment is to observe switching waveforms in a Boost Converter operating at a fixed duty-ratio and consisting of a near-ideal MOSFET and diode.

Exercises:

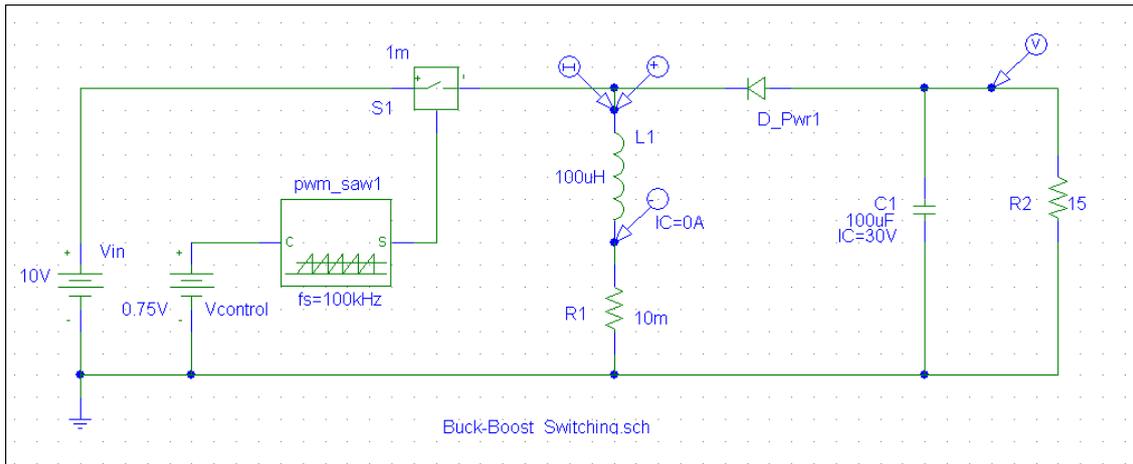
1. Plot the waveforms during the last 10 switching cycles for i_L , v_L and v_o .
2. Plot the average value of v_L .
3. Plot i_L and measure the peak-peak ripple Δi_L and compare it with Eq. 3-21.

4. Plot i_c and i_{diode} waveform. What is the average of i_c . Compare the i_c waveform with the ripple in i_{diode} .
5. Plot the input current waveform and calculate its average. Compare that to the value calculated from Eq. 3-23.
6. Calculate the inductance value of L , if Δi_L should be $1/3^{\text{rd}}$ of the input current. Verify the results by simulations.
7. Change the output power in this circuit to one-half its original value. Measure the peak-peak ripple Δi_L and compare it with that in Exercise 3. Comment on this comparison.
8. Calculate R_{crit} from Eq. 3-45 and verify whether the converter is operating on the boundary of CCM and DCM.

Reference: Chapter 3

Lab Experiment – 6

Step-Down/Up (Buck-Boost) DC-DC Converter in CCM



Objective:

The objective of this experiment is to observe switching waveforms in a Buck-Boost Converter operating at a fixed duty-ratio and consisting of a near-ideal MOSFET and diode.

Exercises:

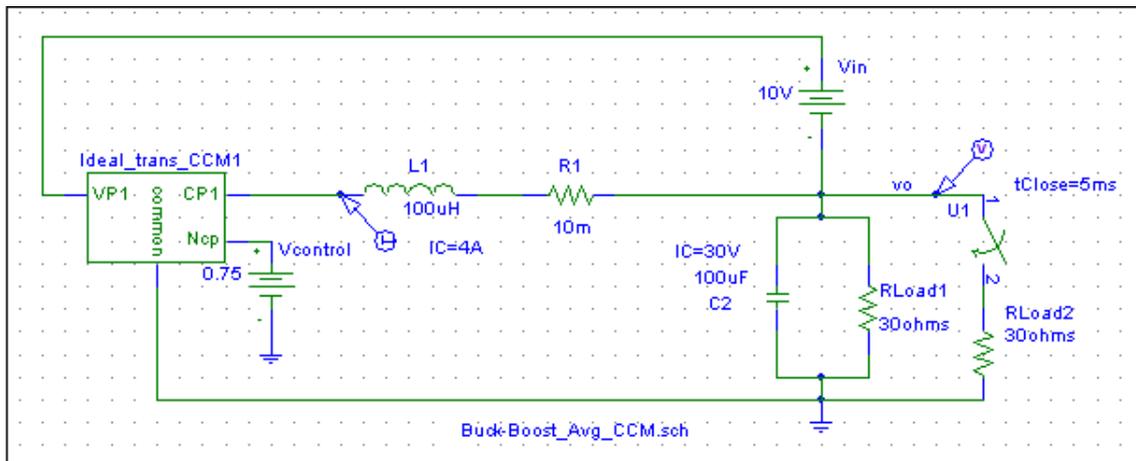
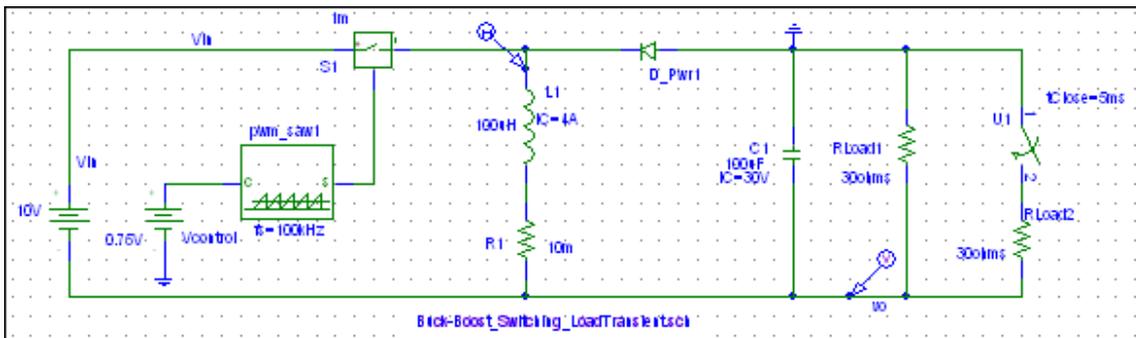
1. Plot the waveforms during the last 10 switching cycles for i_L , v_L and v_o .
2. Plot the average value of v_L .
3. Plot i_L and measure the peak-peak ripple Δi_L and compare it with Eq. 3-28.
4. Plot i_C and i_{diode} waveform. What is the average of i_C . Compare the i_C waveform with the ripple in i_{diode} .
5. Plot the input current waveform and calculate its average. Compare that to the value calculated from Eq. 3-31.
6. Calculate the inductance value of L , if Δi_L should be $1/3^{\text{rd}}$ of the input current. Verify the results by simulations.

7. Change the output power in this circuit to one-half its original value. Measure the peak-peak ripple Δi_L and compare it with that in Exercise 3. Comment on this comparison.
8. Calculate R_{crit} from Eq. 3-45 and verify whether the converter is operating on the boundary of CCM and DCM.

Reference: Chapter 3

Lab Experiment – 7

Comparison of the Dynamic Response of the Switching Model with the Average Model: Buck-Boost Converter in CCM



Objective:

The objective of this experiment is to show that the average model gives an identical dynamic response as a switching model, using a Buck-Boost converter as an example. An additional load is switched on at 5 ms.

