

Power Electronics Laboratory

User Manual

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Engineering**

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Rev E

SAFETY WARNING

Before using this laboratory, read, understand and follow the Safety Precautions mentioned inside this manual.

This is an educational laboratory where high-voltage terminals and large current-carrying components and circuits are exposed for ease of measurements. Therefore, regardless of the voltage and current levels, these should be treated as high voltages and high currents, and the safety precautions mentioned in the manual must be followed.

Contents

<u>Exp. #</u>	<u>Title</u>	<u>Page</u>
	Safety Precautions	3
1.	Laboratory and Power-pole Board Familiarization	6
2.	Buck Converter	16
3.	Switching Characteristic of MOSFET and Diode	20
4.	Boost Converter	23
5.	Buck-Boost Converter	26
6.	Voltage-Mode Control	30
7.	Peak Current Mode Control	36
8.	Flyback Converter	41
9.	Forward Converter	45
	Appendix	49

SAFETY PRECAUTIONS

1. Why is safety important?

Attention and adherence to safety considerations is even more important in a power electronics laboratory than is required in any other undergraduate electrical engineering laboratories. Power electronic circuits can involve voltages of several hundred volts and currents of several tens of amperes. By comparison the voltages in many teaching laboratories rarely exceed 20V and the currents hardly ever exceed a few hundred milliamps.

In order to minimize the potential hazards, we will use dc power supplies that never exceed voltages above 40-50V and will have maximum current ratings of 5A or less. However in spite of this precaution, power electronics circuits on which the student will work may involve substantially larger voltages (up to hundreds of volts) due to the presence of large inductances in the circuits and the rapid switching on and off of amperes of current in the inductances. For example a boost converter can have an output voltage that can theoretically go to infinite values if it is operating without load. Moreover the currents in portions of some converter circuits may be many times larger than the currents supplied by the dc supplies powering the converter circuits. A simple buck converter is an example of a power electronics circuit in which the output current may be much larger than the input dc supply current

2. Potential problems presented by Power Electronic circuits

- Electrical shock may take a life.
- Exploding components (especially electrolytic capacitors) and arcing circuits can cause blindness and severe burns.
- Burning components and arcing can lead to fire.

3. Safety precautions to minimize these hazards

3.1 General Precautions

- Be calm and relaxed, while working in Lab.
- When working with voltages over 40V or with currents over 10A, there must be at least two people in the lab at all times.
- Keep the work area neat and clean.
- No paper lying on table or nearby circuits.
- Always wear safety glasses when working with other than signal-level power.

- Use rubber door mats to insulate yourself from ground, when working in the Lab.
- Be sure about the locations of fire extinguishers and first aid kits in lab.
- A switch should be included in each supply circuit so that when opened, these switches will de-energize the entire setup. Place these switches so that you can reach them quickly in case of emergency, and without reaching across hot or high voltage components.

3.2 Precautions to be taken when preparing a circuit

- Use only isolated power sources (either isolated power supplies or AC power through isolation power transformers). This helps in using a grounded oscilloscope. This reduces the possibility of risk of completing a circuit through your body. This also reduces the possibility of destroying the test equipment.

3.3 Precautions to be taken before powering the circuit

- Check for all the connections of the circuit and scope connections before powering the circuit, to avoid shorting or any ground looping, that may lead to electrical shocks or damage of equipment.
- Check any connections for shorting two different voltage levels.
- Check if you have connected load at the output. **This is very important in Boost and Buck-Boost Converters and converters based on them.**
- Double check your wiring and circuit connections. It is a good idea to use a point-to-point wiring diagram to review when making these checks.

3.4 Precautions while switching ON the circuit

- Apply low voltages or low power to check proper functionality of circuits.
- Once functionality is proven, increase voltages or power, stopping at frequent levels to check for proper functioning of circuit or for any components is hot or for any electrical noise that can affect the circuit's operation.

3.5 Precautions while switching on or shutting down the circuit

- Reduce the voltage or power slowly till it comes to zero.
- Switch off all the power supplies and remove the power supply connections.

- Let the load be connected at the output for some time, so that it helps to discharge capacitor or inductor if any, completely.

3.6 Precautions while modifying the circuit

- Switch on the circuit as per the steps in section 3.5.
- Modify the connections as per your requirement.
- Again check the circuit as per steps in section 3.3, and switch ON as per steps in section 3.4.

3.7 Other Precautions

- No loose wires or metal pieces should be lying on table or near the circuit, to cause shorts and sparking.
- Avoid using long wires, that may get in your way while making adjustments or changing leads.
- Keep high voltage parts and connections out of the way from accidental touching and from any contacts to test equipment or any parts, connected to other voltage levels.
- When working with inductive circuits, reduce voltages or currents to near zero before switching open the circuits.
- BE AWARE of bracelets, rings, metal watch bands, and loose necklace (if you are wearing any of them), they conduct electricity and can cause burns. Do not wear them near an energized circuit.
- Learn CPR and keep up to date. You can save a life.
- When working with energized circuits (while operating switches, adjusting controls, adjusting test equipment), use only one hand while keeping the rest of your body away from conducting surfaces.

Experiment 1

Laboratory and Power-pole Board Familiarization

1.1 Introduction

The power electronics laboratory is built around a reconfigurable circuit board, termed the Power-pole board, along with accessory daughterboards. The details of the Power-pole board are discussed in later sections of this experiment. This first experiment will familiarize you with the laboratory equipment and Power-pole circuit board.

1.2 Laboratory Equipment

Each experiment station has the following equipment.

- Digital Oscilloscope with RS232 interface
- Function generator
- DC power supply 0-60 V - 2 A max
- ± 12 V Signal Power Supply (with DIN connector output)
- Differential voltage probe
- Power Pole circuit board and associated plug-in boards with magnetic components and daughterboards with onboard components for implementing closed loop control.
- Digital Multimeter
- Desktop computer with software for capturing oscilloscope data via RS232 port.

Note: The lab instructor will demonstrate how to use the software to capture oscilloscope waveforms. Students should bring floppy disks or flash drives to download the captured waveforms or data for use in their lab reports.

This equipment will be used to set up the circuits and to perform most measurements. The laboratory will also have several miscellaneous components including power resistors, magnetics boards, hookup wire, etc. as needed for specific experiments.

1.3 Power-pole Board Familiarization

The main feature of the Power-pole Board is the reconfigurable power-pole consisting of two MOSFETs and two diodes. The drive circuits for the MOSFETs are incorporated on the board, and so are the various protection circuits for over current and over voltage. PWM signals to control the MOSFETs can be generated onboard or supplied from an external source. The power-pole can be configured to work in various topologies using three magnetics boards (BB board for

buck, boost and buck-boost converters, Flyback board for flyback converter, and Forward board for forward converter) which plug into the Power-pole Board. In addition, there is an option of doing frequency analysis of each topology by injecting a small-signal sinusoidal control voltage. The board can also be operated in voltage/current feedback mode using an external control circuit mounted on a daughter board which plugs into the Power-pole Board.

The basic block diagram of the Power-pole Board is shown in Fig. 1.1 and the actual board is shown in Fig. 1.2. Please note that the locations of the various components on the board are indicated in Table 1.1.

1.3.1 Power-pole

The power-pole consists of MOSFETs Q10 and Q15 and diodes D10 and D15. The source of the upper MOSFET and the drain of the lower MOSFET are connected to screw terminals for external connection, and so are the anode of upper diode and the cathode of the lower diode. The voltage and current waveforms at the terminals of the MOSFETs and diodes can be observed. Table 1.2 shows the locations of test points on the power pole board.

Note:

Take care whenever you are using oscilloscope probes to measure voltage. If the measurement reference potential is different to the oscilloscope reference potential, you must use differential probe.

To observe the voltage across the upper MOSFET,

- Connect the positive and negative terminals of a differential probe to the DRAIN and SOURCE of upper MOSFET.

To observe the upper MOSFET source current,

- Connect the positive and negative terminals of a differential probe to terminals CS2 and SOURCE (D-2 in Fig. 1.2) of upper MOSFET. The current sense resistor value is 0.05Ω .

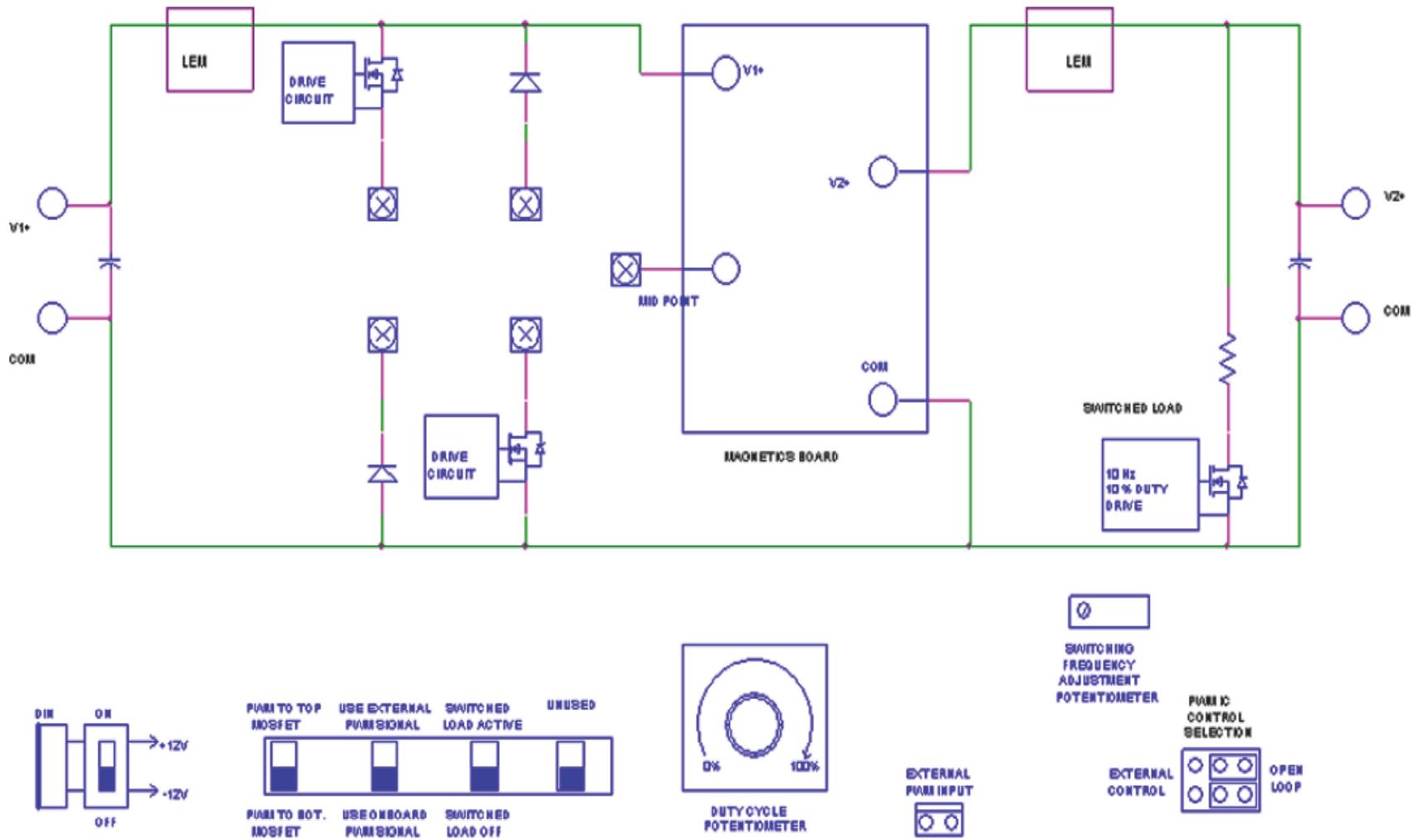


Figure 1.1: Block diagram of Power-pole Board.

