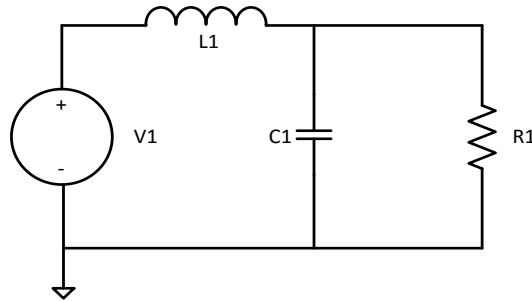


Instructions for LTspice Laboratory Exercise

LC Filter

We consider a power supply that has a resistive load. We want to filter out the high frequency components from the power supply, so we construct an L-C low-pass filter (LPF) and place the resistor in parallel with the filter capacitor. We want to examine the properties of this circuit. The load resistor has a value of $5\ \Omega$. The inductor in the LPF has a value of $500\ \mu\text{H}$ and the capacitor has a value of $1000\ \mu\text{F}$.



1. Open a new schematic: File->New Schematic (Ctrl-N)
2. Add components
 - a. Voltage source: Edit->Component, F2, or AND gate icon from menu->
 - i. Ensure top directory is `..\LTspiceXVII\lib\sym`
 - ii. Select voltage
 - iii. Place and escape to exit
 - b. Inductor: Edit->Inductor or select from menu, place, Ctrl-R to rotate, escape to exit
 - c. Capacitor: Edit->Capacitor or select from menu, place, escape to exit
 - d. Resistor: Edit->Resistor or select from menu, place, escape to exit
 - e. Ground: Edit->GND or select from menu, place, escape to exit
3. Connect components: Edit->Draw Wire, F3, or select Line icon from menu
 - a. Click on GND, draw to V- and click
 - b. Click on V+, draw in right angles to LHS of inductor, clicking on the corners and inductor
 - c. Click on RHS of inductor, draw in right angles to top of resistor, clicking on **corner of** resistor
 - d. Click on bottom of resistor, draw in right angles to bottom of line between GND and V-, clicking on corners and termination line
 - e. Click on line from inductor to resistor and click on top of capacitor
 - f. Click on line from resistor to ground and click on bottom of **capacitor**
 - g. Escape to exit
4. Set the values of the components
 - a. Inductor: Right click on the inductor, enter 500u in inductance box, OK
 - b. Capacitor: Right click on the capacitor, enter 1000u in capacitance box, OK
 - c. Resistor: Right click on the resistor, enter 5 in resistance box, OK
 - d. Voltage source: Right click on the voltage source, go to Advanced, enter 0 in DC value box, enter 1 in AC Amplitude box, OK

Frequency Response

We first find the frequency response of this circuit. The resonant frequency of the filter components is

$$f = \frac{1}{2\pi \sqrt{L1 \cdot C1}} = \frac{1}{2\pi \sqrt{5 \cdot 10^5}} = 225 \text{ Hz}$$

so we Simulate->Edit Simulation Command->AC Analysis and set up a Decade sweep with 1000 points per decade, starting at 10 Hz and ending at 10k Hz. This translates into a command

.ac dec 1000 10 10k, which will appear on the LTspice schematic.

1. Setup the analysis
 - a. Edit->Spice Analysis or Simulate->Edit Simulation Command ->AC Analysis
 - i. Type of sweep: Decade
 - ii. Number of points per decade: 1000
 - iii. Start frequency: 10
 - iv. Stop frequency: 10k
 - v. OK
 - b. Or Edit->Spice Analysis->.ac dec 1000 10 10k, OK
 - c. Click on schematic to place command

2. Save schematic as lcFilterFreq.

3. Run simulation: Select runner icon, or Simulate->Run

(A netlist is created in lcFilterFreq.net. This contains the SPICE commands

```
* C:\files\ltSpiceFiles\examples\2017\lcFilterFreq.asc
```

```
V1 N001 0 0 AC 1
```

```
L1 N001 N002 500μ
```

```
C1 N002 0 1000μ
```

```
R1 N002 0 5
```

```
.ac dec 1000 10 10k
```

```
.backanno
```

```
.end
```

that tell SPICE about your schematic. Note that there are three voltage nodes, N001, N002, and 0 (GND), the four devices V1, L1, C1, and R1, the command for AC analysis (.ac directive), and an LTspice command, backanno, that allows you to select voltages and currents for graphical output.)