Exercises:

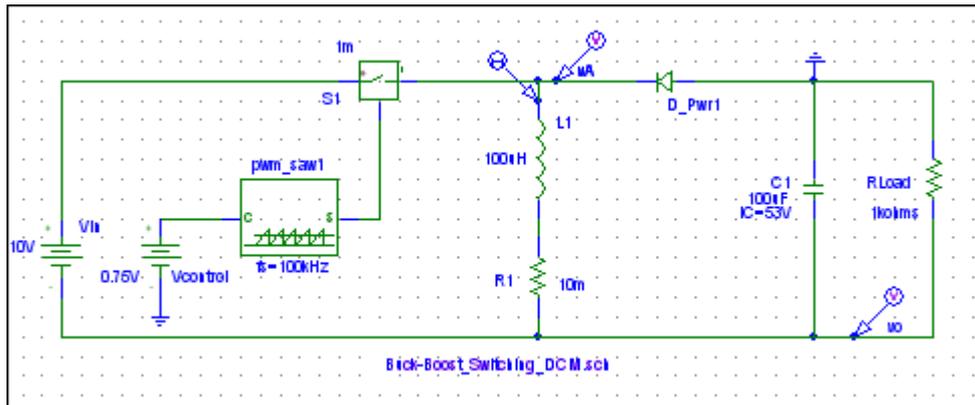
1. Plot the waveforms for i_L and v_o in the switching model.

2. Plot the waveforms for i_L and v_o in the average model. In the Probe window, under the File menu, click on Append Waveform and select the .dat file of the switching waveforms (do not skip sections).
3. Comment on the time it takes to simulate using the average model versus the switching model. Why does the output voltage response in the two models differ?

Reference: Chapter 3

Lab Experiment – 8

Step-Down/Up (Buck-Boost) DC-DC Converter in DCM



Objective:

The objective of this experiment is to observe switching waveforms in a Buck-Boost Converter operating in DCM.

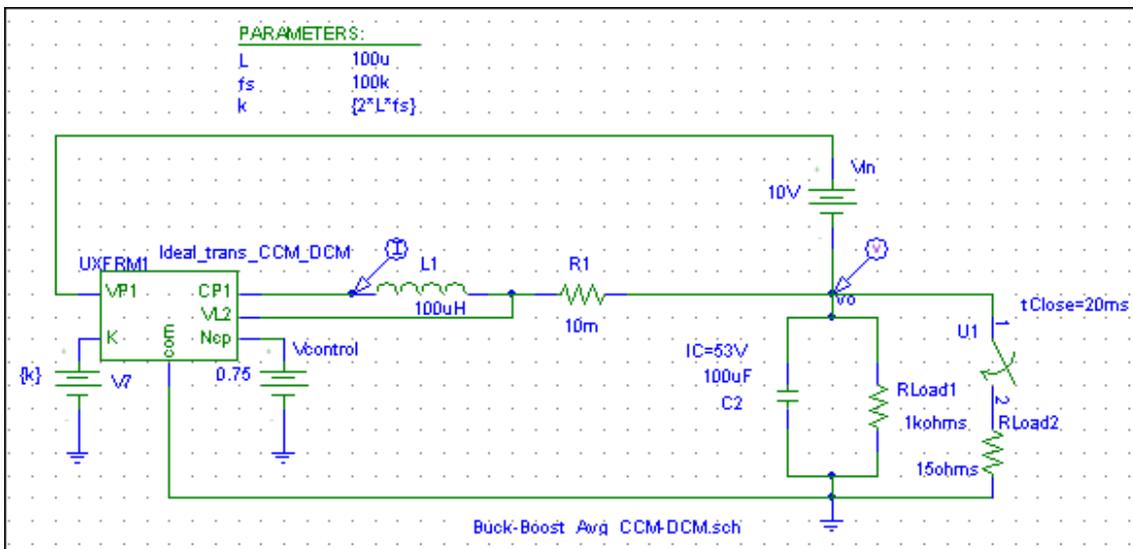
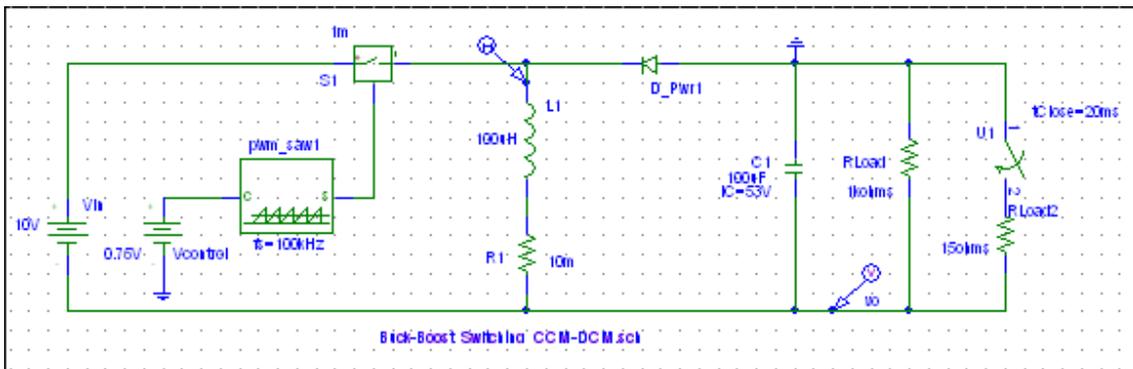
Exercises:

1. Plot the waveforms during the last 5 switching cycles for i_L , v_L and v_o .
2. Plot the average value of v_L .
3. Calculate V_o using Eq. 3-57 and compare it with its measured value.
4. Plot the waveform of v_A , label it in terms of V_{in} and V_o , and compare it with Fig. 3-27a.
5. Show that the hatched area in Fig. 3-27a, averaged over the switching time-period, results in the increase in V_o , compared to its CCM value.
6. For the load-resistance given here, calculate the inductance value that will make the operation at the boundary of CCM and DCM. Verify it using that L value in the simulation.

Reference: Chapter 3

Lab Experiment – 9

Comparison of the Dynamic Response of the Switching Model with the Average Model: Buck-Boost Converter in DCM and CCM



Objective:

The objective of this experiment is to show that the average model gives an identical dynamic response as a switching model in DCM and CCM, using a Buck-Boost converter as an example. An additional load is switched on at 20 ms to make this converter go into CCM.