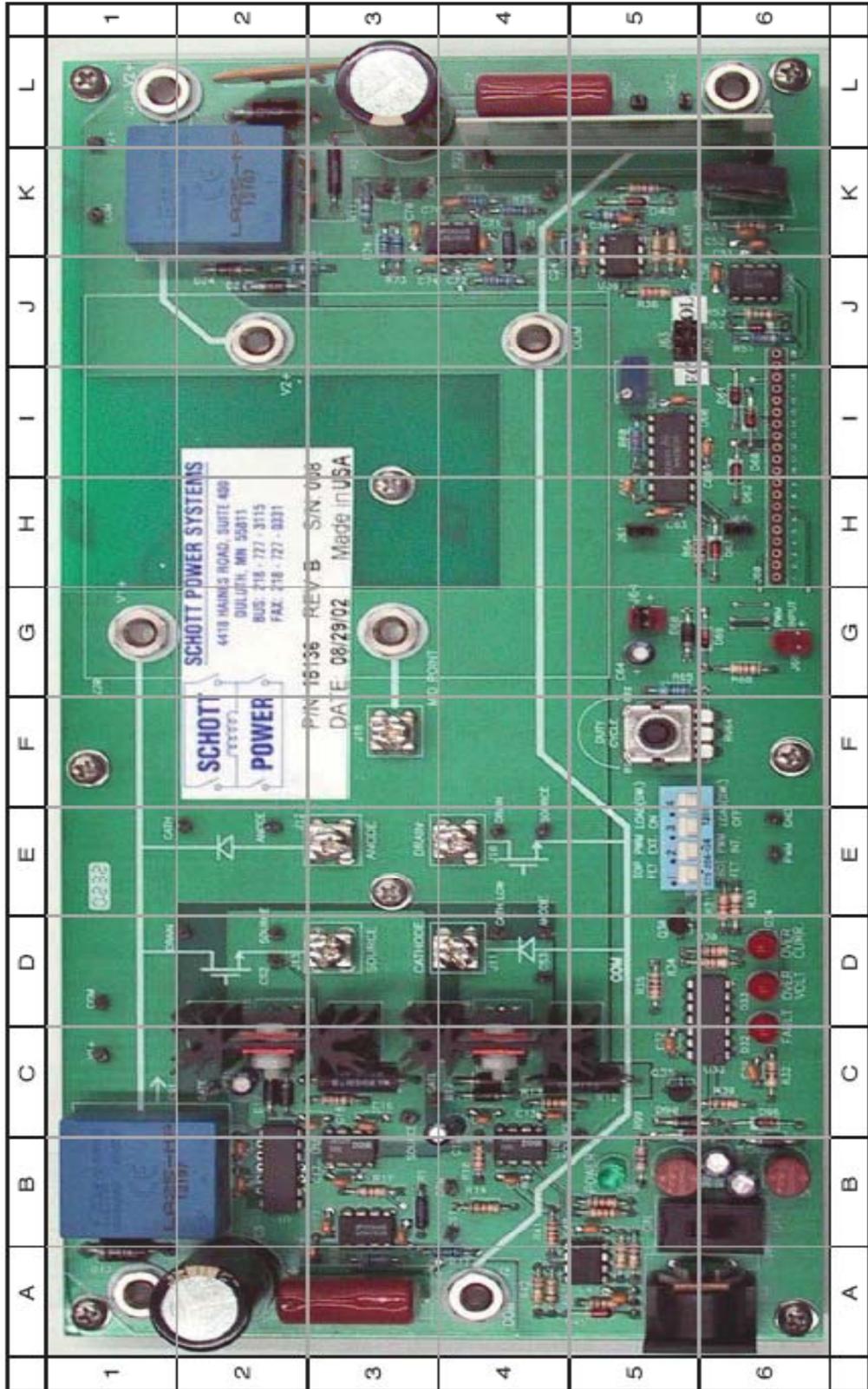


Figure 1.2: Power-Pole board.

Table 1.1: Location of components on Power-Pole board

No.	Component	Ref. Des.	Location in Fig. 1.2
1	Terminal V1+	J1	A-1
2	Terminal V2+	J21	L-1
3	Terminal COM (input)	J2	A-4
4	Terminal COM (output)	J22	L-6
5	DIN connector for ± 12 V signal supply	J90	A-5
6	Signal supply switch	S90	B-6
7	Signal supply +12 V fuse	F90	B-5
8	Signal supply -12 V fuse	F95	B-6
9	Signal supply LED	D99	B-5
10	Fault LED	D32	D-6
11	Over voltage LED	D33	D-6
12	Over current LED	D34	D-6
13	Upper MOSFET , diode and heat sink assembly	Q15, D15	C-2
14	Lower MOSFET , diode and heat sink assembly	Q10, D10	C-4
15	Screw terminal for upper MOSFET source	J13	D-3
16	Screw terminal for lower diode cathode	J11	D-4
17	Screw terminal for upper diode anode	J12	E-3
18	Screw terminal for lower MOSFET drain	J10	E-4
19	Screw terminal for Mid-point	J18	F-3
20	Magnetics Board plug-in space	J20	H-3
21	PWM Controller UC3824	U60	I-5
22	Duty ratio pot RV64	RV64	F-5
23	Switching frequency adjustment pot RV60	RV60	I-5
24	External PWM signal input terminal	J68	G-6
25	Selector Switch Bank	S30	E-5
26	Daughter board connector	J60	H-6
27	Switched load	R22	K-5
28	Resettable Fuse	F21	L-2
29	Control selection jumpers	J62, J63	J-5
30	Ramp select jumper	J61	H-5
31	Current limit jumper	J65	H-6
32	Small-signal ac analysis selection jumper	J64	G-5
33	Input current sensor (LEM)	CS1	B-1
34	Output current sensor (LEM)	CS5	K-2

Table 1.2: Test Point Details and Location on Power-pole Board

No.	Test Point	Description of Test Point	Location in Fig. 1.2
1	V1+	Terminal V1+	C-1
2	V2+	Terminal V2+	K-1
3	CS1	Input current	B-4
4	CS2	Upper MOSFET source current	D-2
5	CS3	Lower diode or MOSFET source current	D-4
6	CS4	Output Capacitor Current	K-3
7	CS5	Output current	K-4
8	CS LOAD 1	Switched Load Voltage +ve	L-5
9	CS LOAD 2	Switched Load Voltage -ve	L-5
10	PWM	PWM Signal	E-6
11	DRAIN (upper MOSFET)	Upper MOSFET drain	D-2
11	SOURCE (upper MOSFET)	Upper MOSFET source	D-2
12	DRAIN (lower MOSFET)	Lower MOSFET drain	E-4
12	SOURCE (lower MOSFET)	Lower MOSFET source	E-4
13	ANODE (upper diode)	Upper diode anode	E-2
13	CATHODE (upper diode)	Upper diode cathode	E-2
14	ANODE (lower diode)	Lower diode anode	D-4
14	CATHODE (lower diode)	Lower diode cathode	D-4
15	GATE (upper MOSFET)	Gate of upper MOSFET	C-2
16	GATE (lower MOSFET)	Gate of lower MOSFET	C-4

To observe the voltage across the lower MOSFET ,

- Connect an oscilloscope probe to the DRAIN and its ground to the SOURCE (E-4 in Fig. 1.2) of the lower MOSFET.

To observe the lower MOSFET source current,

- Connect an oscilloscope probe to terminal CS3 and its ground to the SOURCE (E-4 in Fig. 1.2) of the lower MOSFET. The current sense resistor value is 0.05Ω . The same test points also measure the lower diode current if that is included in the circuit.

To observe the voltage across the upper diode,

- Connect the positive and negative terminals of a differential probe to terminal CATH and ANODE (E-2 in Fig. 1.2) of the upper diode.

To observe the voltage across the lower diode,

- Connect an oscilloscope probe to CATHLOW and its ground to the ANODE of the lower diode (D-4 in Fig. 1.2).

1.3.2 Magnetics Boards

To build various converters using the Power-pole Board , three plug in boards are provided:

1. BB Board (Fig. 1.3(a)): For buck, boost and buck-boost converters
2. Flyback Board (Fig. 1.3(b)): For flyback converter
3. Forward Board (Fig. 1.3(c)): For forward converter

How to use these boards will be described in the subsequent experiments.

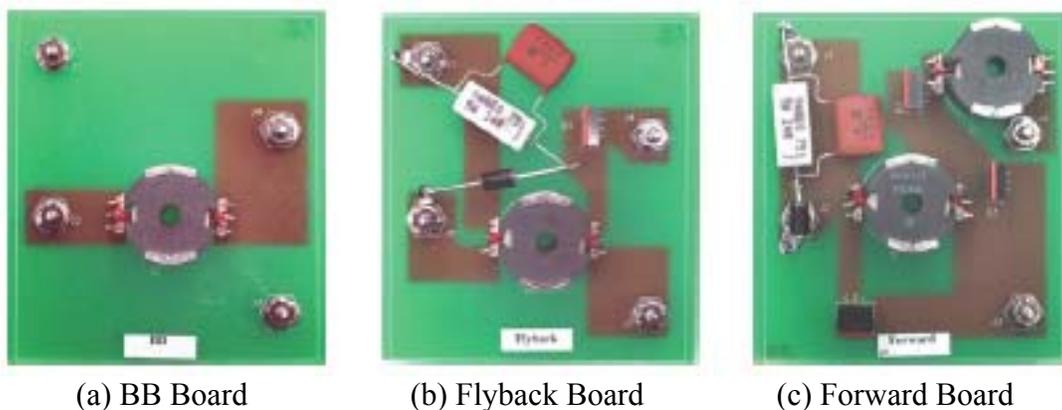


Figure 1.3: Magnetics boards.

1.3.3 Signal Supply

± 12 volts signal supply is required for the MOSFET drive circuits and also the measurement and protection circuits. This is obtained from a wall-mounted isolated power supply, which plugs into the DIN connector J90 (A-5 in Fig. 1.2). Switch S90 (B-6 in Fig. 1.2) controls the signal power to the board. Each time a fault occurs, turn off and turn on this switch to reset the board. The green LED D99 (B-5 in Fig. 1.2) indicates if the +12 V signal supply is available to the board. Fuses F90 (B-5 in Fig. 1.2) and F95 (B-6 in Fig. 1.2) provide protection for the +12 V and -12 V supplies respectively.

1.3.4 Load

Any external load is to be connected across terminals V2+ and COM (L-1 and L-6 in Fig. 1.2). An onboard switched load is provided to facilitate the observation of the transient response of any converter built using the power-pole. Thus it is possible to periodically switch in and out a 20 Ω load (K-4 to K-6 in Fig. 1.2). The frequency and duty ratio of this load is fixed at 10 Hz and 10%.

To select the switched load,

- Put switch 3 of selector switch bank S30 (E-5 in Fig. 1.2) to the top position (Load (SW) ON).

In order to observe the switched load current,

- Connect the positive and negative terminals of a differential probe to CSLOAD1 and CSLOAD2 (L-5 in Fig. 1.2). This measures the voltage across the 20 Ω resistor.
- Switched load current is the measured voltage divided by 20.

1.3.5 Input/Output Voltage Measurement

Test points for input/output voltage measurements are provided on the Power-pole Board. For input voltage measurement,

- Connect the oscilloscope probe to test point V1+(C-1 in Fig. 1.2) and its ground to COM (D-1 in Fig. 1.2).

For output voltage measurement,

- Connect the oscilloscope probe to test point V2+ (K-1 in Fig. 1.2) and its ground to COM (L-1 in Fig. 1.2).

1.3.6 Current Measurement

LEM current sensors (B-1, K-2 in Fig. 1.2) are provided to measure the input and output currents. The input current sensor is located after the input filter capacitor, and the output current sensor is located before the output filter capacitor. Calibration of the current sensors is such that for 1A current flowing through each, the output is 0.5 V. These signals are amplified by a factor of 2 and are brought out to the daughter board connector J60, for use in feedback current control. Currents through the MOSFETs and output capacitor are measured using current sense resistors. Refer to Table 1.2 for details of the various current measurement test points.

To measure input current,

- Connect oscilloscope probe to CS1 (B-1 in Fig. 1.2) and its ground to COM (D-1 in Fig. 1.2).

To measure output current,

- Connect oscilloscope probe to CS5 (K-4 in Fig. 1.2) and its ground to COM (L-1 in Fig. 1.2) .

To measure output capacitor ripple current,

- Connect oscilloscope probe to CS4 (K-3 in Fig. 1.2) and its ground to COM. The current sense resistor value is 0.1 Ω .

1.3.7 MOSFET Drive Circuit

The power-pole MOSFETs are driven by high side drivers IR2127. These drivers have in-built overcurrent protection using a current-sense resistor for each MOSFET (see locations C-3 and C-5 in Fig. 1.2). The voltage across these sense resistors can be observed using test points provided on the board.

To see the upper MOSFET current,

- Connect the positive and negative terminals of a differential probe to CS2 and SOURCE of upper MOSFET .

To see the lower MOSFET current,

- Connect an oscilloscope probe to CS3 and its ground to SOURCE of lower MOSFET .
Note: The lower diode current can also be observed using test point CS3. However the upper diode current cannot be observed.

1.3.8 PWM Signal Generation

PWM signals required for the MOSFETs can be generated using the on-board PWM controller UC3824 (I-5 in Fig. 1.2). There is also an option to supply PWM signals from an external source.

To use the onboard PWM,

- Put switch 2 of the selector switch bank S30 (E-5 in Fig. 1.2) to its bottom position (PWM INT.).

To use external PWM,

- Put switch 2 of the selector switch bank S30 to its top position (PWM EXT.).
- Connect the external PWM signal to the terminal J68 (G-6 in Fig. 1.2).

While using the onboard PWM for operation of the power-pole in open-loop, the duty ratio can be controlled using pot RV64 (F-5 in Fig. 1.2). The duty ratio can be varied from 4% to 98%. The frequency of the PWM can be adjusted using the trim pot RV60 (I-5 in Fig. 1.2). There is a provision for providing an external ramp to the UC3824 IC. This is useful for peak current mode control. For this, remove jumper J61 (H-5 in Fig. 1.2) and use the RAMP pin on daughter board connector J60.

