

# Simulating a switch mode power supply with LTspice

## Aims of this experiment

- Learn how to use an electronic circuit simulator
- Explore the operation of a familiar filter circuit
- Learn how USB chargers and similar power supplies work

## Lab notebook

You should keep a written lab notebook while doing this and other experiments. It should contain

- Diagrams of circuits you simulated or built
- Waveforms, analysis, observations and explanations as prompted by this manual, and things that you decided to pursue. Be quantitative.
- Enough detail to enable someone to quickly pick up the thread of what you did and observed.

## 1 Install a circuit simulator

Computer programs that deduce and solve all the equations (Kirchoff, Ohm etc.) of an electronic circuit are widely used. If used wisely, they can be quite accurate; the typical reason for a mismatch with reality is that reality does not live up to the idealisations of your circuit diagram.

These notes are written for the LTSpice simulator, but others are available, e.g. many other Spice derivatives, and Qucs and its derivatives. They are mostly free software, and most run on multiple operating systems. [spice = simulation program with integrated circuit emphasis; qucs = quite universal circuit simulator]

### 1.1 Installing LTspice

LTSpice is built for Windows and Mac. It runs OK within Wine on Linux. Download the latest version of LTspice (presently XVII) from [www.analog.com](http://www.analog.com) at

<https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html>

## 2 Enter and simulate simple circuits

Check that you can get the same results as shown in section 2.1, and attempt section 2.2.

## 2.1 Resistor-capacitor low pass filter

We begin with a circuit that you may be familiar with, to check that we can reproduce its behaviour. Use LTspice (or other simulator) to draw the circuit shown in Fig. 1.

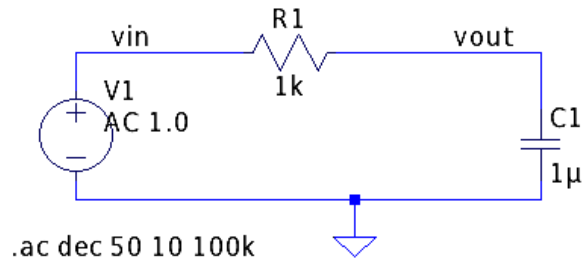


Figure 1: R-C Low pass filter circuit

The resistor, capacitor and ground symbol are selected from the toolbar and placed by clicking. Ctrl-r (or the rotate symbol on the toolbar, that looks like EM) rotates the symbol before placing. Esc deselects the part. There is an Undo option in the Edit menu. The voltage source is found as "voltage" in the list revealed by the Component button (looks like an AND gate). The Wire tool from the toolbar makes connections.

Use a right click to alter the values of the components from their defaults to: R1 = 1k (1000  $\Omega$ ); C1 = 1u ( $10^{-6}$  F); V1: Advanced, small signal AC analysis, AC amplitude = 1.0 (1 volt). Use the Label Net tool (letter A) to apply vin and vout labels to the appropriate points in the circuit.

Select the simulation required from the Edit Menu » Spice Analysis » AC analysis: Type of sweep = Linear, 250 points, start = 10, stop = 100k. Place the `.ac` command that it generates on the schematic.

Save the circuit, and run the simulation by clicking the Run icon (running man). Any errors will appear in a window. Click on the vout and vin wires to see their voltages plotted as a function of frequency, see Fig. 2

