ECE 5610
Lab 1
Laboratory Introduction, Pulse-Width Modulation and Filter Characteristics

Objectives

1. Understand basic safety precautions when working with power electronic circuits.
2. Understand how to build experiments and take measurements using the Power-Pole board.
3. Generate a PWM signal using the Power-Pole's on-board controller.
4. Understand how to simulate power electronic circuits in PSpice.
5. Simulate a circuit with pulse-width modulation and understand the effect of a basic resonant filter.

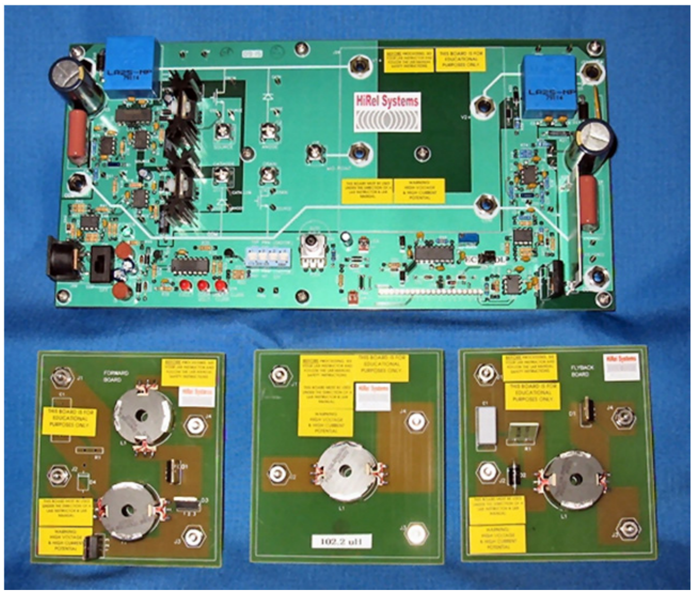


Figure 1: Power pole board (top) and the daughter boards (bottom)

Power-pole board and oscilloscope familiarization

1.1 Introduction

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-currents and over-voltages. PWM signals needed 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 magnetic daughter boards (**BB board** for the buck, boost and buck-boost converters, **Flyback board** for the flyback converter, and **Forward board** for the 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.

1.2 Board Familiarization

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.

1.2.1 Power-pole

The power-pole consists of MOSFETs Q10 and Q15 and diodes D10 and D15 (Figure 2). The source of the upper MOSFET and the drain of the lower MOSFET are connected to screw terminals for external connections, 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.

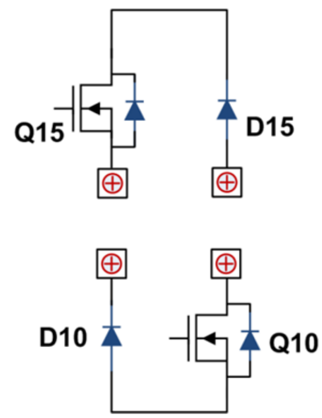


Figure 2

Note 1: The oscilloscope channels share the same signal GND. Therefore, it is recommended to take precautions while measuring two quantities having separate reference potentials. Students are advised to use the circuit connections shown in Figure 3 if you need to take two measurements simultaneously in the oscilloscope.

<u>How to observe waveforms in oscilloscope having separate reference potentials:</u>
Consider the circuit shown in Figure 3 where two waveforms are required to be measured simultaneously while their reference potentials are different. As an example, if you need to see the waveforms across MOSFET (M) and capacitor (C), connect the positive terminals of oscilloscope probes according to Figure 3. The negative terminal of any one of the oscilloscope probes should be connected to the reference terminal (Gnd) of the circuit. Now the voltage across "M" = (Ch1 – Ch2) and you can perform this calculation using the oscilloscopes internal math functions. Waveform across "C" is obtained from Ch3.