1.3.9 Frequency Analysis

Frequency analysis of any converter built using the power-pole can be done by injecting a low voltage sinusoidal signal at jumper J64 (G-5 in Fig. 1.2). To do this,

- Remove jumper J64.
- Connect the small signal sinusoidal source at the jumper terminal J64.

Note: J64 is to be shorted in all other modes of operation.

1.3.10 Power-pole Board in Feedback Control Mode

The power-pole board can be operated in either open or closed loop and is selected by jumpers J62 and J63 (J-5 in Fig. 1.2). For open loop operation,

- Keep J62 and J63 in the righthand positions.

Closed loop operation will be described in the relevant experiment.

Experiment 2

Buck Converter

2.1 Objective

The objective of this experiment is to study the characteristics of a buck converter. The circuit will be operated under continuous current mode (CCM) and open loop conditions (no feedback). Our main goal will be to compare the theoretical results with the experimental results. Simulation results can be obtained by performing Experiment No. 4 in PSpice based Power Electronics Laboratory User Manual.

2.2 Preparing the Setup

Make the connections on the power-pole board as shown in Fig. 2.1 to use the upper MOSFET and the lower diode.

- Use the magnetics board BB board for the buck converter circuit. The inductor is 100 μ H.
- Use a variable load resistor (RL) as a load.
- Use onboard PWM signals.
- Connect the ± 12 signal supply at the DIN connector. Signal supply switch S90 should be OFF.

2.3 Checks before powering the circuit

- Check the circuit connections as per the schematics.
- Have your circuit checked by your Lab Instructor.

2.4 Powering the Circuit

- Switch ON the signal supply. Check for green LED.
- Adjust the duty ratio to 50%.
- Adjust the switching frequency to 100kHz.
- Apply input voltage V_d of 24 volts at terminals V1+ and COM.

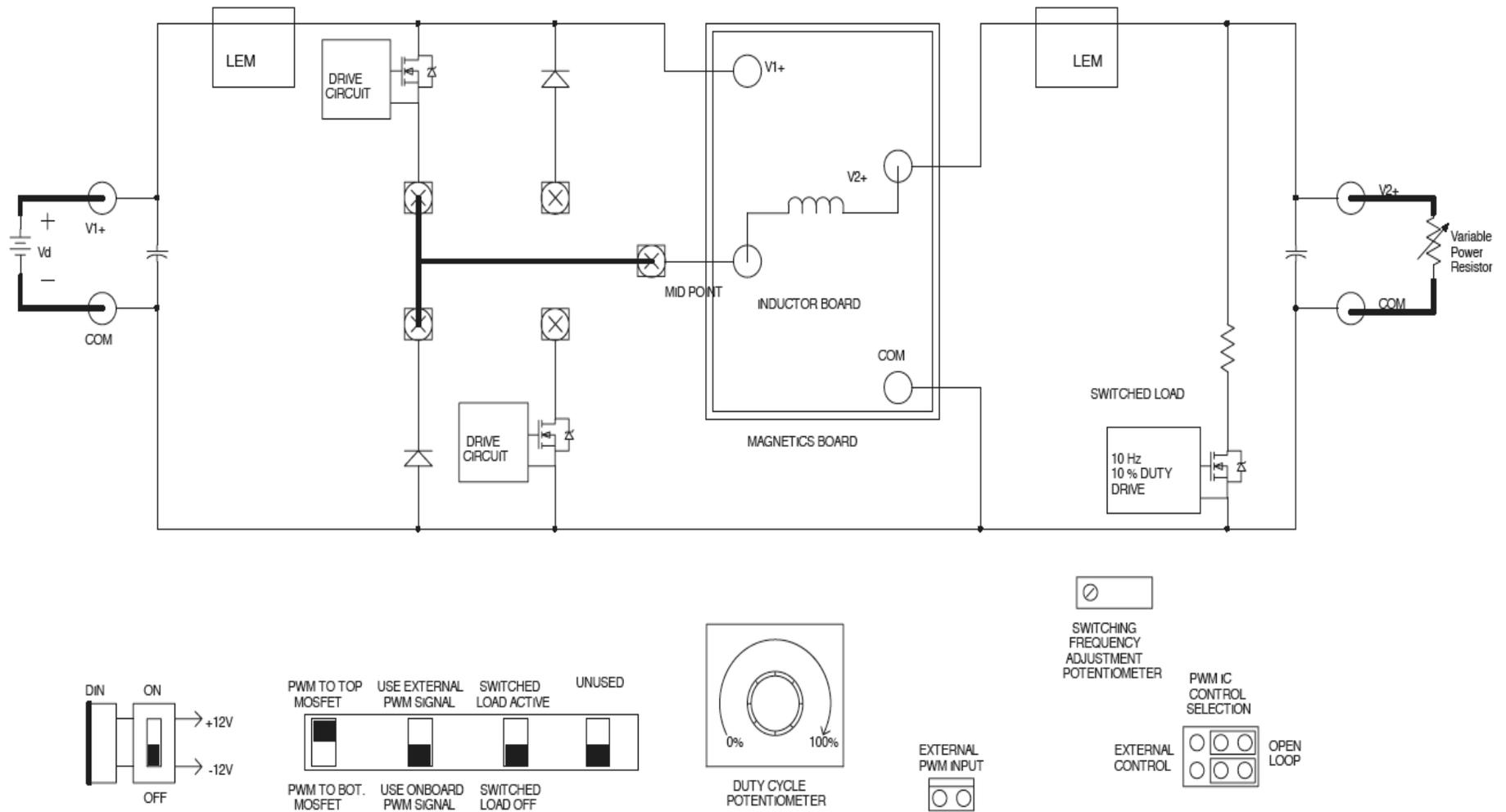


Figure 2.1: Schematic of Buck Converter

2.5 Measurement and Waveforms

Take the following measurements,

2.5.1 Varying Duty Ratio

- Set the duty ratio at 50%, switching frequency at 100 kHz and $RL = 10\Omega$.
- Observe and make a copy of the output voltage and voltage across the diode.
- Vary the duty ratio from 10 % to 90 % (in steps of 10%).
- Measure the average output voltage for the corresponding duty ratio.
- Calculate the theoretical average output voltage for the corresponding duty ratios.

2.5.2 Varying Switching Frequency

- Set the duty ratio to 50 %.
- Measure the peak-peak output ripple voltage and the peak-peak ripple in inductor current.
- Repeat the above procedure for different switching frequencies (40 kHz , 60 kHz, 80 kHz). Make sure that output voltage (V_2) is maintained at 12V.
- Observe and make a copy of the inductor current (CS5) and capacitor current (CS4) waveforms at 40kHz and at 100kHz

2.5.3 Varying Load

- Set the switching frequency at 100kHz and duty ratio at 50%.
- Set the load resistance $RL = 10\Omega$.
- Increase the load resistance and observe the inductor current waveform.
- Keep increasing the load resistance, until the buck converter enters discontinuous current mode operation. Note down the average inductor current value and make a copy of the inductor current waveform when the converter starts entering discontinuous current mode of operation.

2.5.4 Determining Efficiency

Determine the efficiency of the buck converter at frequencies of 40 kHz and 100 kHz.

- Set duty ratio at 50%.
- Set load resistance $R_L=10\Omega$.
- Measure the average output voltage V_{2+} .
- Measure the average output current I_o .
- Measure the average input voltage V_d .
- Measure the average input current I_i .
- Calculate the efficiency of the buck converter for the above two frequencies.

2.6 Lab Report

The lab report should have a brief abstract detailing what has been done in the experiment. The remaining part of the report should consist of the information asked below along with any discussion you feel is necessary.

1. Attach a graph output voltage (V_{2+}) versus duty ratio using data obtained in section 2.5.1. Also plot the theoretically calculated results on the same graph. Compare the two plots and comment about how the buck converter works as a variable dc step down transformer. Enclose output voltage & voltage across diode waveforms for duty ratio 50%
2. Attach a copy of the inductor current ($CS5$) and the capacitor current ($CS4$) waveforms obtained in section 2.5.2. Explain the relation between the two currents. Comment on the ripple in the inductor current for the two frequencies.
3. Plot the peak-peak ripple in the output voltage versus switching frequency using data obtained in section 2.5.2. Plot the theoretical results on the same graph. Compare the two plots. Comment on why you were asked to maintain the average output voltage constant.
4. Attach a copy of the inductor current waveforms obtained in section 2.5.3. Compare the theoretically calculated R_{crit} with the observed value.
5. Comment on the difference in efficiency results obtained for two switching frequencies.

Experiment 3

Switching Characteristic of MOSFET and Diode using Power-Pole Board

3.1 Objective

The objective of this experiment is to study the switching characteristics of power MOSFETs and power diodes using a buck converter. The circuit will be operated in open loop conditions (no feedback). Our main goal is to understand the switching behavior of these two power devices.

3.2 Preparing the Setup

Construct the buck converter circuit as shown in Fig. 3.1 to use the upper MOSFET and lower diode.

- Use the BB magnetics board. The inductor is 100 μ H.
- Use a variable load resistor as a load.
- Connect ± 12 V the signal supply to the DIN connector. Signal supply switch S90 should be OFF.

3.3 Checks Before Powering The Circuit

- Check the circuit connections as per the schematic.
- have your circuit checked by your Lab Instructor

3.4 Powering the Circuit

- Switch ON the signal supply. Check for green LED.
- Adjust the duty ratio to 50%.
- Set the switching frequency of 100kHz.
- Set $R_L = 12\Omega$.
- Apply input voltage V_d of 24 volts.

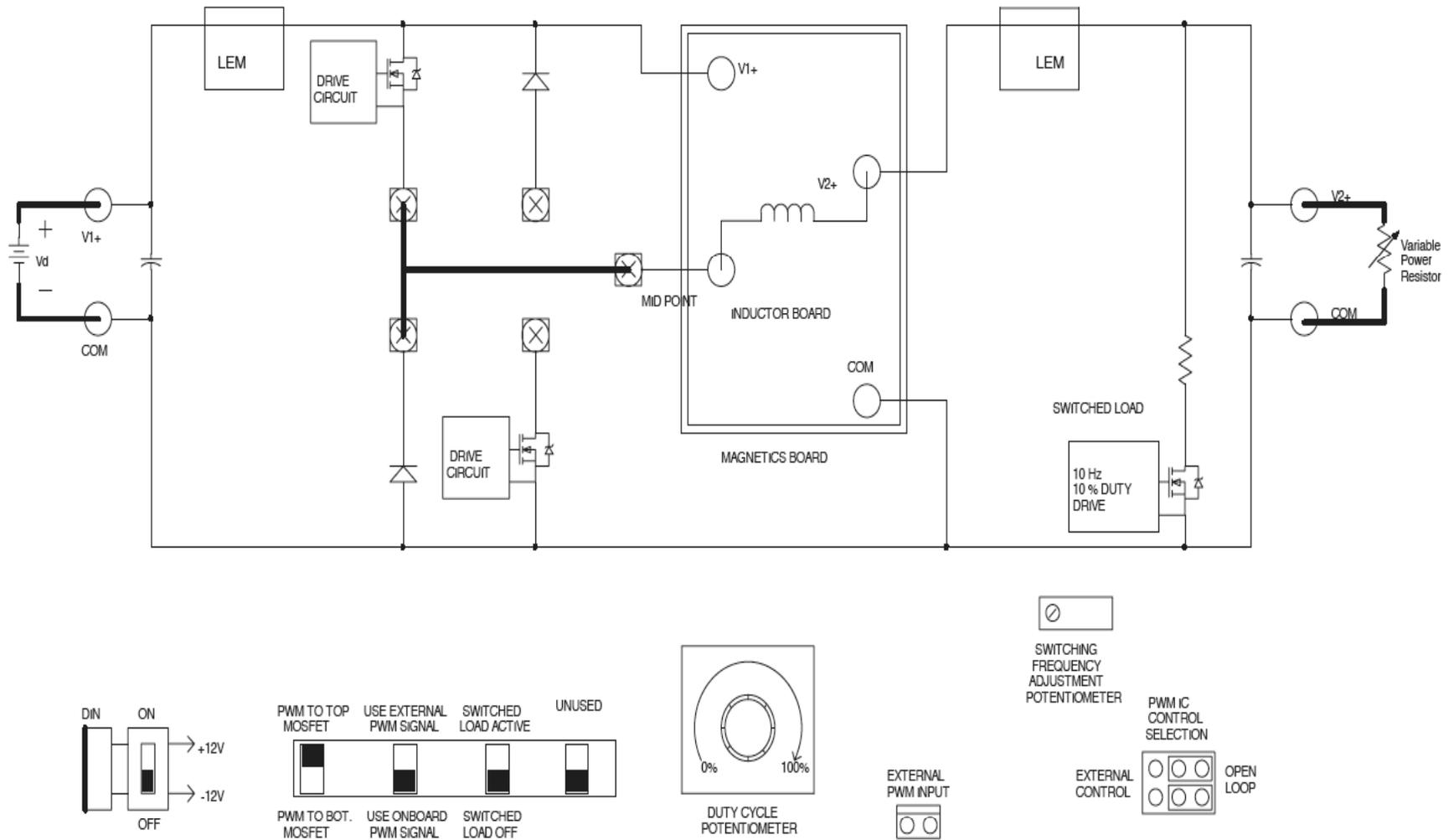


Figure 3.1: Schematic of Buck Converter

3.5 Measurement and Waveforms

1. Observe and make a copy of the Anode-Cathode diode voltage V_{AK} using a differential probe and the diode current using CS3. Adjust the time base to show the switching details during turn-ON and turn-OFF.
2. Measure the forward voltage drop across the diode V_{FM} .
3. Observe and make a copy of the Drain-Source Mosfet voltage V_{DS} using a differential probe and Mosfet current CS1. Adjust the time base to show the switching details during turn-ON and turn-OFF.
4. Measure the voltage drop across the Mosfet during turn-ON period and estimate the $r_{ds(ON)}$ of the Mosfet. (Note: the differential probe might have an offset, adjust your measurement based on this offset value.)
5. Measure the average load current I_o , and the duty cycle of operation.