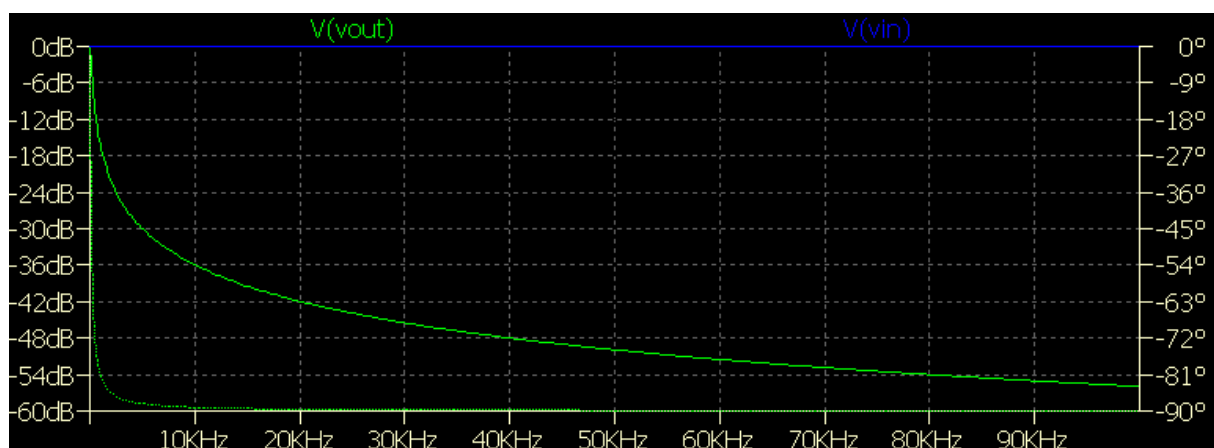


Figure 2: Filter circuit plot

The plot shows that  $V_{in}$  has a constant value of 1 volt at all frequencies, while  $V_{out}$  quickly falls towards zero at high frequencies. A standard representation used in electronics is the Bode plot, which has logarithmic amplitude and frequency axes, so right-click on the frequency axis to make it logarithmic. The amplitude in decibels is automatically a logarithmic scale, but you may prefer to make it logarithmic in voltage units. The linear sweep does not calculate enough points to make a clean plot at low frequencies, so go back and change the ac simulation to use 50 points per decade (a logarithmic sweep), and simulate again.

You can alter the appearance of the plots using the Control Panel tool (hammer) » Waveforms. Dark lines a couple of pixels wide on a light background are advised. The result, Fig. 3, shows why this circuit is called a low-pass filter.