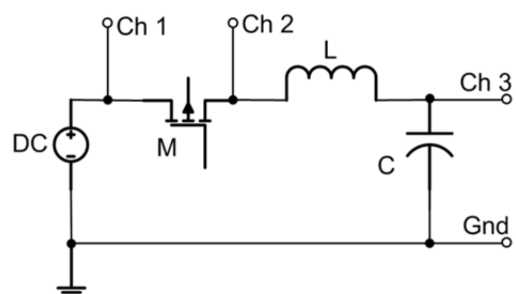


Figure 3: Observing waveforms in oscilloscope.

To observe the voltage across the upper MOSFET,

- Connect the positive and negative terminals of an **oscilloscope probe** to the *DRAIN* and *SOURCE* (D-2 in Fig. 1.2) of the upper MOSFET.

To observe the current through the upper MOSFET,

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

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 current through the lower MOSFET,

- 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 0.05 Ω. 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 an **oscilloscope probe** to terminals *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 *CATH LOW* and its ground to the *ANODE* of the lower diode (D-4 in Fig. 1.2).

Table 1.1: Locations 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

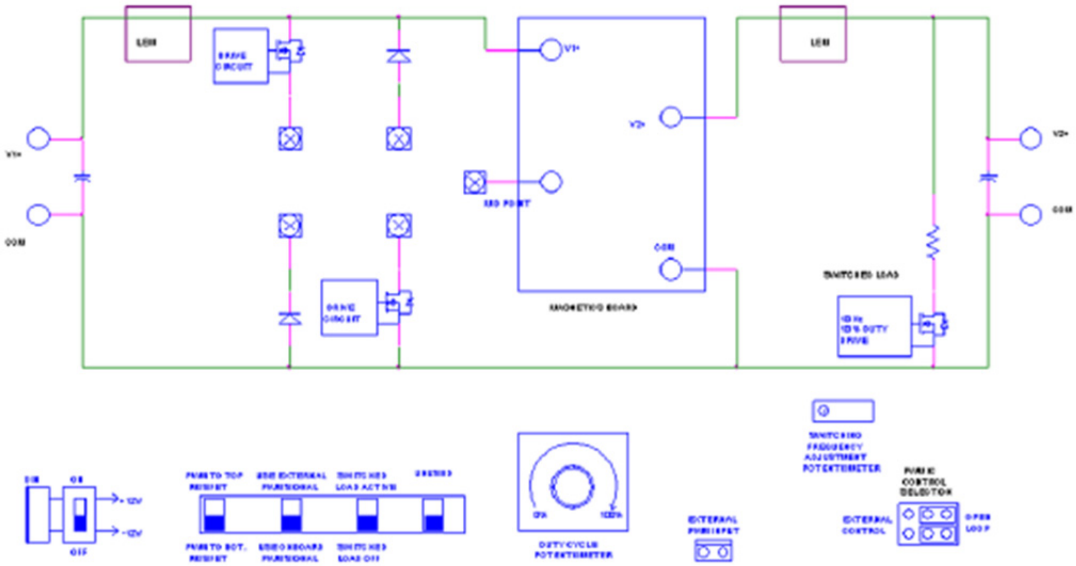


Figure 1.1: Block Diagram of Power-pole Board

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 lower 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