3.6 Exercises:

1. Attach the waveforms for turn-ON and turn-OFF of the diode showing the switching details by expanding the time base.
2. Calculate the conduction loss of the diode using eqn. 2A-1 in the book and the measurements from step 2 of section 3.5.
3. Attach the waveforms for turn-ON and turn-OFF the Mosfet showing the switching details by expanding the time base.
4. Estimate the $r_{ds(ON)}$ of the Mosfet from step 4 of section 3.5 and compare with the datasheet of Mosfet IRF640N.
5. Calculate the conduction loss of the Mosfet using eqn. 2-3 in the book and the measurements from step 4 of section 3.5.
6. Using the values of conduction losses of the Mosfet and the Diode obtained through measurements, and switching losses of the Mosfet obtained through simulation (Refer to Experiment No. 2 in the PSpice-based Power Electronics Laboratory User Manual), estimate the efficiency of the converter. Compare the estimated efficiency with the efficiency obtained for the buck converter in the “Buck Converter Experiment”.

Experiment 4

Boost Converter

4.1 Objective

The objective of this experiment is to study the characteristics of a boost converter. The circuit will be operated under CCM and openloop condition. Our main goal is to compare the theoretical results with the experimental results. For PSpice Simulation refer Exp. No. 5 in PSpice based power electronics lab manual.

Note: It is important that care must be taken while doing the boost converter experiment that the load is always connected to the power-pole board. The input and output terminals in the case of the boost converter are interchanged as compared to that of the buck converter. V2+ & COM is the input and V1+ & COM is the output.

4.2 Preparing the Setup

Make the connections of the power-pole board as shown in Fig. 4.1 to use the lower MOSFET and the upper diode.

- Use the BB magnetics board for the boost circuit. The inductor is 100 μ H.
- Use a variable load resistor as a load.
- Connect the ± 12 signal supply to the DIN connector. Signal supply switch S90 should be OFF.

4.3 Checks before powering the circuit

- Check the circuit connections as per the schematics.
- Confirm that you have connected the input and output terminals correctly to source and load as shown in Fig. 4.1.
- Have your circuit checked by your Lab Instructor.

4.4 Powering the Circuit

- Switch ON the signal supply. Check for green LED.
- Set the duty ratio to its minimum 10% and $R_L=20\Omega$.
- Adjust the switching frequency to 100kHz.
- Apply input voltage V_d of 10 volts at terminals V2+ and COM.

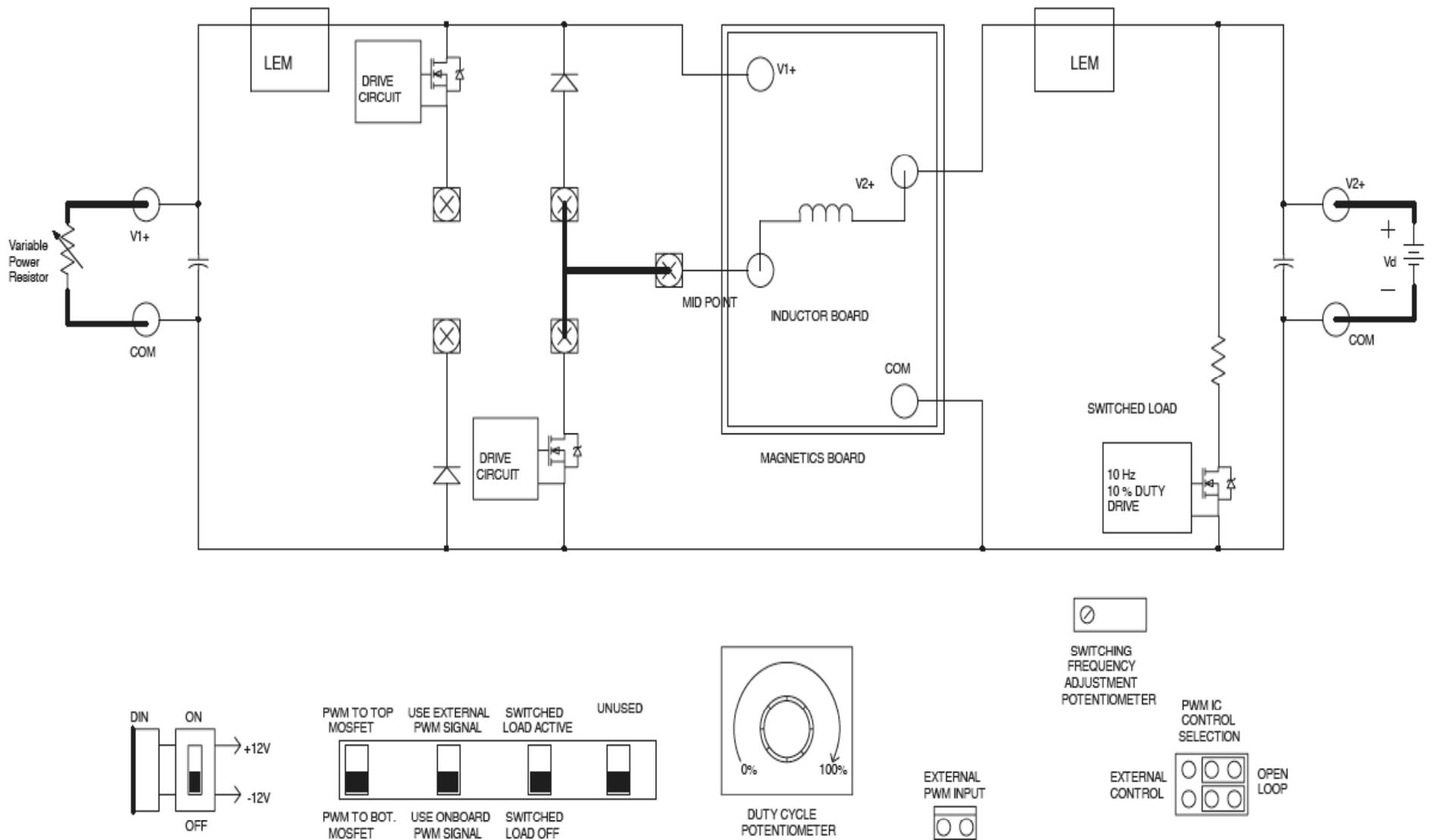


Figure 4.1: Schematic of Boost Converter

4.5 Measurements

Take the following measurements,

4.5.1 Varying Duty Ratio

- Vary the duty ratio from 10% to 60% (in steps of 10%).
- Measure the average DC load voltage (V1+) for the corresponding values of duty ratio .
- Calculate the theoretical average output voltage for the corresponding duty ratios.
- Compare the observed average output voltage results with the calculated ones.

4.5.2 Varying Switching Frequency

- Set the duty ratio to 50%, switching frequency to 100kHz, $R_L = 20\Omega$.
- Observe and make a copy of the input current (CS5) ripple waveform @100kHz.
- Measure the peak-peak input current ripple.
- Repeat the above procedure for different switching frequencies (40 kHz, 60 kHz, 80 kHz).

4.5.3 Determining efficiency

- Set the duty ratio to 50%.
- Adjust the load resistance value to 20Ω .
- Measure the efficiency at switching frequencies of 40kHz and 100 kHz.

4.6 Lab Report

The lab report should consist of the information asked below, along with any discussion you feel is necessary.

1. Attach a graph of duty ratio versus output voltage using the data obtained in section 4.5.1. Also plot the theoretically calculated results on the same graph. Compare the two plots.
2. Attach a copy of the inductor current (CS5) waveform obtained in section 4.5.2. Plot the experimental and theoretically estimated input ripple current on the same graph. Compare the two graphs and comment.
3. Plot efficiency versus frequency using the data obtained in section 4.5.3. Comment on the results you obtain.

Experiment 5

Buck-Boost Converter

5.1 Objective

The objective of the experiment is to study the characteristics of the buck-boost converter. The circuit will be operated under CCM and openloop conditions. Our main goal is to compare the theoretical results with the experimental results. For PSpice Simulation refer Exp. No. 6 in PSpice based power electronics lab manual

Note: It is important that care must be taken while doing the buck-boost converter experiment that the load is always connected to the power-pole board. The input and output terminals in the case of the buck-boost converter are different as compared to that of the buck or boost converters.

5.2 Preparing the Setup

Make the connections for the power-pole board as shown in Fig. 5.1

- Use the BB magnetics board for the buck-boost converter circuit. The inductor value is 100 μ H.
- Use a variable load resistor as a load.
- Connect the ± 12 signal supply to the DIN connector. Signal supply switch S90 should be OFF.

5.3 Checks before powering the circuit

- Check the circuit connections as shown in Fig. 5.1.
- Confirm that you have connected the input and output terminals correctly to source and load as shown in Fig. 5.1.
- Have your circuit checked by your Lab Instructor.

5.4 Powering the Circuit

- Switch ON the signal supply. Check for green LED.
- Set the duty ratio to its minimum.
- Set $R_L = 20\Omega$.
- Adjust the switching frequency to 100 kHz.
- Apply input voltage V_d of 10 volts at the terminals V1+ and V2+.

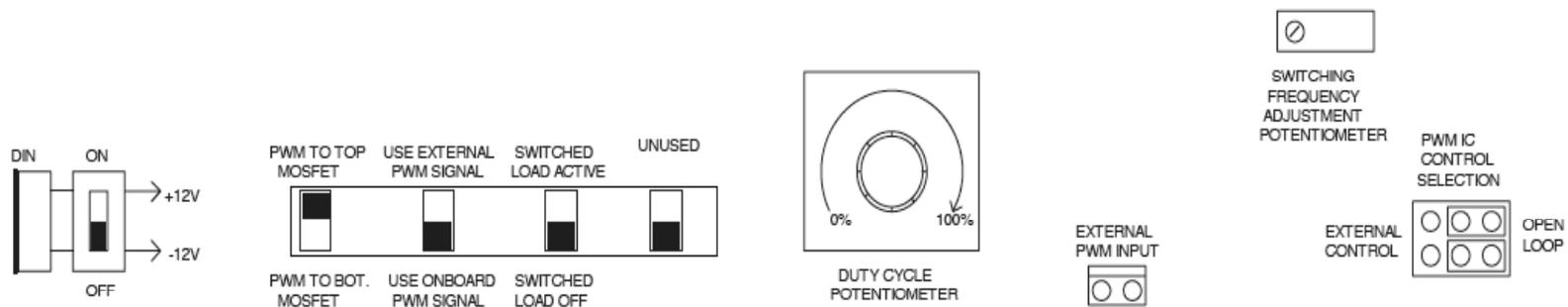
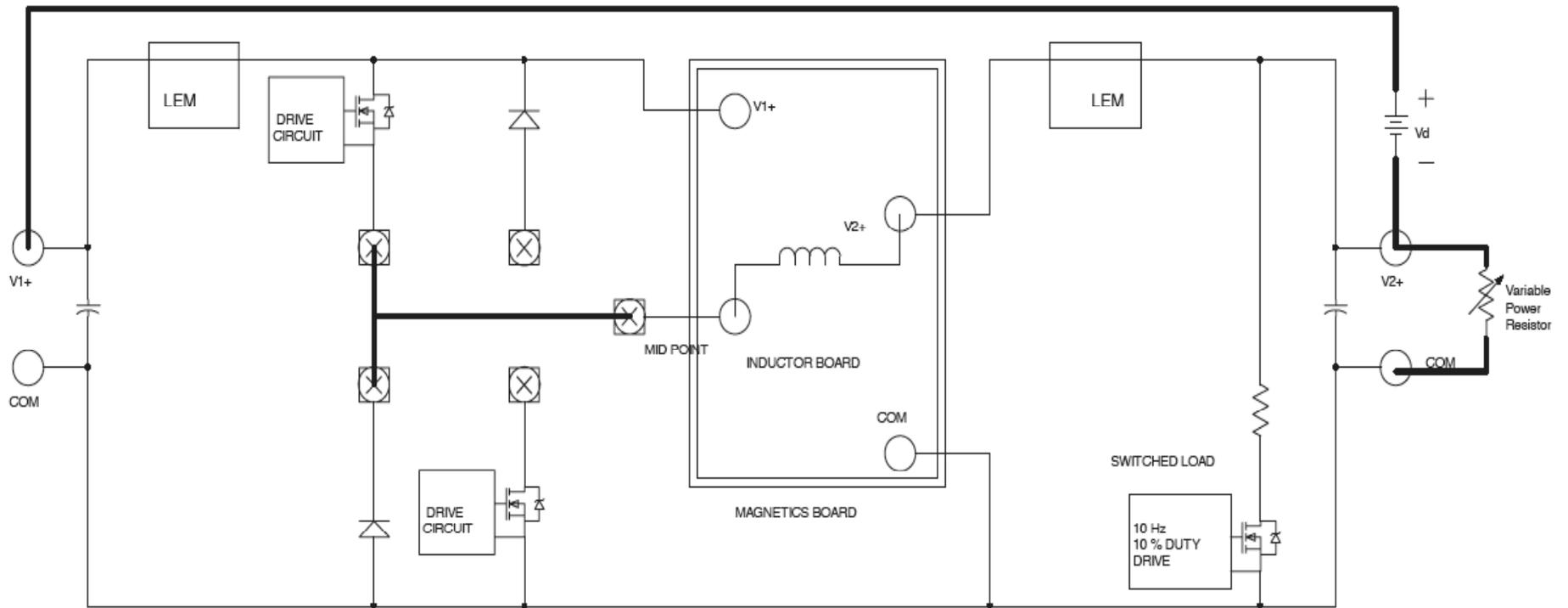