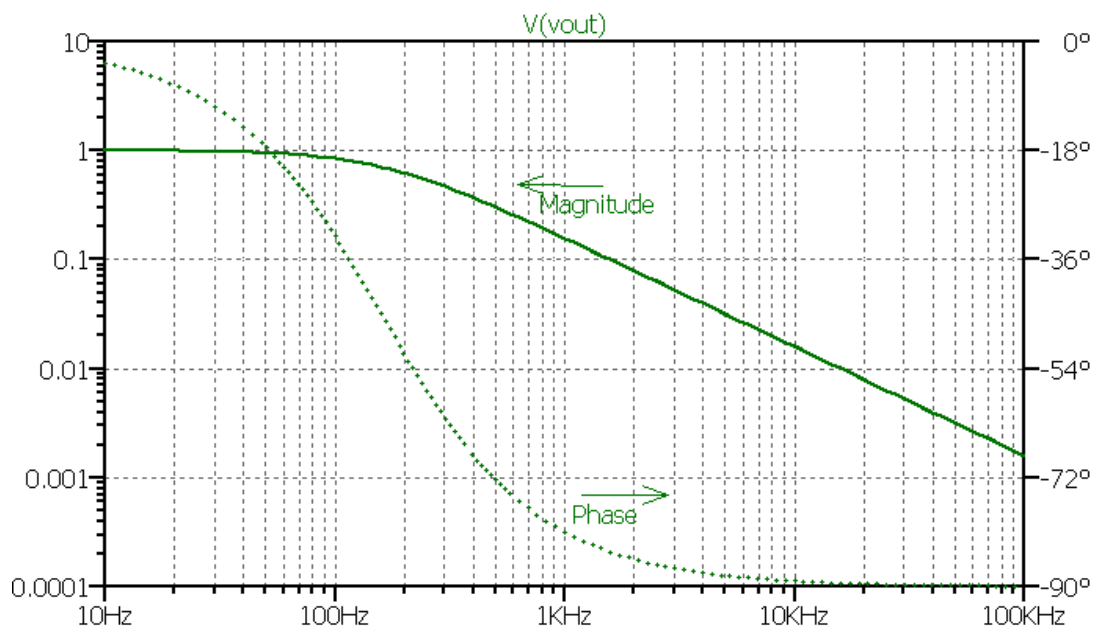


Figure 3: Bode plots of low-pass filter

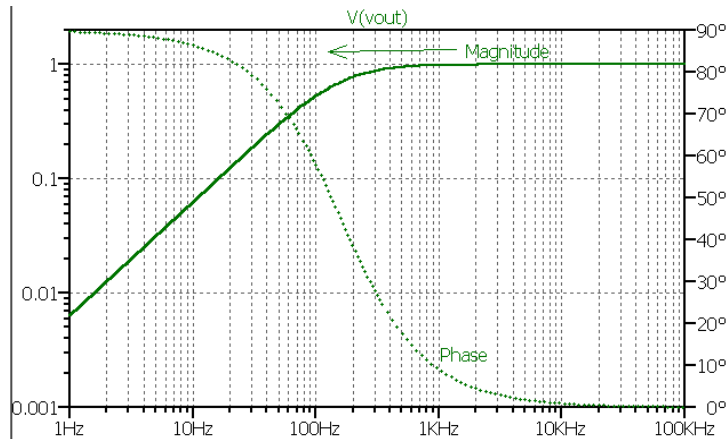
Low frequencies (below 100 Hz, say) pass from input to output with little attenuation, but high frequencies (above 1000 Hz, say) do not. It can be quite a useful circuit fragment, even though the cutoff point is not that sharp.

## 2.2 Resistor-capacitor high pass filter

Interchange the positions of the resistor and capacitor in the circuit of section 2.1 and produce graphs showing the Bode plots for the new circuit. Comment on the results.

*DEMO NOTES: Here is what the high pass filter plots should look like. There should also be a labelled circuit diagram. Most important features are log/log for amplitude and linear degrees vs. log frequency for phase. They can be separate or on the same plot, using left and right axes. Unfortunately, LTspice does not produce such nice plots as Qucs, so we have to live with this. A generally tidy output and extension of simulation to 1 Hz to show more of the curve are worth commending but not essential.*

The crossover from blocking to passing occurs at the same frequency as the LPF. Also there is a phase lead at low frequency, where the capacitor is a significant series impedance, in contrast to the phase lag in the LPF case, where the capacitor is a significant load at the high frequency end. When the (angular) frequency  $\omega = 1/RC$ , the attenuation is  $1/\sqrt{2}$  and the phase change is  $45^\circ$  (in both cases).



### 3 Switch mode power supplies

The need to convert electrical power from one voltage level to another is very common. A USB charger that converts 240 V mains to 5 V to charge a phone is one example, as are the step-up and step-down conversions that the phone may need to power its display ( $\sim 10$  V) and its processor ( $\sim 1$  V) from its nominally 3.7 V battery. In this section, you will investigate how this is done using inductors and electronic switches.

#### 3.1 Inductor and Switch

Consider the circuit of Fig. 4. Its behaviour is governed by the expression for the voltage across an inductor,  $V_L = -L di/dt$ . Before time  $t = 0$ , the current  $i$  in the circuit is zero. At  $t = 0$  the switch is closed. By applying Ohm's and Kirchoff's laws, you should show<sup>1</sup> that the current has the form of an exponential approach to  $V/R$ ,

$$i = \frac{V}{R} \left[ 1 - \exp\left(\frac{-t}{\tau}\right) \right], \text{ where } \tau = L/R.$$

<sup>1</sup>Write down Kirchoff's voltage law, separate the variables  $i$  and  $t$ , then integrate, substitute the limits  $(0, 0)$  and  $(t, i)$ , and take the antilog.

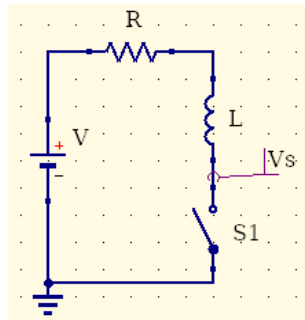


Figure 4: Inductor plus switch

DEMO NOTES:  $L \frac{di}{dt} + iR = V$ ;  $\frac{di}{dt} = \frac{1}{L}(V - iR)$ ;  $\frac{di}{V - iR} = \frac{dt}{L}$ . Integrate to give

$$-\frac{1}{R} \ln(V - iR)|_0^i = \frac{1}{L} t|_0^t; \quad \ln\left(\frac{V - iR}{V}\right) = -\frac{R}{L}t; \quad 1 - \frac{iR}{V} = \exp\left[-\frac{t}{L/R}\right]; \quad i = \frac{V}{R}\left(1 - \exp\left[-\frac{t}{\tau}\right]\right)$$