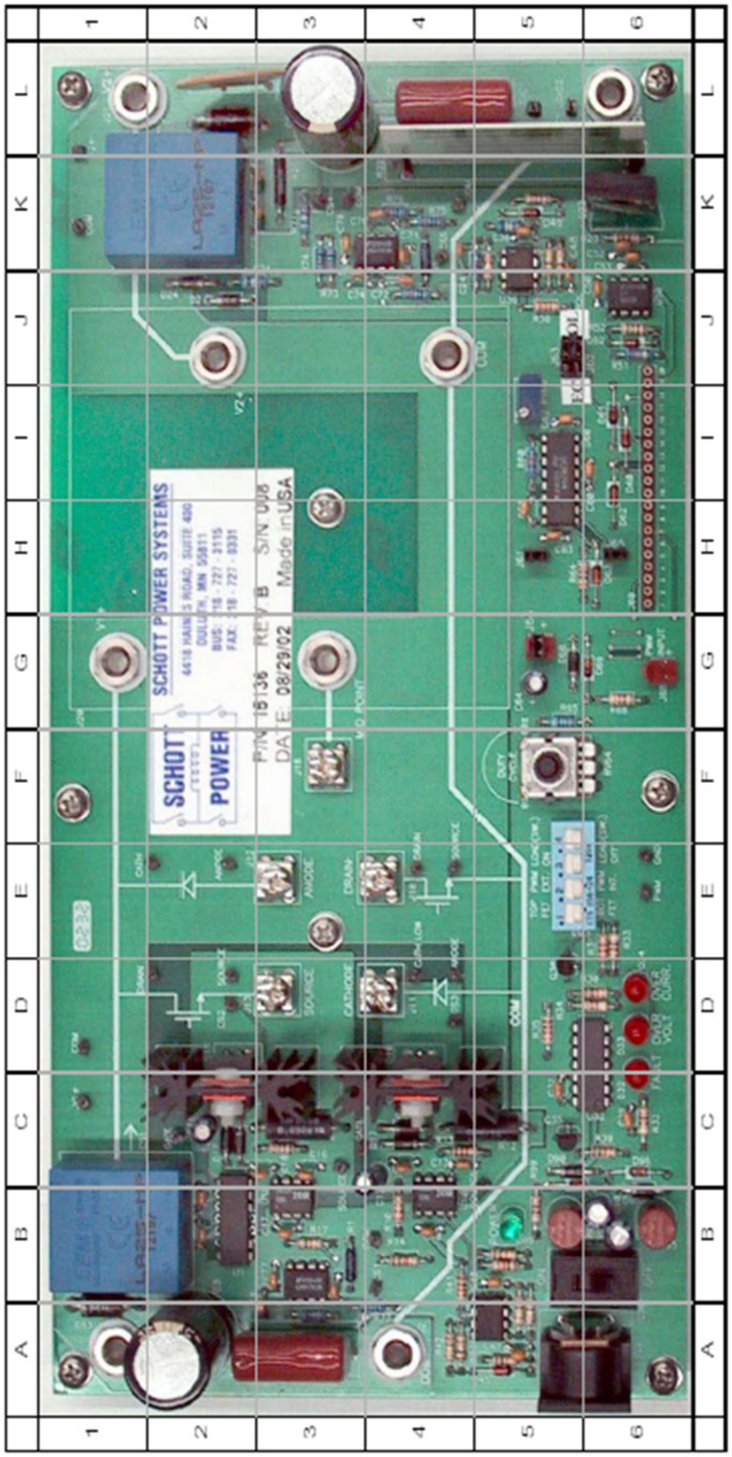
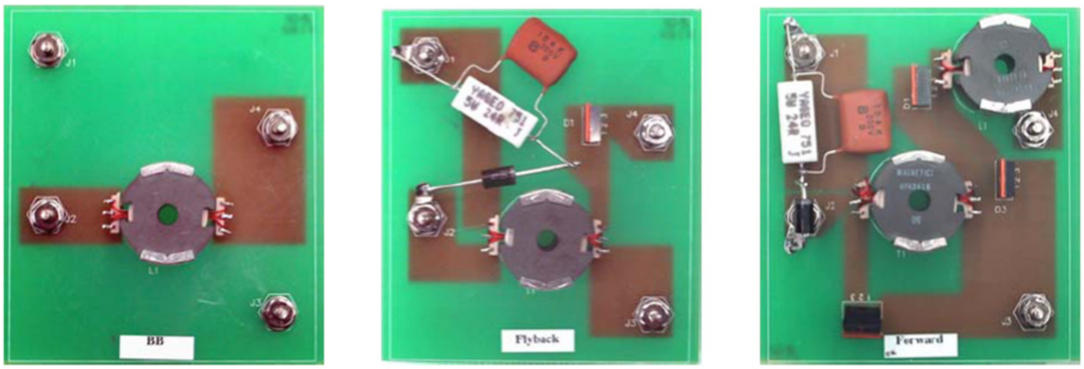