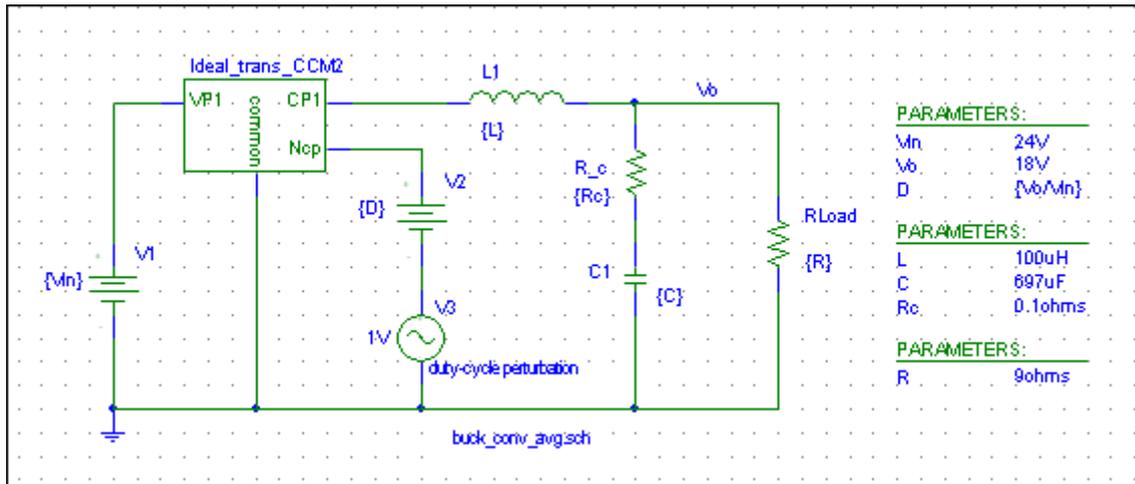
Exercises:

1. Plot the waveforms for i_L and v_o in the switching model.
2. Plot the waveforms for i_L and v_o in the average model. In the Probe window, under the File menu, click on Append Waveform and select the .dat file of the switching waveforms (do not skip sections).
3. Comment on the time it takes to simulate using the average model versus the switching model. Why does the output voltage response in the two models differ?

Reference: Chapter 3

Lab Experiment – 10

Frequency Response Analysis of a Buck Converter using an Averaged Model



Objective:

The objective of this experiment is to obtain the frequency response of a Buck converter, in order to get the plot of the transfer function $\frac{\tilde{v}_o}{\tilde{d}}(s)$.

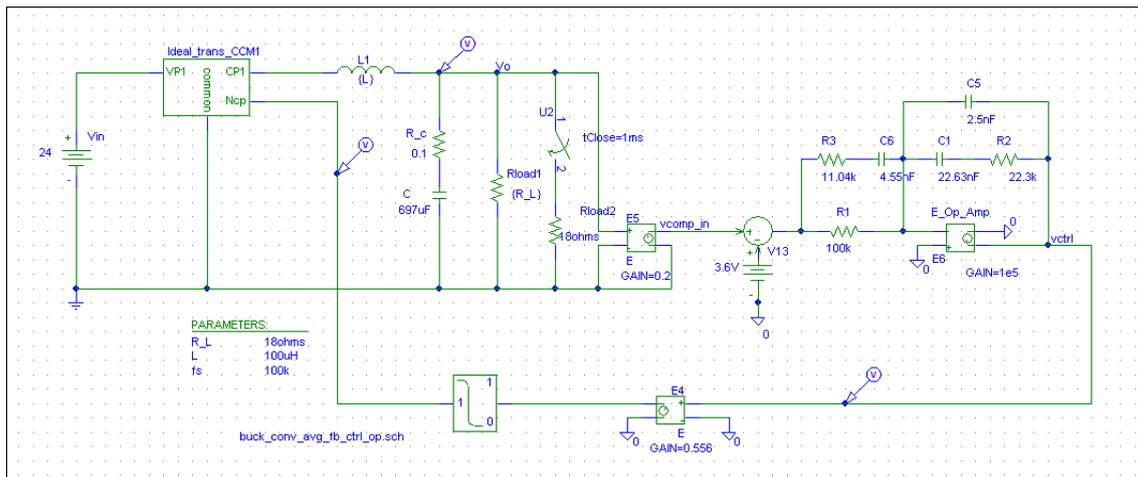
Exercises:

1. Obtain the Bode plots for the transfer function $\frac{\tilde{v}_o}{\tilde{d}}(s)$ as shown in Fig. 4-10 for the values given in this simulation.
2. Obtain the gain and the phase of the transfer function $\frac{\tilde{v}_o}{\tilde{d}}(s)$ in part 1 at the frequency of 1 kHz, which will be chosen as the crossover of the open-loop transfer function $G_L(s)$.

Reference: Chapter 4

Lab Experiment – 11

Designing the Feedback Control for a Buck Converter using the Voltage-Mode Control



File Name: buck_conv_avg_fb_ctrl_op.sch

Objective:

The objective of this experiment is to design the feedback controller using voltage-mode, for the Buck converter in Exercise 10. $k_{fb} = 0.2$ and $G_{PWM}(s) = 0.556$. An appropriate crossover frequency and the Phase margin are chosen.

Exercises:

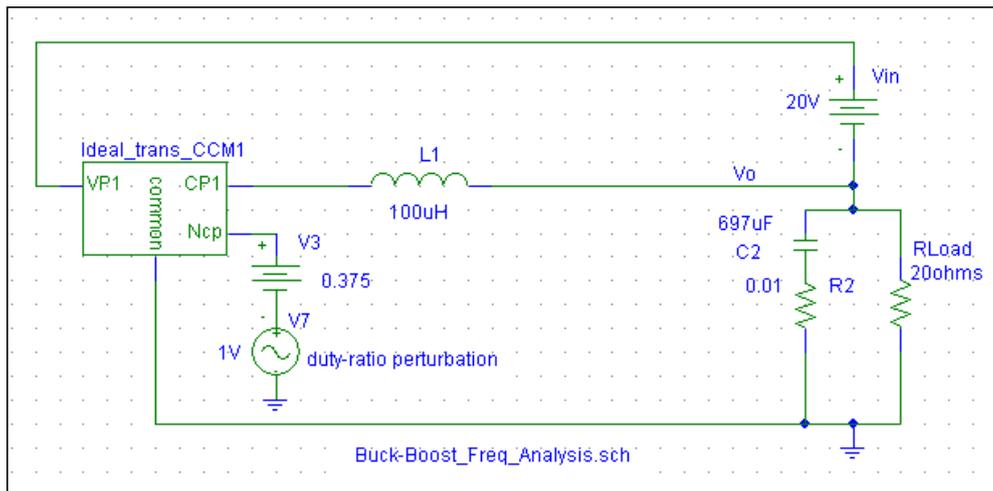
1. Look at the Bode plot of $\tilde{v}_o(s)$ in Exercise 10 and choose the open-loop crossover frequency to be 1 kHz (or close to it). Why not 5 kHz?
2. Design the feedback controller $G_c(s)$ described in the reference textbook for the phase margin of 60° . The following MATLAB program is included for your reference: FeedbackControlCalculationsforExperiment11.m.
3. This feedback controller is implemented in the schematic above using an op-amp. Obtain the output voltage response for a step-change in load.

4. Repeat part 2 with a phase margin of 45° . Compare the output voltage response with that in part 3 with 60° .
5. Repeat parts 1 through 3 for a crossover frequency of 2 kHz and compare the response in part 3.

Reference: Chapter 4

Lab Experiment – 12

Frequency Response Analysis of Buck-Boost Converter Using Averaged Model



Objective:

The objective of this experiment is to obtain the frequency response of a Buck-Boost converter, in order to get the plot of the transfer function $\frac{\tilde{v}_o}{\tilde{i}_L}(s)$.