Thus the current builds up, at a rate determined by the  $L/R$  time constant, to  $V/R$ . The exciting part happens when the switch is then opened and the current stops. If this is done instantaneously ( $dt = 0$ ), then  $L \frac{di}{dt} = -\infty$ , so an infinite voltage appears at  $V_s$ . While this is a good way of generating an increased voltage, a numerical circuit simulator cannot handle instantaneous infinities, and in any case they do not occur in a real circuit, so we will next simulate something a little more realistic.

### 3.2 Step up (“boost”) converter

Set up a simulation of the circuit shown in Fig. 5. Set the values of the resistor and inductor to 1  $\Omega$  and 1 mH to give a time constant  $\tau = L/R$  of 1 ms.

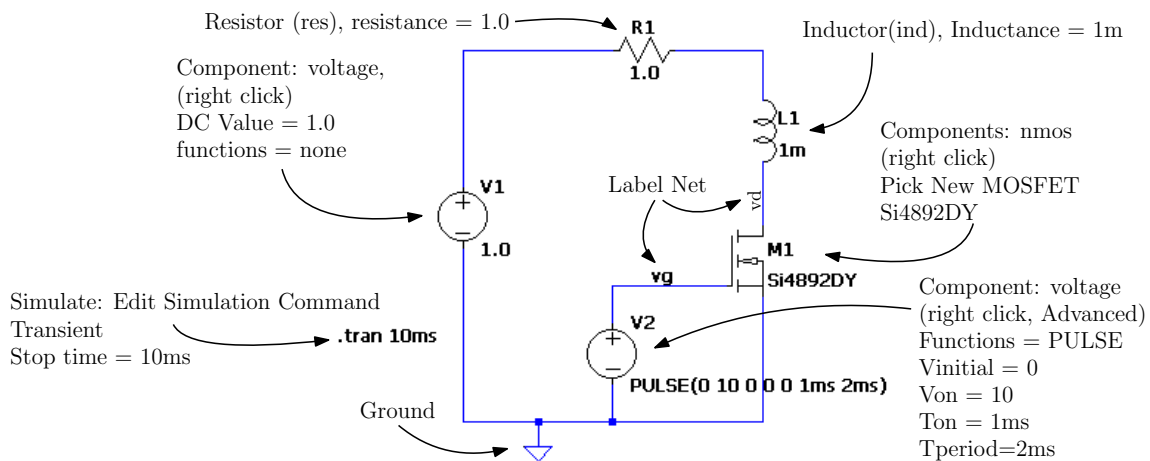


Figure 5: Boost converter

The MOSFET M1 (see Fig. 6) acts as the switch in this circuit. When a positive voltage of a few volts is applied to its gate electrode, it conducts strongly between source and drain. Without the gate

voltage, it switches off. Here we replace the electronics that would normally drive the gate by a source of rectangular voltage pulses, V2. In contrast to this, voltage source V1 is set to a constant 1 volt, like a battery.

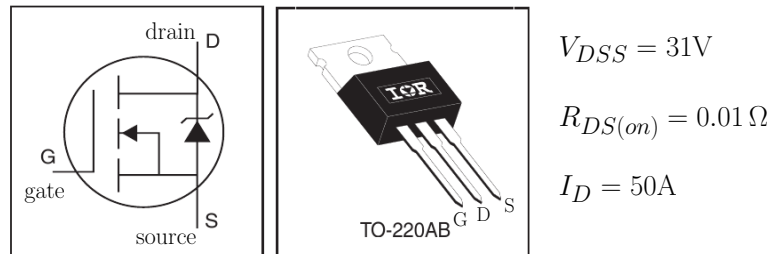


Figure 6: Si4829DY MOSFET.  $R_{DS}$  is the resistance when on;  $V_{DSS}$  is the voltage at which the isolation breaks down when off.

Because the circuit is neither linear nor time-independent, an AC simulation is of little help. Instead, we use a transient simulation that numerically integrates the differential equations of the circuit.