Figure 1.2: Power-pole Board

1.2.2 Magnetic Boards

To build various converters using the Power-pole Board, three plug-in boards are provided:
1. BB Board (Fig. 1.3(a)): For the buck, boost and buck-boost converters
2. Flyback Board (Fig. 1.3(b)): For the flyback converter
3. Forward Board (Fig. 1.3(c)): For the forward converter

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



(a) BB Board (b) Flyback Board (c) Forward Board

Figure 1.3: Magnetics Boards

1.2.3 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.

1.2.4 Load

Any external load needs 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 an **oscilloscope probe** to *CS LOAD 1* and *CS LOAD 2* (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.

1.2.5 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+* (L-1 in Fig. 1.2) and its ground to *COM* (K-1 in Fig. 1.2).

1.2.6 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 these current sensors is such that for 1A current flowing through each, the output is 0.5 V. So these sensors are actually current to voltage converters. 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-4 in Fig. 1.2) and its ground to *COM* (B-4 in Fig.1.2).

To measure output current,

- Connect oscilloscope probe to *CS5* (K-4 in Fig. 1.2) and its ground to *COM* (K-4 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* (K-3 in Fig.1.2). The current sense resistor value is 0.1 Ω.

Note: The lower diode current can also be observed using test point CS3. However the upper diode current cannot be observed.

1.2.7 MOSFET Drive Circuit

The power-pole MOSFETs are driven by high side drivers IR2127. These drivers have in-built over current 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.

1.2.8 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.

1.2.9 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.

1.2.10 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 right-hand positions.

Closed loop operation will be described in the relevant experiment.

1.3 Using an oscilloscope to measure waveforms

In power electronics labs, oscilloscopes are frequently used to measure waveforms. Using an oscilloscope is one the most important skills for the lab. Here is a brief introduction of how to use an oscilloscope to measure waveforms

1.3.1 To connect a probe to the oscilloscope:

- Align the slot in the probe connector with the key on the desired channel BNC, push to connect and twist to the right to lock the probe in place.
- Be sure that the Attenuation switch on the probe matches the probe option in the oscilloscope. Switch settings are 1X and 10X.

1.3.2 Before connecting a probe to the target waveform:

- Clip the ground clip to proper ground point; be aware that the selected ground point must be the same ground with the oscilloscope. If not sure about this, use a multimeter to make sure.

1.3.3 To select a certain channel to be displayed:

- CHn MENU button controls the display of channel n. n here can be 1, 2, 3 or 4. Push the CHn MENU button which will switch between channel n being displayed and being hidden.

1.3.4 If the target waveform is not displayed:

- Make sure the oscilloscope is powered on.
- Make sure the proper channel of the scope is set to be displayed.
- Push AUTOSET button, within a few second, the target waveform will be displayed.
- The channel reference indicator (located on the left of the graticule) identifies each waveform on the display. The indicator points to the ground level of the waveform.

1.3.5 Scaling and positioning waveforms:

If the waveform displayed after pushing OUTOSET button is not in desired scale or position, you can change the scale and position of the waveform manually. When you change the scale, the waveform display will increase or decrease in size. When you change the position, the waveform will move up, down, right or left.

- To change the vertical scale, use VOLTS/DIV knob under VERTICAL sign of the proper channel to select calibrated scale factors.
- To change the vertical position, use the POSITION knob under VERTICAL sign of the proper channel to move the waveform up or down.
- To change the horizontal scale, use SEC/DIV knob under HORIZONTL sign.
- To change the horizontal position, use POSITION knob under HORIZONTAL sign to move the waveform right or left.

1.3.6 Taking measurements

There are several ways to take measurements. You can use the graticule, the cursors, or an automated measurement.