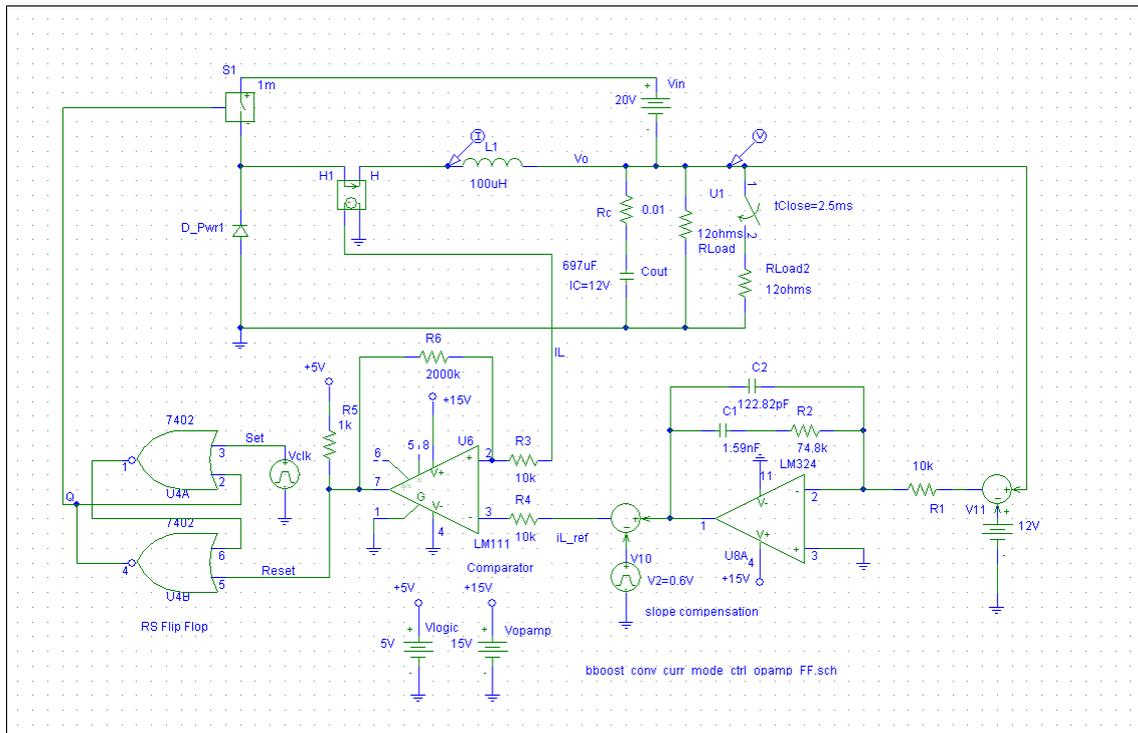
Exercises:

1. Obtain the Bode plots for the transfer function $\frac{\tilde{v}_o}{\tilde{i}_L}(s)$ as shown in Fig. 4-18 for the values given in this simulation.
2. Obtain the gain and the phase of the transfer function $\frac{\tilde{v}_o}{\tilde{i}_L}(s)$ in part 1 at the frequency of 5 kHz, which will be chosen as the crossover of the open-loop transfer function $G_L(s)$.

Reference: Chapter 4

Lab Experiment – 13

Peak Current Mode Control of Buck-Boost Converter with Slope Compensation



File Name: bboost_conv_curr_mode_ctrl_opamp_FF.sch

Objective:

The objective of this experiment is to design the feedback controller using peak-current-mode, for the Buck-Boost converter in Exercise 12. An appropriate crossover frequency and the Phase margin are chosen.

Exercises:

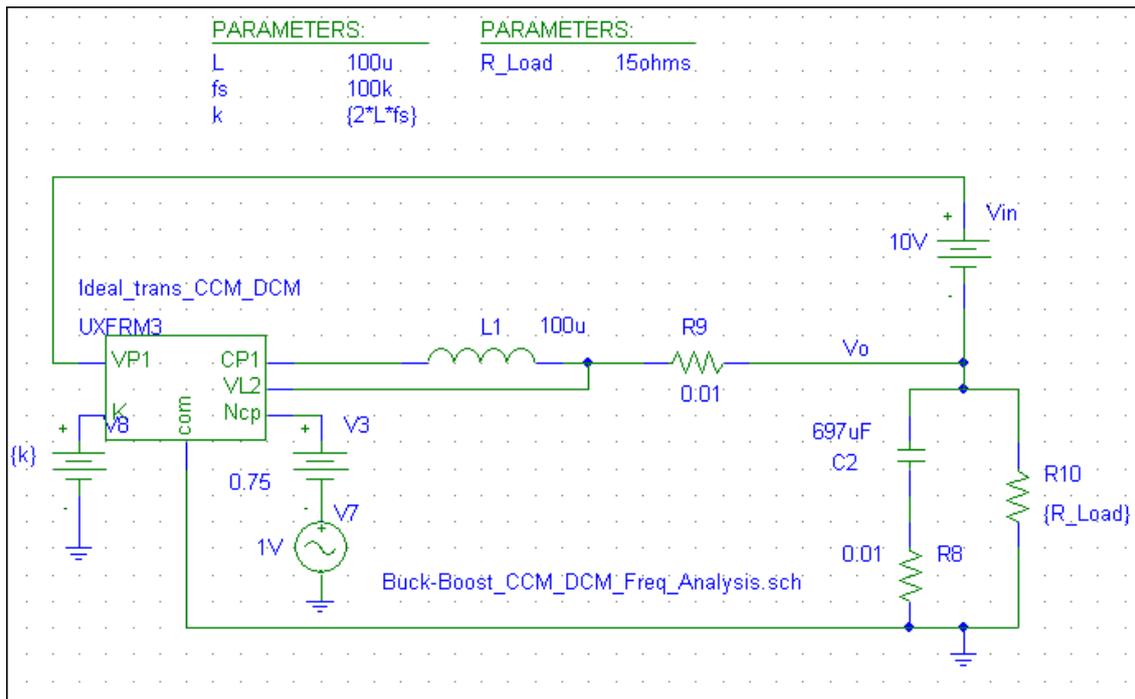
1. Look at the Bode plot of $\frac{\tilde{v}_o}{\tilde{i}_L}(s)$ in Exercise 11 and choose the open-loop crossover frequency to be 5 kHz (or close to it).

2. Design the feedback controller $G_c(s)$ described in the reference textbook for the phase margin of 60° . The following MATLAB program is included for your reference: Peakcurrentmodecontrolcalculations.m.
3. Obtain the output voltage and the inductor current response for a step-change in load.

Reference: Chapter 4

Lab Experiment – 14

Comparison of Frequency Response of a Buck-Boost Converter in CCM and DCM



Objective:

The objective of this experiment is to show the difference in the frequency response of a Buck-Boost converter in CCM and DCM.