4. Plots:

- a. Voltage: Hover over a wire with the cursor. If the wire is not at ground potential, a voltage probe will appear and the voltage node it is over will appear in the lower left corner of the LTspice window. The voltage on any node can be plotted by clicking on a wire connected to the node. A voltage difference can be plotted by first depressing the mouse key on one node, then sliding the probe over to a second node while the key is still depressed, and then releasing the key.
- b. Current: Hover over a device with the cursor. A current probe will appear and the device it is over will appear in the lower left corner of the LTspice window. The current through any device can be plotted by clicking on that device.
- c. Power: Depress the Alt key and hover over a device that can dissipate power (resistor or semiconductor). A thermometer will appear. Click and the power dissipated in that device will be plotted.

- d. Functions of basic plots: Sometimes one wants to plot an arithmetic function of node voltages and/or branch currents. To do this, make the plot window (.raw) the active window and then add a trace by opening another window using either Plot Settings->Add trace or Ctrl-A, and then entering the mathematical expression in the "Expression(s) to add" box. For example, another way to add the voltage across the inductor, enter $V(n001) - V(n002)$, OK, or to calculate the power through the damping resistor R1 would be to enter $(V(n00x)-V(n00y))*I(R1)$, OK, where n00x is the node on one side of R1 and n00y is the node on the other side.
 - e. Cursors: The waveform plotting routine has two cursors. One can activate the cursor by left clicking on the label of a plot. A cursor box will appear with the horizontal and vertical coordinates of the waveform point under the cursor. Alternatively, one can right click on the desired plot label and select the cursors from the Attached Cursor box at the top of the Expression Editor. The choices are none, 1st, 2nd, or 1st & 2nd.
 - f. One can change parameters of the plot by hovering the cursor along an axis outside of a plot until a ruler icon appears and then right clicking. That can allow you to change the axis values and, if a vertical axis, delete a family of plots, such as amplitude or phase for a Bode plot.
5. Run the simulation and then place a voltage probe on the resistor and view the amplitude and phase of the result. The peak of the response is close to 225 Hz (it is a little lower because of the resistor)
 6. The phase of the response changes from 0° to -180° as the frequency goes through the resonance.
 - a. Record the frequency at which the response is a maximum and record the amplitude, in dB, at that frequency

_____ Hz _____ dB

7. Record the frequencies and amplitudes at which the phases are -45°, -90°, and -135°, respectively

-45° _____ Hz _____ dB

-90° _____ Hz _____ dB

-135° _____ Hz _____ dB

This shows the maximum amplitude occurs at approximately -90° and that the amplitudes are down approximately 3dB 45 degrees on either side of 90 degrees.

Step Response

We now find the time response of this signal to a step impulse.

1. Delete (Edit->Delete, F5, or scissors icon) the .ac directive from the schematic
2. Right click on the voltage source, already in Advanced, enter 1 in DC value box, enter 0 in AC Amplitude box, OK.
3. Edit->Spice Analysis or Simulate->Edit Simulation Command -> Transient
 - a. Stop time: 50m
 - b. Time to start saving data: 0
 - c. Select "Start external DC supply voltages at 0V"

d. OK

4. Or enter Transient command: .tran 0 50m 0 startup, then OK
5. Click to enter command on schematic
6. Save file as lcFilterStep
7. Run simulation: Select runner icon, or Simulate->Run
8. Place a voltage probe on R1
9. Observe the ringing of the voltage on the resistor
10. Sketch the output voltage waveform over 50ms. Estimate and record the time between the initial peaks. To what frequency does this correspond?