Figure 5.1: Schematic of Buck-Boost Converter

5.5 Measurements

Take the following measurements,

5.5.1 Varying Duty Ratio

- Vary the duty ratio from 10% to 70% (in steps of 10%).
- Measure the average DC load voltage (V_{2+}) for the corresponding values of duty ratio.
- Calculate the average theoretical DC output voltage for the corresponding duty ratios.
- Compare the observed average output voltage results with the calculated ones.

5.5.2 Varying Switching Frequency

- Set the duty ratio to 60%, switching frequency to 100kHz, $R_L = 15\Omega$.
- Observe and make the copy of the inductor current (CS5) ripple waveform @100kHz.
- Measure the peak-peak inductor current ripple.
- Repeat the above procedure for different switching frequencies 40 kHz, 60 kHz, 80 kHz.

5.5.3 Determining Efficiency

- Set the duty ratio to 60%.
- Adjust the load resistance to $R_L = 15\Omega$.
- Measure the efficiency at switching frequencies of 40 kHz and 100 kHz.

5.5.4 Varying Load

- Set the duty ratio to 40%, $R_L = 20\Omega$ and switching frequency to 40 kHz.
- Keep increasing the load resistance until the converter enters into the discontinuous conduction mode and note the value of load resistance.

5.6 Lab Report

The lab report should consist of the information asked below along with any discussion you feel is necessary.

1. Attach a graph of duty ratio versus output voltage (CS5) using the data obtained in section 5.5.1. Also plot the theoretically calculated results on the same graph. Compare the two plots.
2. Attach a copy of the inductor current (CS5) waveform obtained in section 5.5.2. Plot the experimental and theoretically estimated ripple current waveforms on the same graph. Compare the two graphs and comment.
3. Plot the efficiency versus frequency using the data obtained in section 5.5.3. Comment on the results you obtain.
4. Calculate the critical value of load resistance $R_{\text{crit,Buck-Boost}}$ at which the converter is in the border of Continuous-Discontinuous and compare with that obtained in section 5.5.4.

Experiment 6

Voltage-Mode Control

6.1 Objective

The objective of this experiment is to design a controller to operate the buck converter in voltage control mode. For this experiment, a plug-in daughter board will be used to accomplish the control objective. The small-signal transfer function $\tilde{v}_o(s)/\tilde{d}(s)$ (\tilde{d} is a small-signal perturbation in the duty cycle and \tilde{v}_o is the corresponding variation in the output voltage) must first be obtained for the buck converter. The plug-in daughter board is used to implement the voltage-mode control feedback with the required open-loop gain.

6.2 Preparing the Setup and Open-Loop Mode

Construct the buck converter circuit as shown in Fig. 6.1 using the BB magnetics board.

- Connect and turn on the $\pm 12\text{V}$ signal supply and check for green LED.
- Adjust the duty ratio to 50%.
- Adjust the switching frequency to 100kHz.
- Switch ON the switched load to active position using selector switch bank as shown in Fig. 6.2.
- Adjust the variable load resistance R_L to 10Ω .
- Have your circuit checked by your Lab Instructor.
- Apply DC supply voltage V_d to 30V.

6.3 Measurements in Open-Loop Operation

Observe and make a copy of the output voltage waveform (V_2+). Adjust the time base to show the details of the switching transients as the load is switched.

6.4 Using PSpice to find $\frac{\tilde{v}_o(s)}{\tilde{d}(s)}$

Using the schematic file “buck_conv_avg.sch” (Refer to Exp. 10 in PSpice based power electronics lab manual), perform the following experiment.

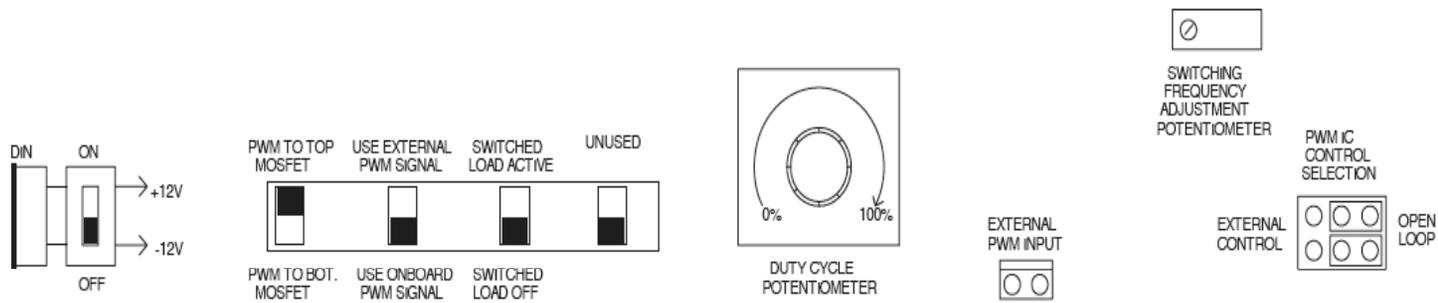
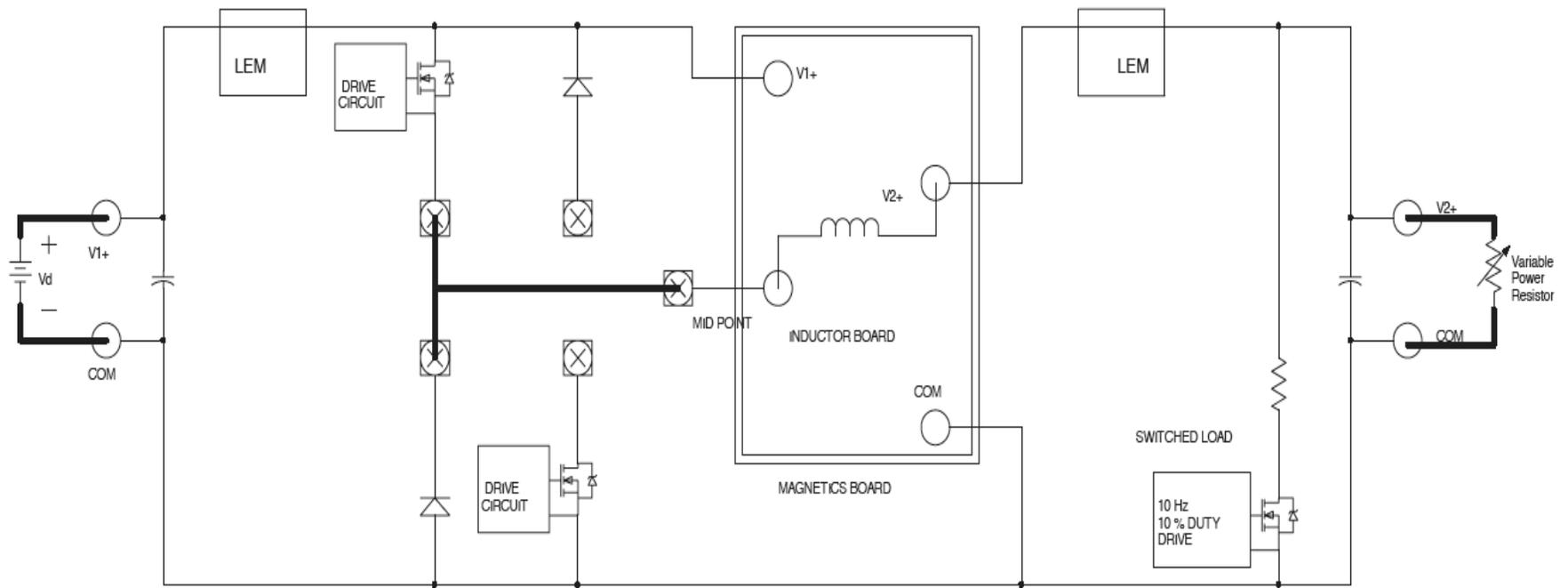


Figure 6.1: Buck Converter using Power-pole board.

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

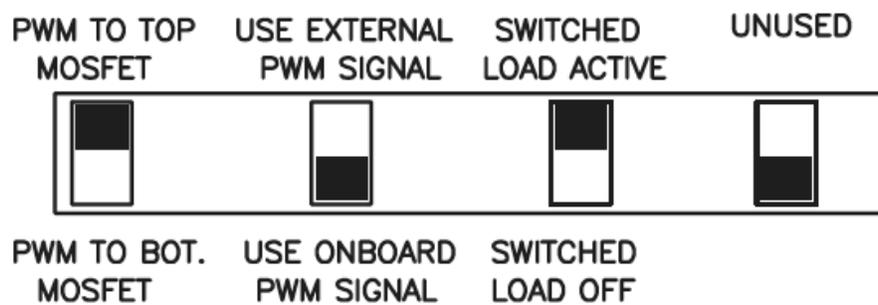
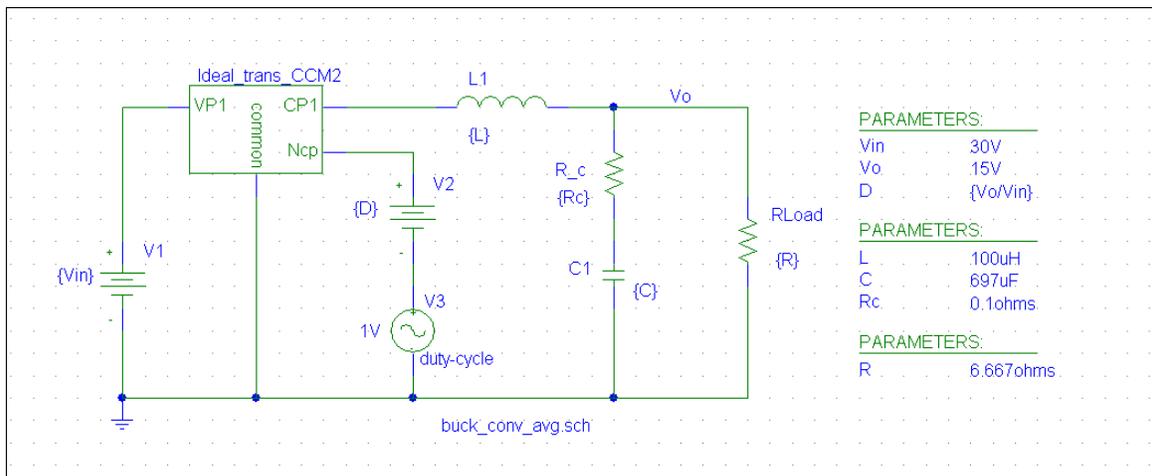


Figure 6.2: Selector switch position for switched load.

6.5 Type 3 Voltage Controller

Once you get the transfer function or the Bode-plot of the buck converter, you can design a Type-3 voltage controller. The Type-3 voltage control board has the schematic as shown in Fig. 6.3.

The values of the resistors and capacitors of the voltage control board are given in Table. 6.1

- Reference value V_{REF} can be set using the duty ratio pot.
- Reference value V_{REF} can't be set below 10V.
- For the pin details of terminal strip J60, please refer the schematic of the power-pole board.