- Graticule

This method allows you to make a quick, visual estimate. You can take simple measurements by counting the major and minor graticule divisions involved and multiplying by the scale factor.
For example, if you counted five major vertical graticule divisions between the minimum and maximum values of a waveform and knew you had a scale factor of 100mV/div. then you could easily calculated the peak-peak voltage as:

$$5 \text{ divisions} * 100\text{mV/div} = 500\text{mV}$$

- Cursors

This method allows you to take measurements by moving the cursors, which always appear in pairs, and reading their numeric values from the display readouts. There are two types of cursors: Voltage and Time.
When using cursors, be sure to set the Source to the waveform on the display that you want to measure.
To use cursors, push the CURSOR button. CURSOR1 and CURSOR2 LED lights will light to indicate the alternative function of the knobs. Use the POSITION knobs indicated by CURSOR1 and CURSOR2 LED to move the cursors. Use the readouts on the screen to calculate the voltage or time difference between the cursors.

- Automatic

The Measurement Menu can take up to five automatic measurements.

To use the automatic measurement, push the MEASUREMENT button; choose the channel on which to take a measurement in the Source option; choose the type of measurement in the Type option; read the result of the measurement from the readout on the screen.

2. Experiment

2.1. Introduction to Power-Pole Board

Take some time to examine Fig. 1.1. This figure outlines the basic structure of the board. Refer to this figure when making connections and inserting the magnetic boards. Now refer to Fig. 1.2. Use this figure in conjunction with Table 1.1 in order to locate particular board components. Table 1.2 describes useful test points and their location on the board. Note that the current-sensing resistor value of the MOSFETs is 0.05 Ω. Remember to 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 oscilloscope connections as shown in Figure 2.

PWM signals required for the MOSFETs can be generated using the on-board PWM controller UC3824. To use the on-board PWM, put switch 2 of the selector switch bank S30 to its bottom position. The duty-cycle of the signal can be controlled using potentiometer RV64. The duty ratio can be varied from 4% to 98%. The frequency of the PWM can be adjusted using the trim pot RV60.

2.2. Experiment

Generate PWM signal using the on-board generator. Include plots of at least three different duty-cycles for two different switching frequencies.

3. Simulation

3.1. Introduction to PSPICE

PSpice is a general-purpose electronic circuit simulator. We will use PSpice to observe the behavior of several common power electronics circuits. Each PSpice simulation is held in a file called a schematic. You can open a schematic from PSpice by clicking File > Open. Schematics are executed by clicking on the run icon or by clicking on Analysis > Simulate. The schematics provided to you will automatically open Probe, PSpice's plotting utility. Probe will plot the waveforms selected by the markers in the schematic. You can use these plots to observe circuit behavior and perform measurements.

You can download the student version of PSPICE 9.1 here:
http://www.electronics-lab.com/downloads/schematic/013/. Note that PSpice only runs natively under Windows 98. Some newer versions of Windows may have trouble running the software.

Note: Please see the instructions of the txt file "how to install library files".

3.2. PWM and Filter Characteristics

Open the file **SwitchingWaveform.sch**. Notice that this circuit has a square-wave source with d = 0.75. The load is a simple L-C resonant circuit. Simulate the circuit. Plot the input voltage v_A and the output voltage v_O after v_O has reached steady-state. How does v_O relate to v_A? Set d = 0.6 and plot v_A and v_O as before. Are the results what you expect?

Set d = 0.75. Simulate the circuit. Navigate to the simulation window and click 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 of the input relate to its switching frequency? 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?

Increase the switching frequency of the source to 20 kHz maintaining the same duty-cycle. Make sure to increase the simulation time and change the center frequency of the Fourier analysis. Simulate the circuit. Compare the averages of the waveforms. Now 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?

Set the switching frequency back to 1 MHz. Set d = 0.5. Simulate the circuit. Calculate the amplitude of the fundamental frequency component in v_A and compare with the Fourier results in the simulation.

[NOTE: Students are strongly advised to have the handout of Lab 1 while performing the other labs]