11. Record the ratio of the amplitude of the second peak to the amplitude of the first peak. A single pole damped circuit decays exponentially. Using the ratio of these peaks and the time difference between the peaks, calculate a damping time τ using the formula $e^{-t/\tau}$ to fit the data.

$$\frac{v(t+T)}{v(t)} = \frac{V_0 e^{-\frac{t+T}{\tau}} \sin \omega(t+T)}{V_0 e^{-\frac{t}{\tau}} \sin \omega(t)} = e^{-\frac{t}{\tau}}$$

Since the value of $\sin \omega t$ is the same at the two measurement times, solving for τ we get

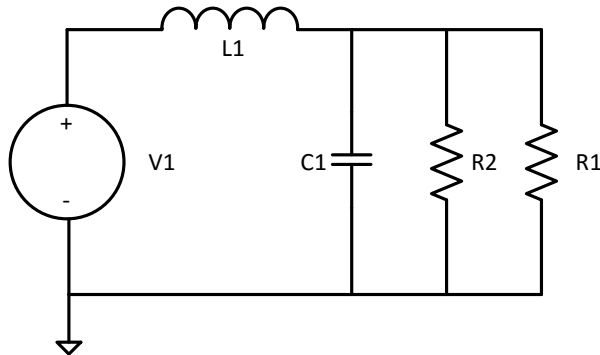
$$\tau = \frac{T}{\ln \frac{v(t+T)}{v(t)}}$$

Ratio: _____

Damping time τ : _____

Damped Filter

In order to damp the frequency response of our L-C filter, we add a damping resistor to the circuit. We will use LTspice to see what value of damping resistor to add in parallel with our load resistor.



Parametric Analysis

In order to efficiently select the filter we will use the LTspice `.STEP` function that allows us to perform a parametric analysis. This introductory section gives an overview of how to perform such an analysis on the resistor in a damped filter. You will be stepped through the instructions later in this section of the laboratory exercise.

Vary the parametric component by right clicking on it. Under *Component Properties (Resistor, capacitor, or Inductor)* enter **{R}**, or **{C}**, or **{L}** in the *Resistance, Capacitance, or Inductance* box. Note that the braces **{}** around the parameter name are required. This tells LTspice the component value is a global parameter. Close the component box by selecting the *OK* button.

Add a spice directive to the circuit in one of three ways. Depress the *s* key, use the `.op` command at the right hand side of the menu, or select the *SPICE Directive* from the *Edit* pull down menu. All of these ways opens a dialog box *Edit Text on the Schematic*. Ensure highlight of the *SPICE Directive* radio button. Type the needed command (see the example below) then left click the directive onto the circuit diagram.

For example, the command `.step dec param R 0.01 1.0 4`, steps the parameter **R** logarithmically from 0.01 ohms to 1.0 ohms in four steps per decade when the *Run* command is chosen. Display the plots for all of the steps by then selecting the voltage or current of interest and displaying the plot. To select only specific plots, choose *Select Steps* to display the traces of interest from the *Plot Settings* drop down menu.

In order to step through the parameter in linear increments, we modify the command to `.step param R 0.05 0.15 0.02`, which starts with **R** at 0.05 ohms, and steps in increments of 0.02 ohms to 0.15 ohms.

To return to the original value we can either delete the `.step` command and replace it with a command used to set **R** `.param R 0.1`, or remove the command altogether, to return to the damping resistor properties and replace **{R}** with the desired value.

This concludes the introduction.