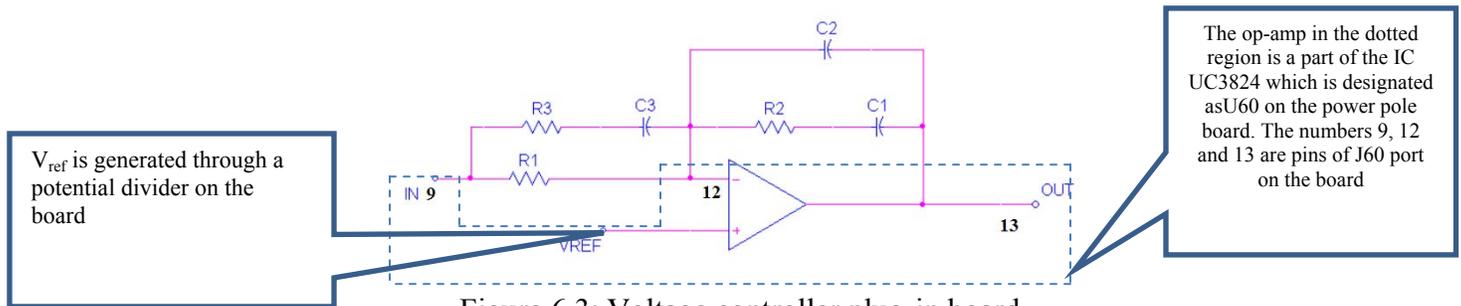


Figure 6.3: Voltage controller plug-in board.

Table 6.1: Voltage control board component values

Component	Calculated Value	Actual value used
R1	100k Ω	100k Ω
R2		20k Ω
R3		10k Ω
C1		22nF
C2		2.2nF
C3		4.7nF

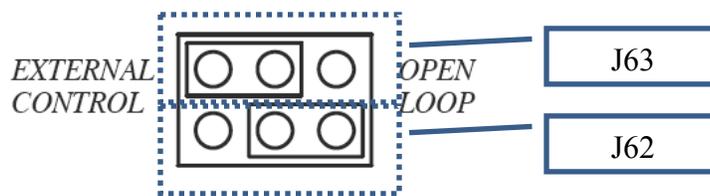


Figure 6.4: Control selection for Voltage-Mode Control plug-in board

6.6 Preparing the Setup for Voltage-Mode Control Operation

- Set the control selection jumpers J62 and J63 as shown in Fig. 6.4.
- Insert the Voltage-Mode Control plug-in board in the terminal strip 60.

- Keep $R_L = 10\Omega$.
- Switch ON the switched load to the active position using the selector switch bank as shown in Fig. 6.2.
- Turn ON $\pm 12V$ signal supply and check for green LED.
- Have your circuit checked by your Lab Instructor.
- Set V_d to 30V.
- Use the duty cycle pot RV64 to set V_{2+} to 15V.

6.7 Measurements in Voltage-Mode Control Operation

Observe and make a copy of the output voltage V_{2+} .

6.8 Lab Report

The lab report should have a brief abstract detailing what has been done in the experiment. The remaining part of the report should consist of the information asked below along with any discussion you feel is necessary.

1. Attach the Bode magnitude and phase plot of the small-signal transfer function $\frac{\tilde{v}_o(s)}{\tilde{d}(s)}$ from the results obtained in section 6.4
2. Obtain the following quantities from the Bode plot, $|G_{PS}(s)|_{f_c}$ and $\angle G_{PS}(s)|_{f_c}$ for a crossover frequency of 1kHz.
3. Calculate the needed phase boost ϕ_{boost} using the values obtained through PSpice above with a required phase margin of 60 degrees
4. Calculate the controller gain at the crossover frequency given $k_{FB} = 0.2$ and $|G_{PWM}(s)|_{f_c} = 0.556$
5. Use the K-factor method described in chapter 4 of the book to design a type 3 voltage mode controller for the buck converter i.e, determine k_c , ω_z and ω_p of the controller $G_c(s)$.
6. Determine the values of the resistors and capacitors used to implement the controller in Fig. 6.3 and substitute them in Table 6.1.

7. The controller is implemented in hardware using the values given in Table 6.1 column #3. Compare the responses of the output voltage for a step load change with and without closed loop control. Attach the waveforms obtained in steps 6.3 and 6.7.

Experiment 7

Peak Current Mode Control

7.1 Objective

In this experiment, we will be using a plug-in board to accomplish peak current mode control for a buck-boost converter. First the aspects of constant frequency peak current mode control will be explored. Then the plugin board will be used to achieve feedback voltage control of the converter. The goal is to understand how to design a peak current mode controller with voltage feedback.

7.2 Preparing setup for Open Loop Operation

- Reconstruct the buck-boost converter used in Expt. 3 as in Fig. 7.1.
- Turn on the signal power supply and set the switching frequency to 100 kHz and duty cycle such that output voltage $V_o=12$ V.
- Change the switch positions of the switch bank as shown in Fig. 7.2.
- Set V_d to 20 V and the variable power resistor to 20 Ω .

7.2.1 Measurements

- Observe the output voltage V_2+ and inductor current on the oscilloscope.
- Store the waveform.

7.3 Preparing setup for closed loop operation and measurements

7.3.1 Closed Loop Operation Without Slope Compensation

- Setup the control selection as in Fig. 7.3.
- Remove shorting link from J61 and insert the Type 2 Controller plug-in board whose circuit is shown in Fig. 7.4 into the terminal strip J60 (The pin numbers shown in the figure correspond to pin numbers on the terminal strip). This board will add the voltage feedback to the control.
- Set the duty cycle pot to minimum.
- Switch ON the main power supply and set it to 25 V.

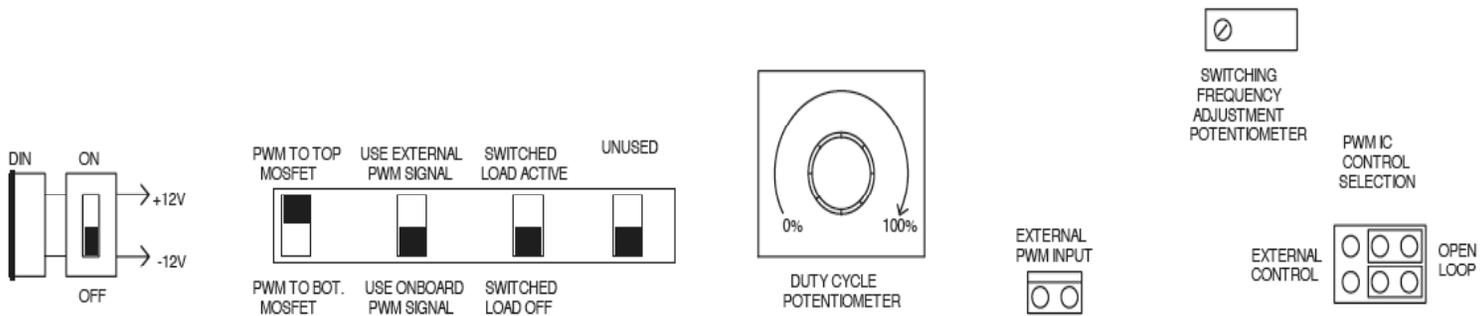
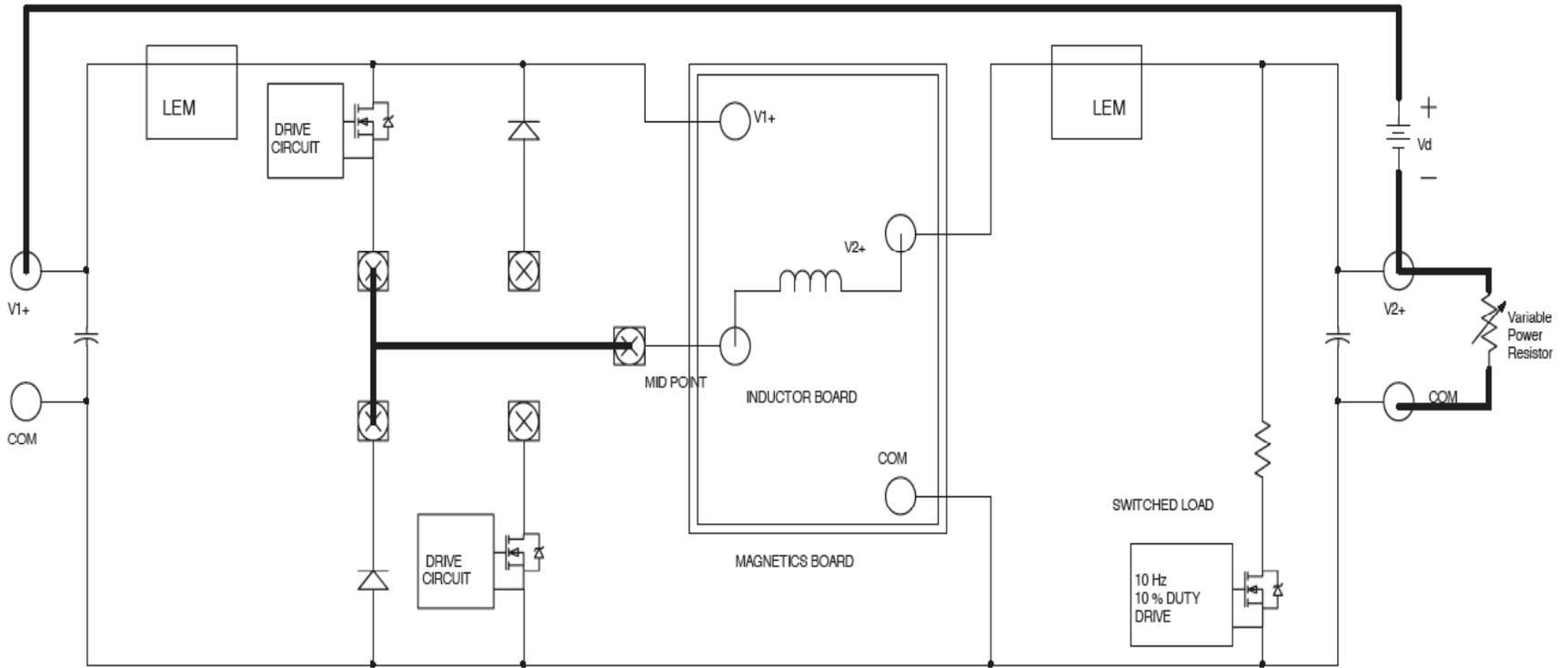


Figure 7.1: Peak Current mode controller schematic.

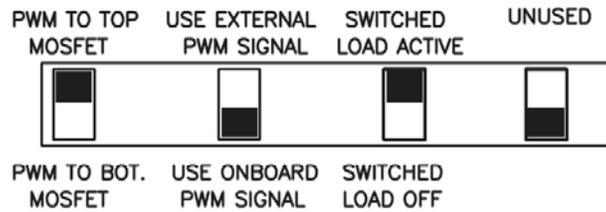


Figure 7.2: Switch positions for switched load.

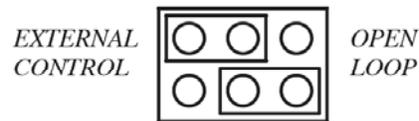


Figure 7.3: Switch Position for Closed Loop Operation

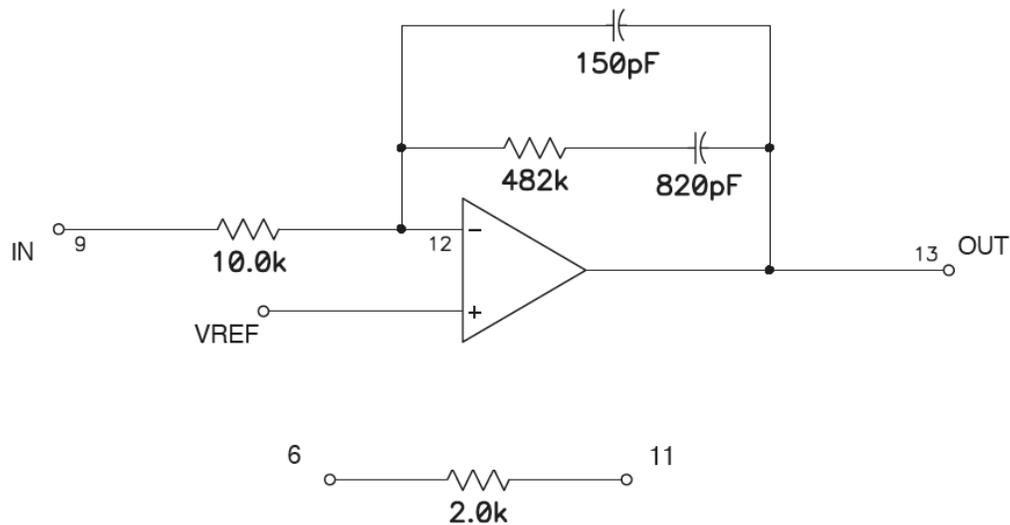


Figure 7.4: Type 2 Controller

- Change the switch positions of the switch bank as shown in Fig. 7.1.
- Switch ON the signal power supply. Ensure that main power supply is ON before signal power supply is switched ON.
- Observe the PWM and the inductor current waveforms.
- Slowly increase the reference voltage by turning the duty cycle pot clockwise. Observe the point where the inductor current starts displaying oscillatory behavior. Record the corresponding duty cycle from the scope.