Exercises:

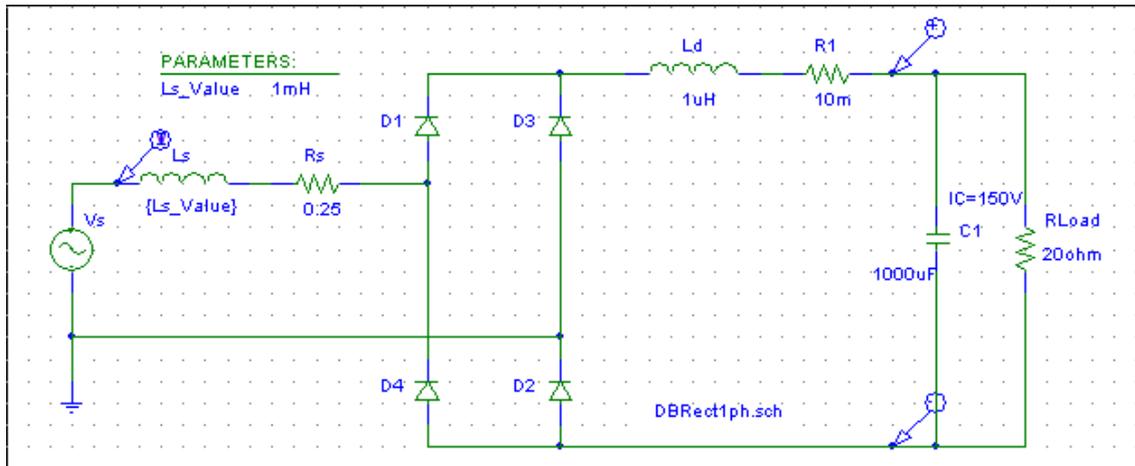
1. Look at the phase and gain plots of $\frac{\tilde{v}_o}{\tilde{d}}(s)$ in CCM with a load resistance of 15Ω and in DCM with the load resistance of 500Ω, for designing a voltage-mode feedback control. Comment on the difficulty in doing so under CCM.

2. Look at the phase and gain plots of $\frac{\tilde{v}_o}{\tilde{i}_L}(s)$ in CCM with a load resistance of 15Ω and in DCM with the load resistance of 500Ω , for designing a peak-current-mode feedback control. Comment on the advisability of using the peak-current-mode control versus the voltage-mode control in DCM.

Reference: Chapters 3 and 4.

Lab Experiment – 15

Single-Phase Diode-Bridge Rectifiers



Objective:

The objective of this experiment is to look at the input current and output voltage waveforms in a single-phase diode-rectifier bridge with a large capacitor on the dc-side.

Exercises:

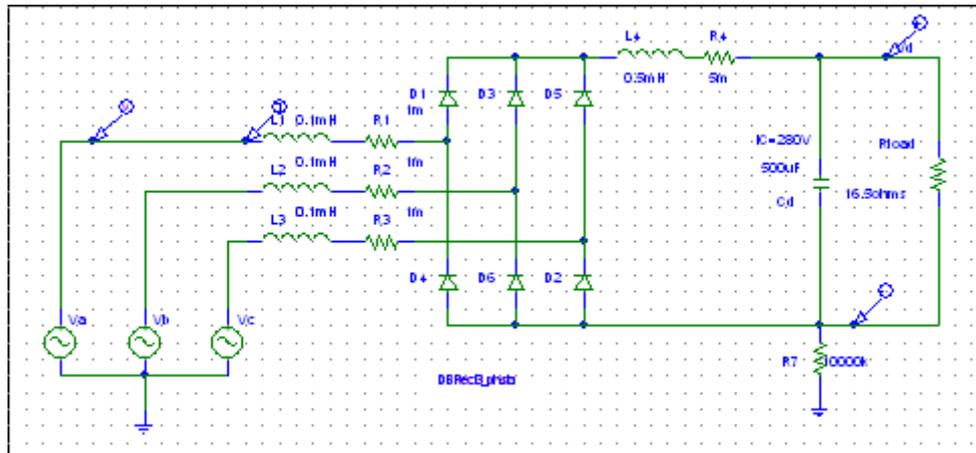
1. Comment on the input current waveform as a function of the ac-side inductance.
2. Obtain the %THD in the input current for the three values of the input inductance.
3. Comment on the output voltage waveform as a function of the ac-side inductance. Measure the average and the peak-to-peak ripple in the output voltage for the three values of the input-side inductance.
4. Keep the input inductance value as $1mH$ and change the dc-side capacitance values to be $220\mu F$, $470\mu F$ and $1,000\mu F$. Repeat parts 1, 2 and 3.

5. Keeping the output capacitance at $1,000 \mu F$, measure the peak-to-peak ripple in the output capacitor current for the three values of the input-side inductance. What is fundamental frequency of this current?
6. Keeping the input-side inductance at $1 mH$, measure the peak-to-peak ripple in the output capacitor current for the three values of the output capacitance: $220 \mu F$, $470 \mu F$ and $1,000 \mu F$.

Reference: Chapter 5

Lab Experiment – 16

Three-Phase Diode-Bridge Rectifiers



File Name: DBRect3_ph.sch

Objective:

The objective of this experiment is to look at the input current and output voltage waveforms in a three-phase diode-rectifier bridge with a large capacitor on the dc-side.

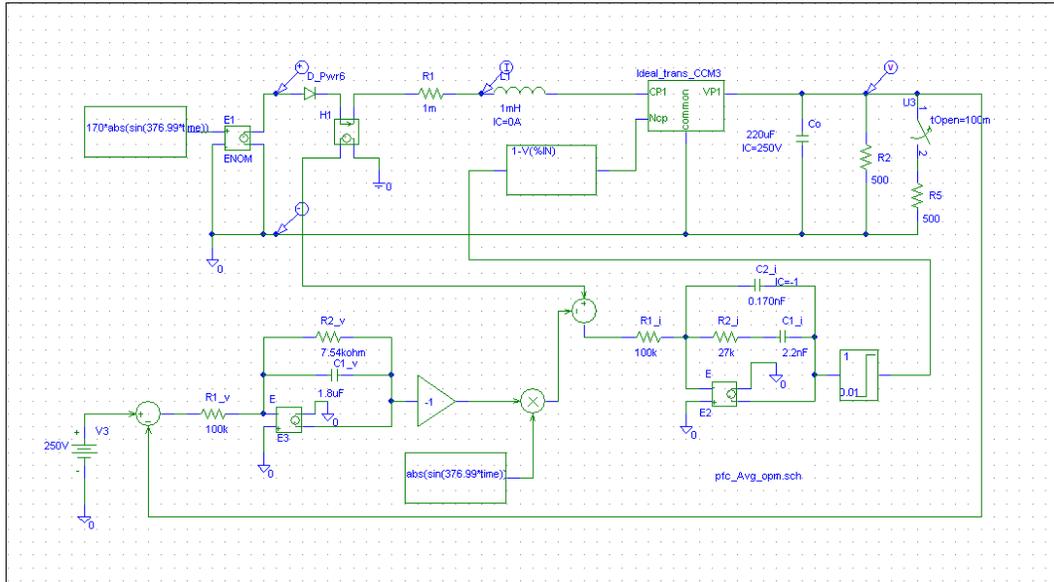
Exercises:

1. Comment on the input current waveform as a function of the ac-side inductance for values of 0.1 mH, 0.5 mH and 1.0 mH.
2. Obtain the %THD in the input current for the three values of the input inductance.
3. Comment on the output voltage waveform as a function of the ac-side inductance. Measure the average and the peak-to-peak ripple in the output voltage for the three values of the input-side inductance.
4. Measure the peak-to-peak ripple in the output capacitor current for the three values of the input-side inductance. What is fundamental frequency of this current?

Reference: Chapter 5

Lab Experiment – 17

Power Factor Correction (PFC) Circuit



File name: pfc_Avg_opm.sch

Objective:

The objective of this experiment is to study the single-phase power factor correction circuit (PFC).