Parametric Analysis

1. Either work with the existing schematic, or load a previous schematic, File->Open lpFilterFreq.asc
2. Add an additional shunt resistor for extra damping: Edit->Resistor or select from menu, place, escape to exit
3. Connect resistor to existing circuit using Edit->Draw Wire, F3, or select Line icon from menu. Escape when finished.
4. Set this second resistor as a parameterized object: Right click on the resistor and enter the resistance as {R} to tell LTspice that this resistance will be treated as a parameterized value.
5. Delete the .tran directive. Add the SPICE command to tell LTspice the parameters of interest: Edit->SPICE Directive
.step dec param R 0.01 10 4
This tells LTspice that R will be a parameter, where the value of R will be varied logarithmically from 0.01 Ω to 10 Ω with four steps per decade.
6. Set up an AC analysis from 20 Hz to 2 kHz:
 - a. Edit->Spice Analysis or Simulate->Edit Simulation Command ->AC Analysis
 - i. Type of sweep: Decade
 - ii. Number of points per decade: 1000
 - iii. Start frequency: 20
 - iv. Stop frequency: 2k
 - v. OK
 - b. Or Edit->Spice Analysis->.ac dec 1000 20 2k, OK
 - c. Click on schematic to place command
7. Save file as lcFilterDampFreq
8. Run simulation: Select runner icon, or Simulate->Run
9. Plot Settings->Select Steps allows you to select which of the parameterization values of R you wish to plot
10. Replace the .step command with a command that will vary the parameter linearly from 0.5 Ω to 2 Ω in steps of 0.1 Ω . Right click on the .step command to bring up the .step Statement Editor:
 - a. Either use the prompts
 - i. Name of parameter to sweep: R
 - ii. Nature of sweep: Linear
 - iii. Start value: 0.5
 - iv. Stop value: 2.0
 - v. Increment: 0.1
 - b. Or enter .step param R 0.5 2.0 0.1 in the bottom box
 - c. OK
11. Run simulation: Select runner icon, or Simulate->Run
12. Choose the desired resistor value (when the output voltage is essentially critically damped)
13. Replace the Resistance value {R} with the desired value and record this value
Hint: $R = \sqrt{L_1/C_1}$

-
14. Delete the .step Spice command from the circuit. Run an AC simulation to verify this resistor value has the desired response and sketch the confirmation

Transient Analysis

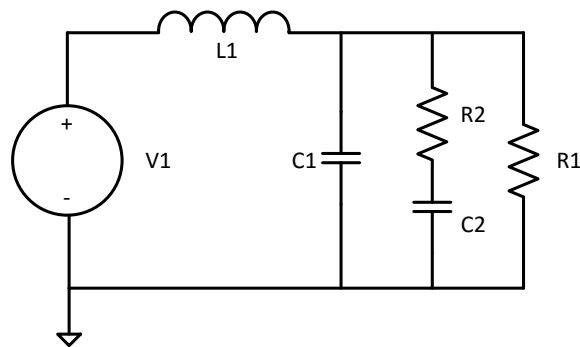
Leaving the circuit alone, modify the excitation to obtain a step response

1. Right click on the voltage source to set the source to a DC value
 - a. DC value: 1
 - b. AC Amplitude: 0
 - c. OK
2. Right click on the .ac command to open the Edit Simulation Command box and
 - a. Either
 - i. Stop time: 10m
 - ii. Time to start saving data: 0
 - iii. Select Start external DC supply voltages at 0V
 - b. Or in lower box enter
 - i. .tran 0 10m 0 startup
 - c. OK
3. Save file as lcFilterDampStep.asc
4. Run simulation: Select runner icon, or Simulate->Run
5. Sketch the circuit output voltage. Sketch and record the power dissipated in the resistor (see sections 4.c and 4.d in the discussion of Frequency Response - Plots above).
 - a. Output Voltage

b. R2 Dissipated Power

Praeg Filter

The circuit we just designed has the desired frequency response, but at the expense of dissipating most of the power in the damping resistor. If we mainly want to drive a DC load, we can insert a capacitor in series with our damping resistor to block the DC current and reduce the power dissipated in this resistor.