- Plug in the slope compensation jumper on to J61. The slope compensation jumper circuit is shown in Fig. 7.5. Observe how the inclusion of slope compensation affects the stability of the converter.



Figure 7.5: Slope Compensation Jumper

7.3.2 Closed Loop Operation With Slope Compensation

- Ensure that the plug-in board and the slope compensation jumper are plugged in.
- Set the duty cycle pot to minimum.
- Switch ON the main power supply and set it to 15 V.
- Switch ON the signal power supply.
- Observe the PWM and the inductor current waveforms.
- Slowly increase the reference voltage by turning the duty cycle pot clockwise. Observe the point where the inductor current starts displaying oscillatory behavior. Record the corresponding duty cycle from the scope.

7.3.3 Dynamic Performance of Closed Loop System

- Ensure that the plug-in board and the slope compensation jumper are plugged in.
- Set the duty cycle pot to minimum.
- Switch on the main power supply and set it to 20 V.
- Switch on the signal power supply.
- Slowly increase the reference voltage to 12 V by turning the duty cycle pot clockwise.
- Observe the output voltage V_{2+} and the inductor current on the oscilloscope. Store the waveform.

7.4 Lab Report

The lab report should have a brief abstract detailing what has been done in the experiment. The remaining part of the report should consist of the information asked below along with any discussion you feel is necessary.

- Plot the output voltage V_o and inductor current i_L obtained in step 7.2.
- What is the maximum duty ratio stable operation of the converter in step 7.3.1? Plot the inductor current waveform for stable and unstable operation.
- What is the maximum duty ratio stable operation of the converter in step 7.3.2? Plot the inductor current waveform for stable and unstable operation.
- Explain how slope compensation affects the range of duty cycle obtainable in constant frequency peak current mode control.
- Explain why in step 7.3.1, it is important to switch on the signal power supply after turning on the main power supply.
- Plot the output voltage V_o waveforms and inductor current in closed loop operations with output voltage feedback (step 7.3.3).
- Comment on the effect of peak current controller on the operation of converter.

Experiment 8

Flyback Converter

8.1 Objective

The objective of this experiment is to study the characteristics of the flyback converter using the power-pole board in open loop control mode. Our main goal is to compare the theoretical results with the experimental results.

Note: It is important that care must be taken while doing the Flyback converter experiment that the load is always connected to the output in the power-pole board.

8.2 Preparing the Setup

Make the connections on the power-pole board as shown in Fig. 8.1 to use the lower MOSFET.

- Use the Flyback magnetics board. The turns ratio $N_1/N_2=2$
- Use a variable load resistor as a load.
- Connect the $\pm 12V$ signal supply to the DIN connector. Signal supply switch S90 should be OFF.

8.3 Checks before Powering the Circuit

- Check the circuit connections as per the schematic.
- Check that the lower MOSFET has been selected.
- Have your circuit checked by your Lab Instructor

8.4 Powering the Circuit

- Switch ON the signal supply. Check for green LED.
- Set the switching frequency to 100kHz and the duty ratio to 50%.
- Set $R_L= 10\Omega$.
- Apply input voltage V_d of 15V at terminal V1+ and COM.

8.5 Measurements

Take the following measurement,

8.5.1 Varying Duty Ratio

- Vary the duty ratio from 0% to 50% (in steps of 10%).

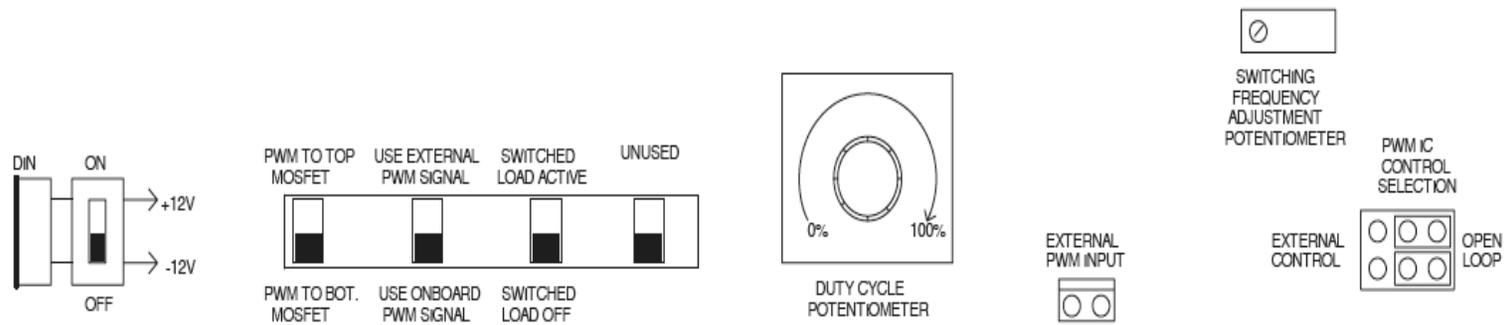
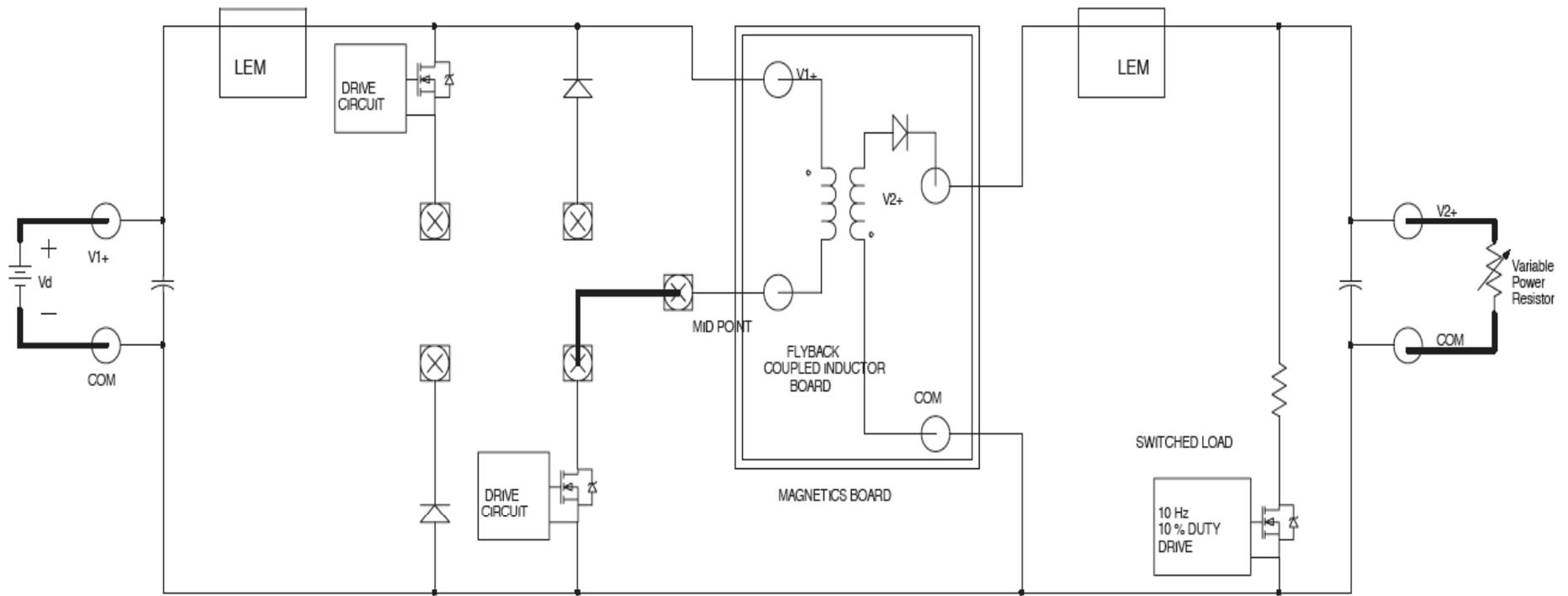


Figure 8.1: Schematic of Flyback Converter

- Measure the average output voltage (V_{2+}) for the corresponding values of duty ratios.
- Calculate the theoretical average output voltage value for the corresponding duty ratios.
- Compare the observed average output voltage results with the calculated ones.

8.5.2 Constant Duty Ratio with varying switching frequency and load

- Set the duty ratio to 40%, switching frequency to 100 kHz and $R_L = 10\Omega$
- Observe and make a copy of the voltage across the secondary side of the coupling inductor.
- Observe and make a copy of the input current (CS1) and output current (CS5) in the same graph
- Repeat the above step (make a copy of the current waveforms and not the voltage waveform) for $R_L = 7.5\Omega @ F_s = 100 \text{ kHz}$; $R_L = 10\Omega @ F_s = 40 \text{ kHz}$ and $R_L = 7.5\Omega @ F_s = 40 \text{ kHz}$

8.6 Lab Report

The lab report should consist of the information asked below along with any discussion you feel is necessary.

1. Attach a graph of duty ratio versus output voltage (V_{2+}) using data obtained in section 8.5.1. Also plot the theoretically calculated results on the same graph. Compare the two plots.
2. Attach the copy of the voltage waveform obtained in section 8.5.2. Construct the voltage across the primary side of the coupled inductor. Label the waveform, both voltage and time axis appropriately. Note: Ignore the ringing in the waveform
3. Using the voltage waveform obtained in section 8.5.2, construct the voltage across the primary side switch. Label the waveform, both voltage and time axis appropriately. You can verify your calculation by observing the waveform on the board. Note: Ignore ringing and voltage when snubber circuit is on.

4. Attach the waveforms obtained in section 8.5.2 and estimate the following: (Need to be calculated for all the four operating conditions $RL=10\Omega$ @ $F_s=100$ kHz; $RL=7.5\Omega$ @ $F_s=100$ kHz; $RL=10\Omega$ @ $F_s=40$ kHz and $RL=7.5\Omega$ @ $F_s=40$ kHz)
- Inductance as seen from the primary side L_{m1}
 - Peak to peak ripple in the flux $\Delta\phi_{p-p}$ given the number of turns in the primary is 42
 - Given the core area $A_c=93.9\text{mm}^2$ what is the value of the peak flux density \hat{B} ?

Experiment 9

Forward Converter

9.1 Objective

The objective of this experiment is to study the characteristics of the forward converter. The forward converter will be operated in open loop mode (no feedback). Our main goal is to compare the theoretical results with the experimental results.

9.2 Preparing the Setup

Make the connections on the power-pole board as shown in Fig. 9.1 to use the lower MOSFET.

- Use the Forward magnetics board. The turns ratio is 1:1:1.
- Use a variable load resistor as a load.
- Connect the $\pm 12\text{V}$ signal supply to the DIN connector. Signal supply switch S90 should be OFF.

9.3 Checks before powering the circuit

- Check the circuit connections as per Fig. 9.1
- Confirm that you have selected the lower MOSFET.
- Have your circuit checked by your Lab Instructor.

9.4 Powering the Circuit

- Switch ON the signal supply. Check for green LED.
- Set the switching to 100 kHz.
- Set the duty ratio to its minimum.
- Set $R_L = 10\Omega$.
- Apply input voltage V_d of 20 V at the terminals V1+ and COM.