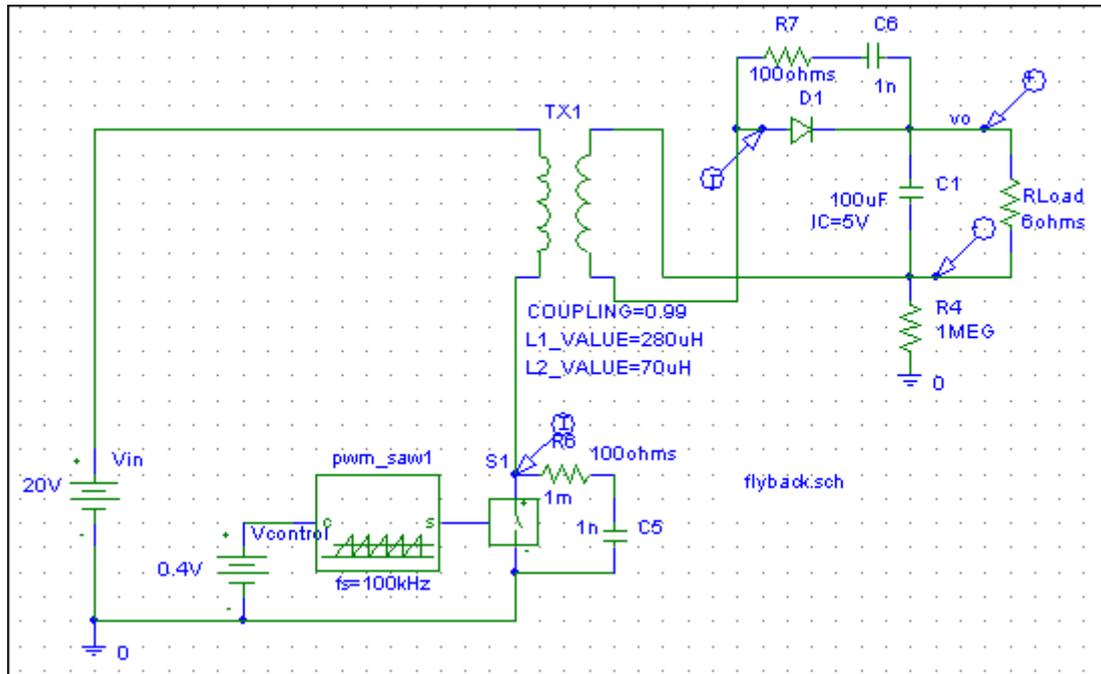
Exercises:

1. Observe the input voltage to the boost converter (output of the diode-rectifier bridge, not modeled here), the inductor current and the voltage across the load.
2. List the harmonic components of the inductor current i_L and the capacitor current i_C .
3. Confirm the validity of Eq. 6-5 for the current into the output stage of the PFC.
4. Use the switching model of the above experiment, “pfc_Switching_opm.sch” and compare the results from average and switching models.

Reference: Chapter 6

Lab Experiment – 18

Flyback DC-DC Converter



Objective:

The objective of this experiment is to study the operation of a Flyback converter.

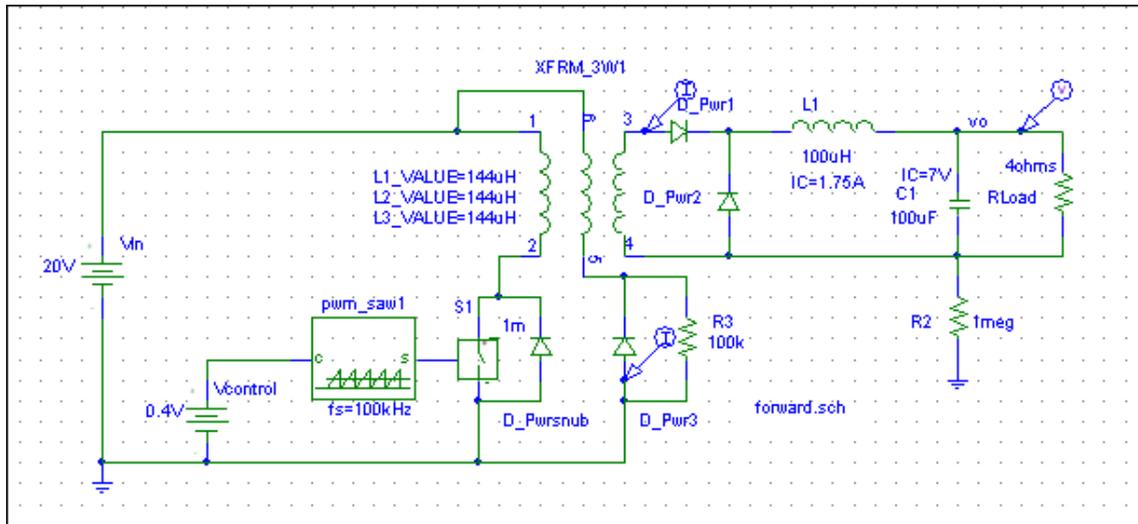
Exercises:

1. What is the turns-ratio $\frac{N_1}{N_2}$ in this converter?
2. Observe the waveforms for i_{in} , i_{out} and v_o . What is the relationship between i_{in} and i_{out} at the time of transition from S_1 to D_1 and vice versa?
3. What is the value of R_{crit} in this converter?
4. For $R=100\Omega$, obtain the waveforms for i_{in} , i_{out} and v_o .

Reference: Chapter 8

Lab Experiment – 19

Forward DC-DC Converters



Objective:

The objective of this experiment is to study the operation of a Forward converter.

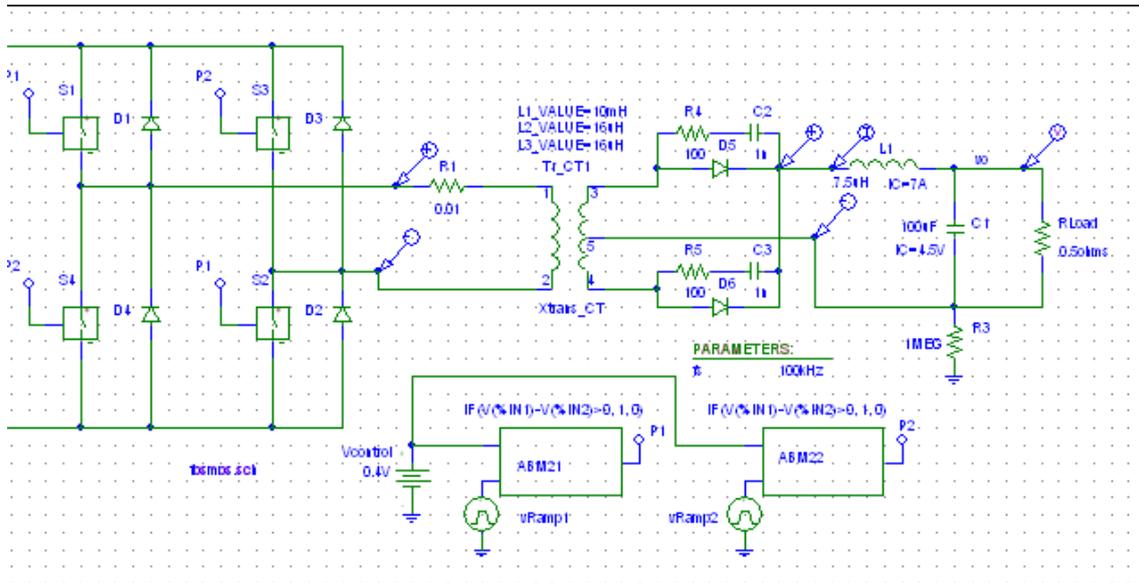
Exercises:

1. Observe the waveforms for i_1 , i_3 , i_{D1} , i_L and v_o . What is the relationship between i_1 , i_3 and i_{D1} at the time of transitions when the switch turns-on, turns-off and the core gets demagnetized?
2. What is the voltage across the switch?
3. What is the value of R_{crit} in this converter?
4. For $R = 50\Omega$, obtain the waveforms for i_1 , i_3 , i_{D1} , i_L and v_o up to 0.3 ms.