Parametric Analysis

1. Load the lpFilterDampFreq.asc: File->Open lpFilterDampFreq.asc
2. If not already done, set up an AC analysis from 20 Hz to 2 kHz:
 - a. Edit->Spice Analysis or Simulate->Edit Simulation Command ->AC Analysis
 - i. Type of sweep: Decade
 - ii. Number of points per decade: 1000
 - iii. Start frequency: 20
 - iv. Stop frequency: 2k
 - v. OK
 - b. Or Edit->Spice Analysis->.ac dec 1000 20 2k, OK
 - c. Click on schematic to place command
3. Delete the .step statement: F5, select, escape

4. Modify the damping resistor (R2) parameter to include the desired resistance: Right click on resistor, replace {R} with desired value, OK.
5. Modify the circuit layout, if necessary, to allow a capacitor in series with R2. F7 is Move, F8 is Drag. Drag is similar to move, but wires rubber band along with selected objects.
6. Delete the wire connecting R2 to ground: F5, select, escape
7. Add a capacitor: Edit->Capacitor or select from menu, place, escape to exit
8. Connect the capacitor to R2 and GND using Edit->Draw Wire (F3), escape to exit
9. Set C2 to be parameterized
 - a. Right click on C and set Capacitance to {C}
 - b. Add the SPICE command to tell LTspice the parameters of interest: Edit->SPICE Directive
 .step param C 3000u 7000u 1000u
 OK then place
 to step through five values of the capacitance.
10. Save the file as praegFreq.asc: File->Save As praegFreq.asc
11. Run simulation: Select runner icon, or Simulate->Run
12. Select and record an acceptable capacitor value for this load
 Hint: From class notes $C_2 = 5 * C_1$

_____ μF

AC Analysis

Perform an AC analysis to obtain the frequency response .ac dec 1000 20kHz 2kHz

13. Record the frequency at the peak of the response and the relative gain (in dB) at this frequency

_____ Hz, _____ dB

14. Compare these results with those from the damped filter.

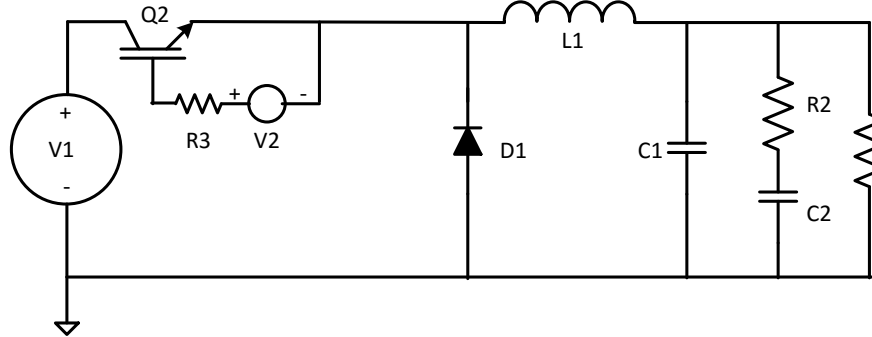
Transient Analysis

Leaving the circuit alone, modify the excitation to obtain a step response

1. Right click on the voltage source to set the source to a DC value
 - a. DC value: 1
 - b. AC Amplitude: 0
 - c. OK
 2. Right click on the .ac command to open the Edit Simulation Command box and
 - a. Either
 - i. Stop time: 10m
 - ii. Time to start saving data: 0
 - iii. Select Start external DC supply voltages at 0V
 - b. Or in lower box enter
 - i. .tran 0 10m 0 startup
 - c. OK
 3. Save file as praegStep.asc
 4. Run simulation: Select runner icon, or Simulate->Run
 5. Select desired capacitance and replace the parameter C with that value. Delete the .step statement.
 6. Sketch the output voltage versus time
-
7. Sketch the power dissipated in the damping resistor ($V(n002) - V(n001) * I(R_2)$) over 50ms. Note that the steady state resistor power is zero

Buck Regulator

Now that we have the desired load and filter, we will build a buck regulator power supply and look at its step responses.