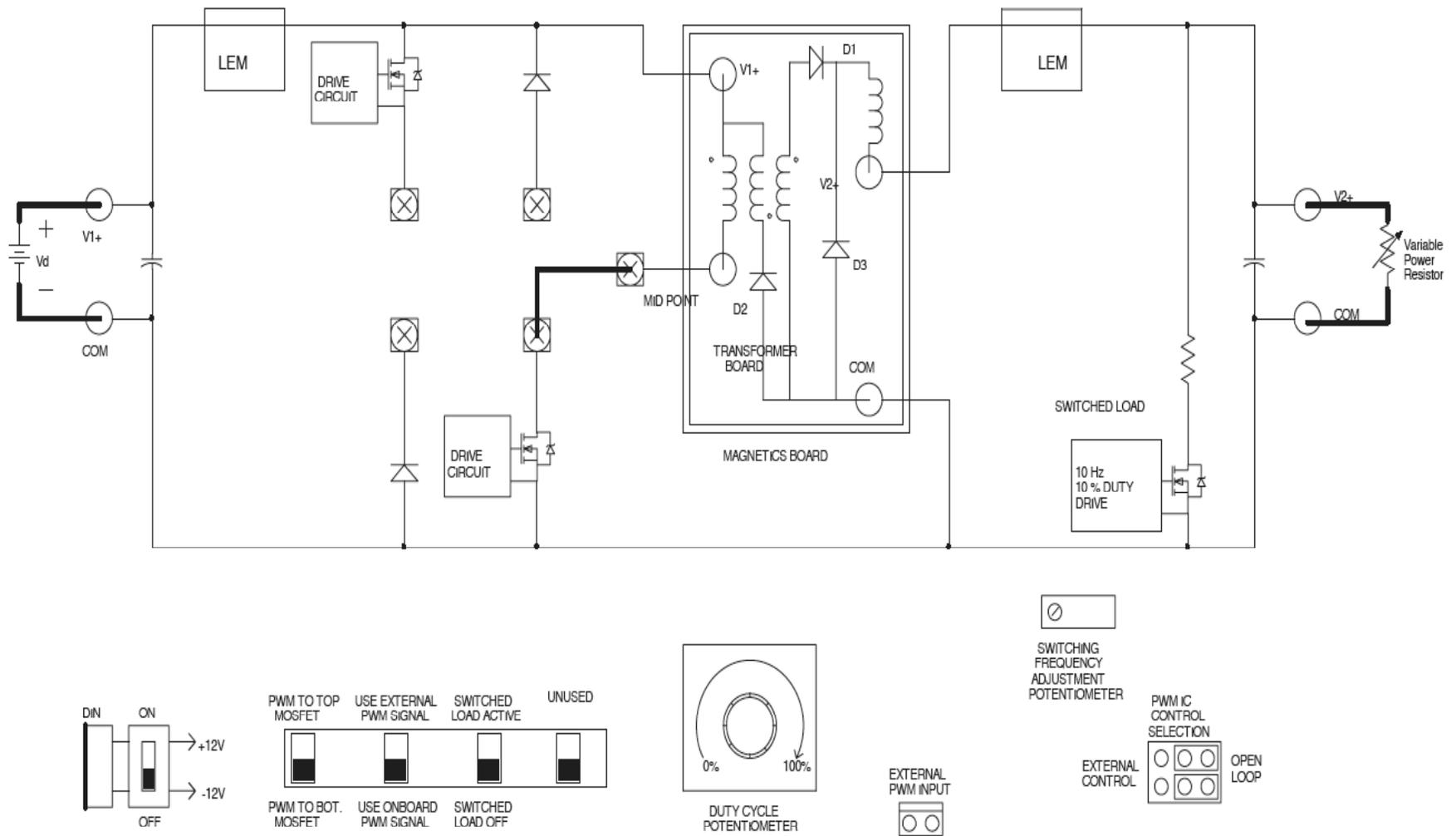


Figure 9.1: Schematic of Forward Converter

9.5 Measurements

Take following measurements,

9.5.1 Varying Duty Ratio

- Vary duty ratio from minimum to 40% (in steps of 10%).
- Measure the average output voltage (V_{2+}) for the corresponding values of duty ratio.
- Calculate the theoretical average output voltage for the corresponding duty ratios.
- Compare the observed average output voltage results with the calculated ones.

9.5.2 Constant Duty Ratio with varying switching frequency and load

- Set the duty ratio to 40%, switching frequency to 100 kHz and $R_L = 10\Omega$
- Observe and make a copy of the voltage across the switch (Mosfet)
- Observe and make a copy of the input current (CS1) and output current (CS5) in the same graph
- Repeat the above step (make a copy of the current waveforms and not the voltage waveform) for $R_L = 7.5\Omega @ F_s = 100 \text{ kHz}$; $R_L = 10\Omega @ F_s = 40 \text{ kHz}$ and $R_L = 7.5\Omega @ F_s = 40 \text{ kHz}$

9.6 Lab Report

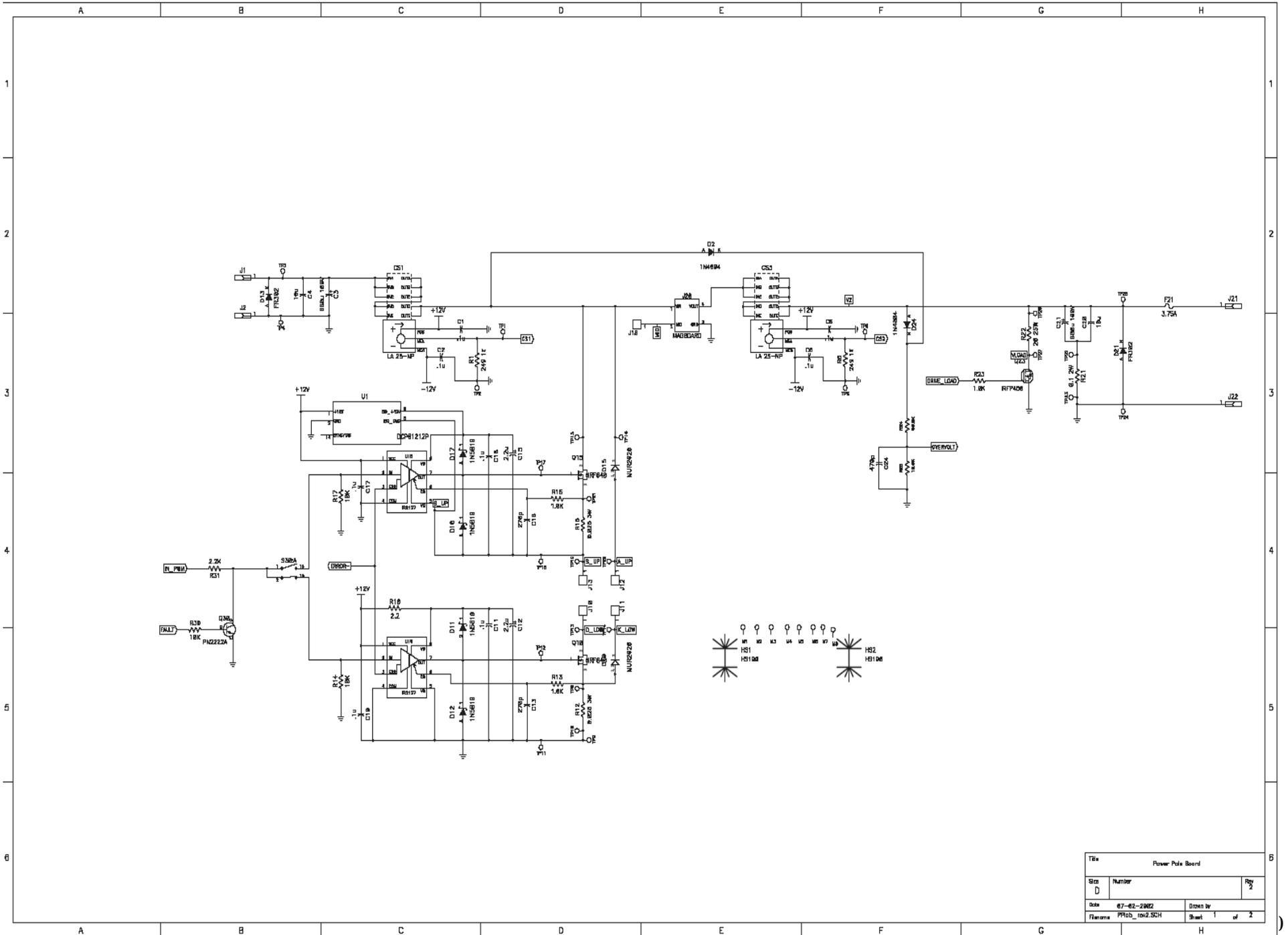
The lab report should consist of the information asked below along with any discussion you feel is necessary.

1. Attach a graph of duty ratio versus output voltage (V_{2+}) using data obtained in section 9.5.1. Also plot the theoretically estimated results on the same graph. Compare the two plots.
2. Attach a copy of the voltage waveform across the switch obtained in section 9.5.2. Estimate theoretically the same waveform and compare. (Ignore the voltage ringing due to the leakage inductance of the transformer)
3. Attach the waveforms of input current and output current obtained in section 9.5.2. Also answer the following questions:

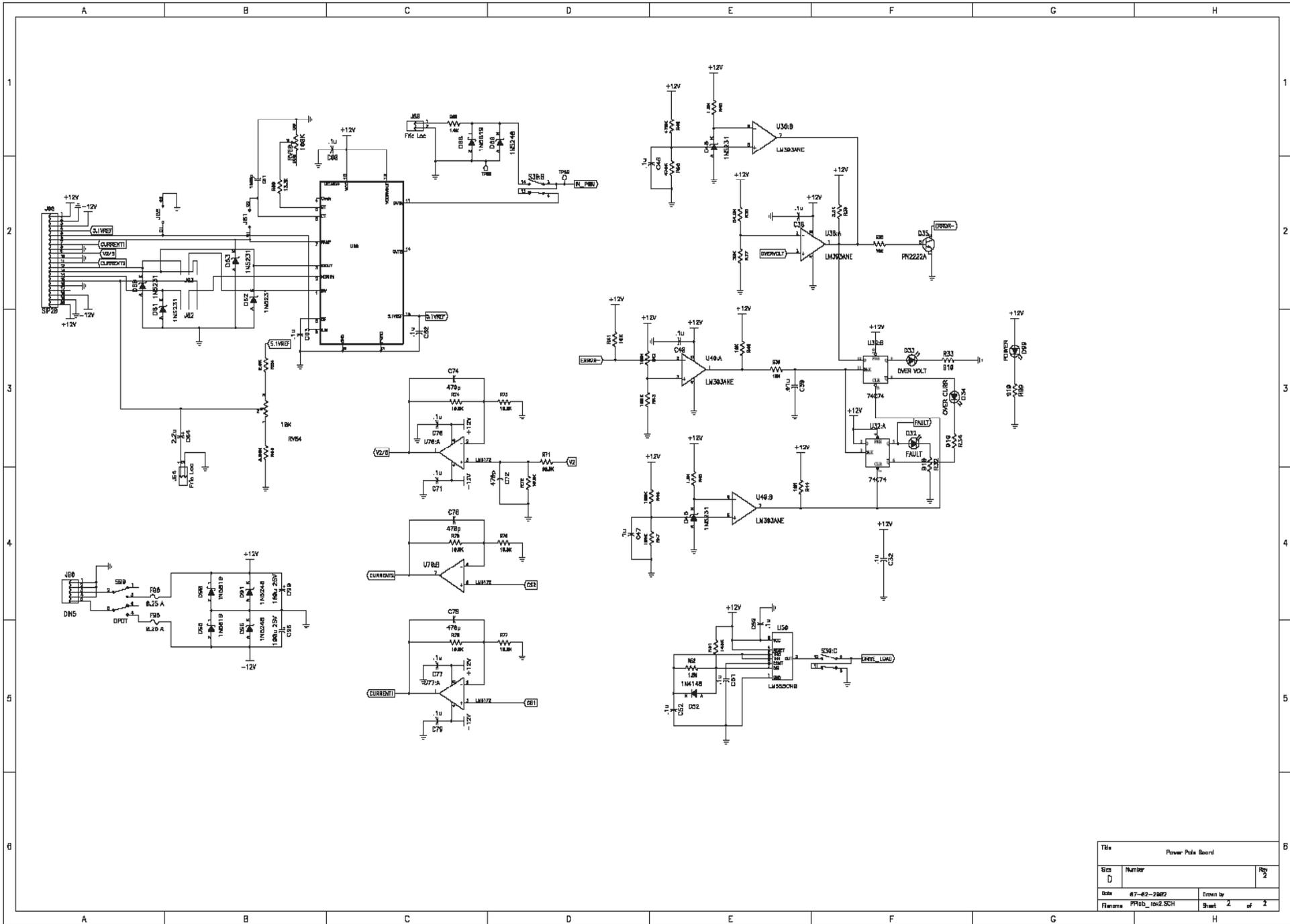
- a. Why is the input current negative for some interval?
 - b. What is the minimum value of this negative current for all four operating conditions?
 - c. Theoretically should the above value change with load? Give reasons for your answer.
4. Estimate the following: (Need to be calculated for all the four operating conditions $R_L=10\Omega$ @ $F_s=100$ kHz; $R_L=7.5\Omega$ @ $F_s=100$ kHz; $R_L=10\Omega$ @ $F_s=40$ kHz and $R_L=7.5\Omega$ @ $F_s=40$ kHz.)
- a. Output inductor value L .
 - b. Core flux as given in Fig. 8-6 in the book. Number of turns in the primary is 16 and the magnetizing inductance L_{m1} is 0.2mH. Hint: Use the minimum value of the negative current seen at the input.

APPENDIX

The detailed circuit of the power-pole is attached. It consists of two sheets.



Title		Power Pole Board	
Size	D	Number	Rev
Scale	07-02-2002	Drawn by	
Filename	PP05_Rev2.SCH	Sheet	1 of 2



Title		
Power Pda Board		
Size	Number	Rev
D		2
Date	87-02-0882	Drawn by
Filename	PF10b_10v2.SCH	Sheet 2 of 2