Reference: Chapter 8

Lab Experiment – 20

Full-Bridge DC-DC Converters



Objective:

The objective of this experiment is to study the operation of a Full-Bridge DC-DC converter.

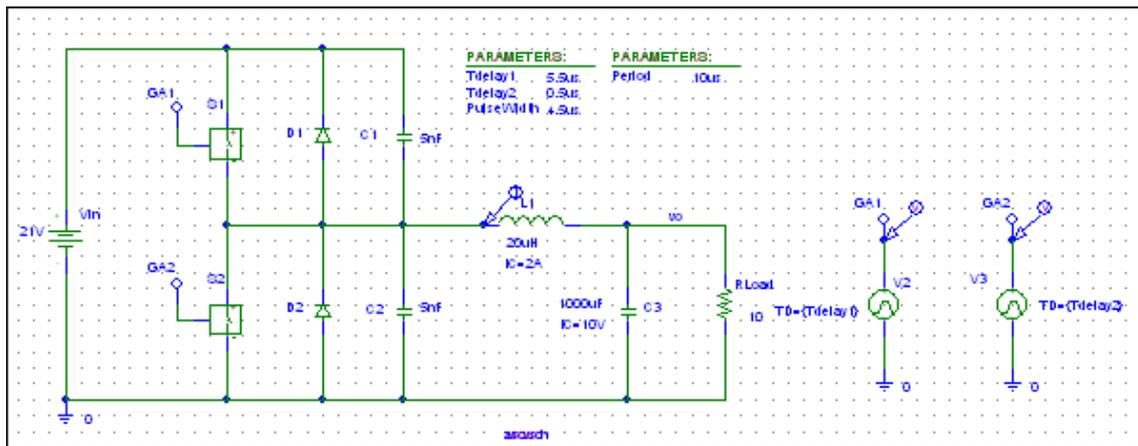
Exercises:

1. Observe the waveforms for v_1 , v_2 , v_A and v_o . What are their values when all switches are off?
2. Plot the waveforms of i_1 , i_{D1} , i_{D2} and i_L defined in Fig. 8-12. What are their values when all switches are off?
3. Based on the converter parameters and the operating conditions, calculate the peak-peak ripple current in i_L and verify your answer with the simulation results.

Reference: Chapter 8

Lab Experiment – 21

Zero-Voltage-Switching in a Synchronous Buck Converter



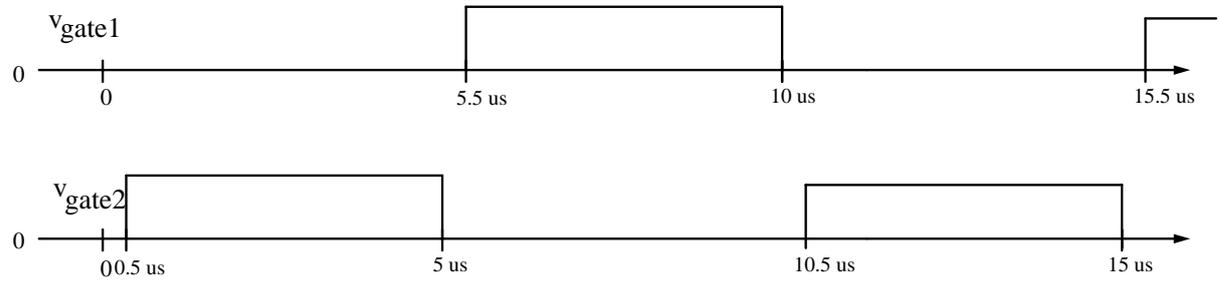
Objective:

The objective of this experiment is to study the soft-switching concept by means of a Synchronous Buck Converter.

Exercises:

1. Observe the waveforms for v_A and i_L .
2. Obtain the voltage across and the current through one of the switches. Comment on the zero voltage/current switchings.
3. Around the blanking time, obtain the currents through one of the switches and through its associated diode and the snubber capacitors.
4. Obtain the average value of v_A . How much lower is it compared to the nominal value of 10 V for V_O ?
5. Calculate the peak-to-peak ripple in the inductor current as a ratio of the average inductor current. What should its value be to provide zero voltage switching?
6. Change C_{S1} and C_{S2} to be 2.5 nF. Repeat Problems 1 through 4.

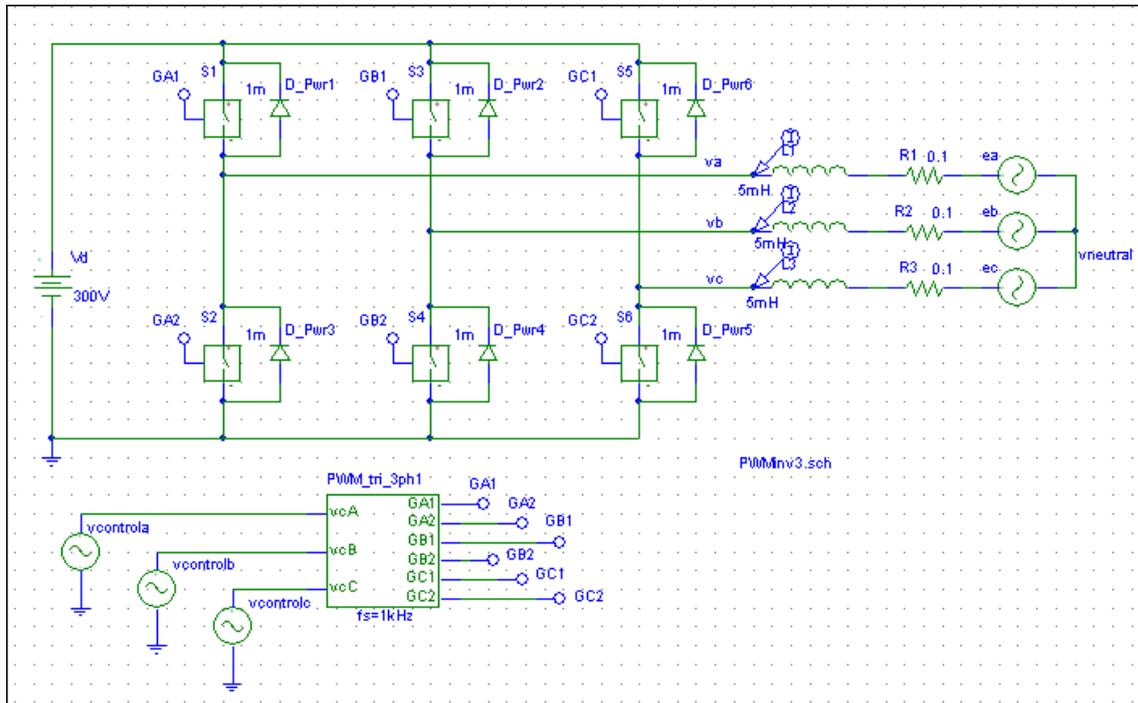
Controller



Reference: Chapter 10

Lab Experiment – 22

Three-Phase PWM Inverters



File name: PWMInv3.sch

Objective:

The objective of this experiment is to study the operation of a three-phase PWM inverter.