Initial Response

1. Load praegFreq.asc: File->Open praegFreq.asc
2. Ensure that the parameters for R2 and C2 have been replaced by the desired components and delete (F5) any unneeded step statements
3. Drag (F8 and select) the filter components to the right of the schematic to make room for other components. Left click when the components are in the desired location, then escape.
4. Add components:
 - a. IGBT:
 - i. Edit->Component, F2, or AND gate icon from menu
 - ii. In top line, pull down menu and select custom directory (ltSpiceFiles\sym)
 - iii. Select irgp4063dpbf, click OK
 - iv. Rotate the device (Ctrl-R) until the gate faces down
 - v. Place and escape to exit
 - b. Voltage source:
 - i. Edit->Component, F2, or AND gate icon from menu
 - ii. Ensure top directory is ..\LTspiceXVII\lib\sym
 - iii. Select voltage, OK, rotate (Ctrl-R) until positive terminal faces left
 - iv. Place and escape to exit
 - c. Diode:
 - i. Edit->Component, F2, or AND gate icon from menu
 - ii. Ensure top directory is ..\LTspiceXVII\lib\sym
 - iii. Select diode, OK, rotate (Ctrl-R) until the cathode faces up
 - iv. Place and escape to exit
 - d. Resistor: Edit->Resistor or select from menu, rotate (Ctrl-R) until it is horizontal, place, escape to exit
5. Modify schematic
 - a. Delete (F5) trace between V1 and L1, escape to exit
 - b. Move (F7) components to look like figure.
 - c. Draw Wire (F3) to connect the devices as in the figure.
6. Set the remaining component values
 - a. Set V1 to 100 VDC: Right click on V1, DC value 100, AC Amplitude 0, OK
 - b. Set R3 to 10 Ω : Right click on R3, Resistance 10, OK

- c. Set D1 to carry at least 20 A with a breakdown voltage greater than 250 VDC (conservative choices)
 - i. Right click on D1
 - ii. Pick New Diode
 - iii. Select RF1501NS3S
 - iv. OK
 - d. Set V2 to be the gate drive, a pulse train to give a pulse-width modulated control of the IGBT. A gate value of -5 V keeps the IGBT off and a gate value of 20 V turns the IGBT on. We will start the pulse train immediately ($T_{\text{delay}} = 0$), set the pulse period for $100 \mu\text{s}$, set its duty cycle to 25% ($T_{\text{on}} = T_{\text{period}}/4$), and set some reasonable rise and fall times. Based on our filter response we expect the filter to settle out within a few ms, we set the number of cycles to 100 for a 10 ms excitation time. We will see the command `PULSE(-5 20 0 2u 2u 25u 100u 200)` by V2
 - i. Right click on V2
 - ii. Advanced
 - iii. Select PULSE function
 - iv. $V_{\text{initial}} = -5$; $V_{\text{on}} = 20$; $T_{\text{delay}} = 0$; $T_{\text{rise}} = 2\text{u}$; $T_{\text{fall}} = 2\text{u}$; $T_{\text{on}} = 25\text{u}$; $T_{\text{period}} = 100\text{u}$; $N_{\text{cycles}} = 200$
 - v. OK
7. Set up a transient simulation:
- a. Simulate->Edit Simulation Cmd
 - i. Transient
 - ii. Stop time: 20m (this is $N_{\text{cycles}} \cdot T_{\text{period}}$)
 - iii. Time to start saving data: 0
 - iv. OK
 - b. This gives a simulation command of `.tran 0 20m 0`
8. Save file File->Save As buckInitial.asc
9. Run simulation: Select runner icon, or Simulate->Run
10. Sketch $V(R_1)$, $I(R_1)$, on one plot

11. Sketch $I(C_1)$, the current in the main Praeg capacitor C1 over 50ms and then over two cycles under steady-state conditions

12. On one plot sketch two cycles of the filter inductor L1 voltage (V(n002)-V(n003)), and current (IL1) under steady state conditions

13. On one plot sketch two cycles of the free-wheeling diode VD1, and ID1 under steady state conditions

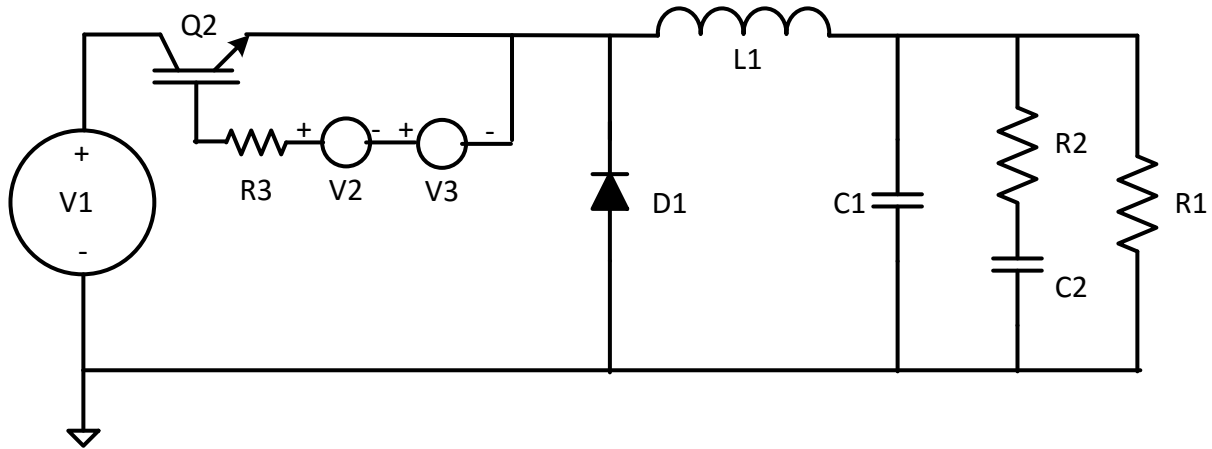
14. On one plot sketch two cycles of the drain-to-source IGBT voltage (V(n001)-V(n002)) and current (-I(V1)) under steady state conditions

15. On one plot sketch two cycles of the input voltage (V_1) and current ($-I(V_1)$) under steady state conditions



Buck Regulator, Modified (Step Change in Operating Point)

We will now modify the circuit slightly to see how it responds to a step change in its operational point.



We do this by adding a second voltage source in series with V2 and setting the pulses of each so that:

- They are each have different duty cycles
- They are set to zero volts while the other source is pulsing

1. Load buckInitial.asc: File->Open buckInitial.asc
2. Drag (F8, select, and drag) the diode and passive components, if necessary, to get extra space. Select to place and escape to exit.
3. Delete (F5) the wire connecting V2- to the IGBT emitter, escape to exit
4. Add a voltage source:
 - a. Edit->Component, F2, or AND gate icon from menu
 - b. Ensure top directory is ..\LTspiceXVII\lib\sym
 - c. Select voltage, OK, rotate (Ctrl-R) until positive terminal faces left
 - d. Place and escape to exit
5. Wire the new voltage source, V3, to be in series with V2.
 - a. Draw Wire (F3)
 - b. Place at each destination
 - c. Escape to exit
6. Set PULSE parameters of V3. We will hold this off for the first 20 ms while V2 is pulsing, then turn it on at a different duty cycle for another 20 ms. Since V2 will be at -5 V when it is not pulsing, V2 needs to pulse between 0 V and 25 V.
 - a. Right click on V3
 - b. Advanced
 - c. Select PULSE function
 - d. Vinitial = 0; Von = 25; Tdelay = 20m; Trise = 2u; Tfall = 2u; Ton = 30u; Tperiod = 100u; Ncycles = 200
 - e. OK

7. Modify the simulation command to calculate for 40 ms
 - a. Simulate->Edit Simulation Cmd
 - i. Transient
 - ii. Stop time: 40m (this is $2 \cdot N_{\text{cycles}} \cdot T_{\text{period}}$)
 - iii. Time to start saving data: 0
 - iv. OK
 - b. This gives a simulation command of `.tran 0 20m 0`
 8. Save file File->Save As buckSteadyState.asc
 9. Run simulation: Select runner icon, or Simulate->Run
 10. Examine the behavior, especially at $t=20$ ms, when the supply changes its operating point. Sketch the change in output voltage during the transition.
-