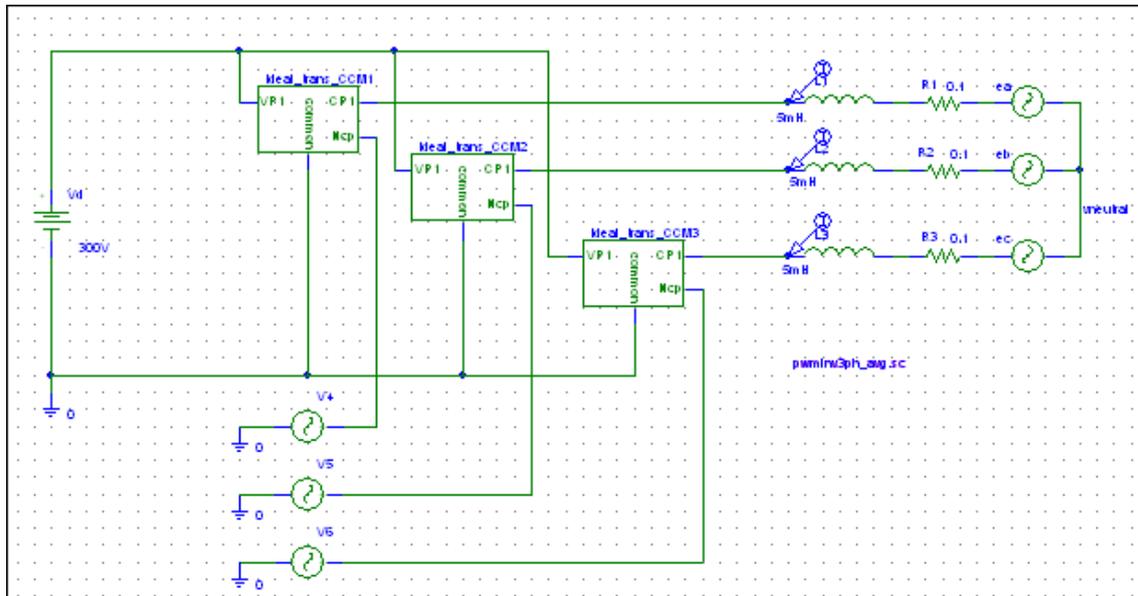
Exercises:

1. Obtain the waveforms for v_{an} (with respect to load-neutral), i_a and i_d .
2. Obtain v_{an1} by means of Fourier analysis of the v_{an} waveform. Compare v_{an1} with its pre-calculated nominal value.
3. Using the results of part 2, obtain the ripple component v_{ripple} waveform in the output voltage.

Reference: Chapter 12

Lab Experiment – 23

Average Model of Three-Phase PWM Inverter



File Name: pwminv3ph_avg.sch

Objective:

The objective of this experiment is to study the average model of a three-phase PWM inverter.

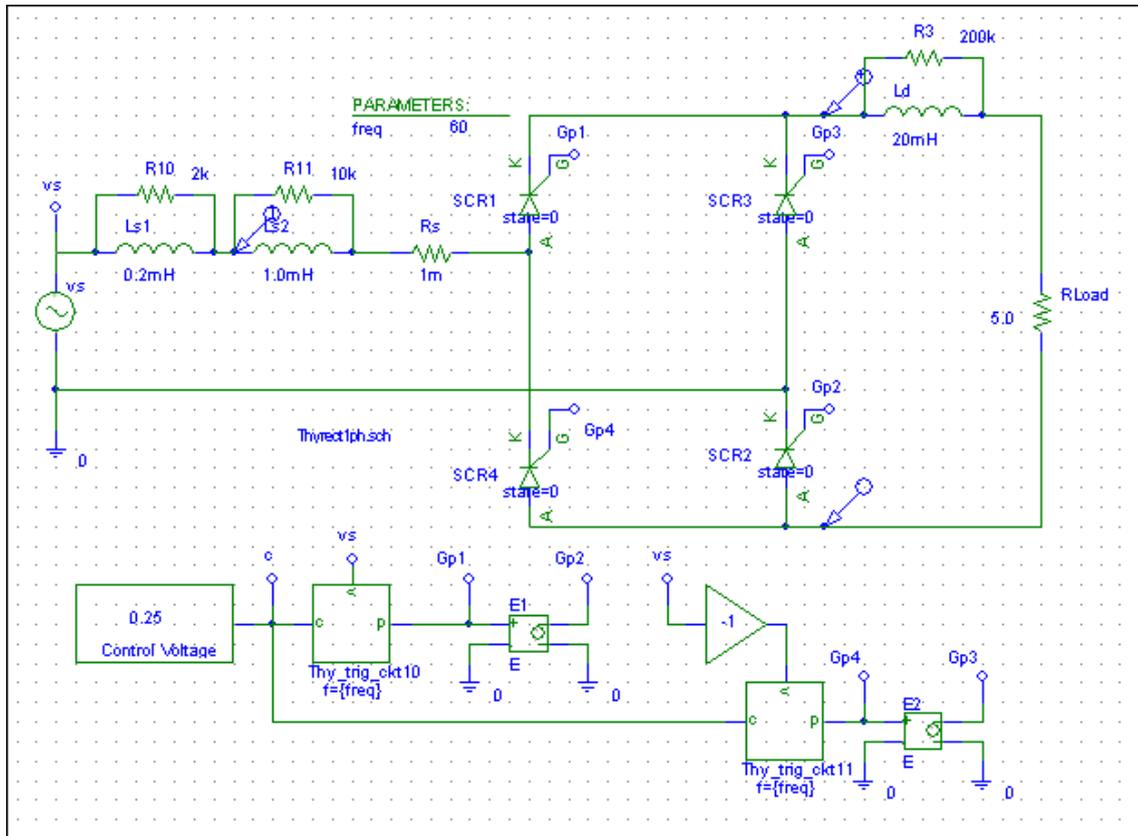
Exercises:

1. Observe the waveforms for v_{an} , i_a and i_d .
2. Append the output current waveforms of the switching model of Exercise 22.

Reference: Chapter 12

Lab Experiment – 24

Single-Phase Thyristor-Bridge Rectifier



File Name: Thyrect1ph.sch

Exercises:

- Obtain v_s , v_d and i_d waveforms.
 - Obtain v_s and i_s waveforms.
 - Obtain v_M and i_s waveforms.
- From the plots, obtain the commutation interval u and the dc-side current at the start of the commutation.
- By means of Fourier analysis of i_s , calculate its harmonic components as a ratio of I_{s1} .

4. Calculate I_s , %THD in the input current, the input displacement power factor and the input power factor.
5. Obtain the average dc voltage V_d . Verify that

$$V_d = 0.9 V_s \cos\alpha - \frac{2\omega L_s}{\pi} I_d.$$

Where first use the average value of i_d for I_d and then its value at the start of the commutation interval as calculated in Problem 2.

Reference: Chapter 13