By running the simulation, you should be able to make a plot like Fig. 7, which shows the switch control Vg in blue, the steady rise of the inductor current in red, and a large voltage transient at Vd in green. To make a plot like this, click on the Vg and Vd wires when the cursor changes to a voltage probe, and click on the body of the inductor when it shows a little ammeter. Plot Settings » Add Plot Pane allows you to add a second graph, then you can drag the curve labels between graphs.

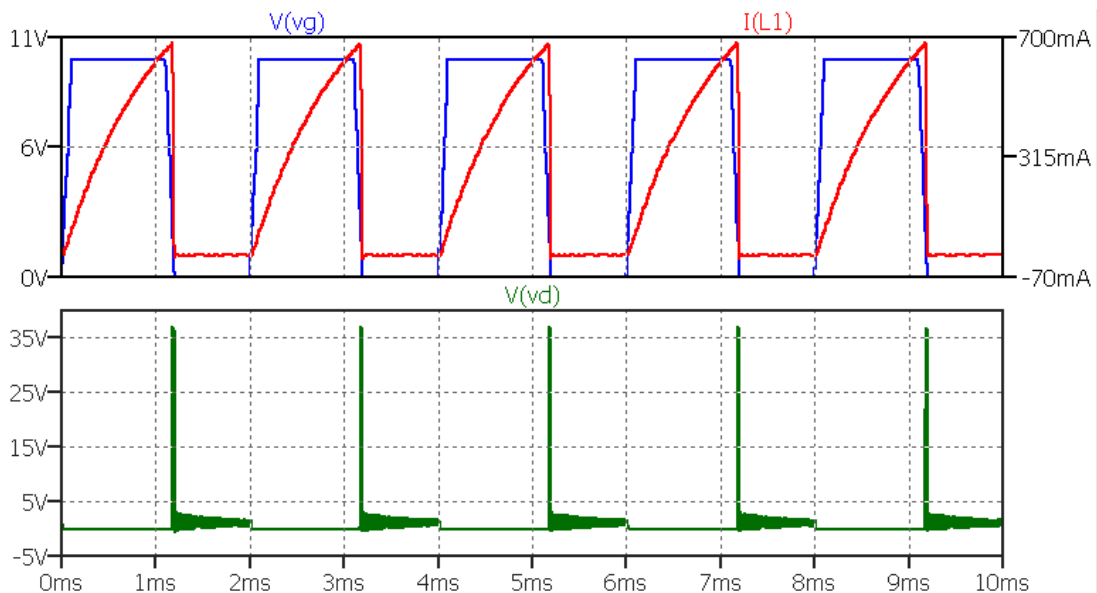


Figure 7: Boost converter in operation

Record the waveforms that you get, and carefully annotate your graph to show how you understand the relationship between the opening and closing of the switch, the varying current in the inductor, and

the voltage that is generated. Be as quantitative as possible. What determines the size and duration of the voltage spike? The fat voltage trace near zero volts is worth exploring too. You can zoom into the plotted data using the magnifying lens buttons on the toolbar.

DEMO NOTES: *Things we'd like to see:*

- Current rises as in sect. 3.1 while switch closed. After 1 ms,  $t/\tau = 1$ , so expect  $1 - 1/e = 0.63$  times the final current of 1 A. Numerical results will differ slightly because the simulation correctly models the on-resistance of the switch and the rise time of the generator.
- While switch is being opened (again, the opening time of around 20  $\mu\text{s}$  is modelled correctly), the current falls and a large  $V_d$  is generated throughout this time.
- The voltage does not exceed  $\sim 37\text{ V}$  because the transistor starts to break down above 31 V (see Fig. 6). Again, this is modelled correctly.
- The voltage is actually oscillating after the high voltage pulse (L1 and internal capacitances in the transistor).

### 3.3 Storing the output voltage

A continuous high voltage output would be more useful than pulses. Add a diode (from the toolbar), a capacitor of capacitance 1 $\mu$  and resistor of resistance 50k as shown in Fig. 8. The idea is that the 1  $\mu\text{F}$  capacitor C1 stores the output voltage, while the 50 k $\Omega$  resistor R2 represents a load circuit that makes some use of the high voltage power.

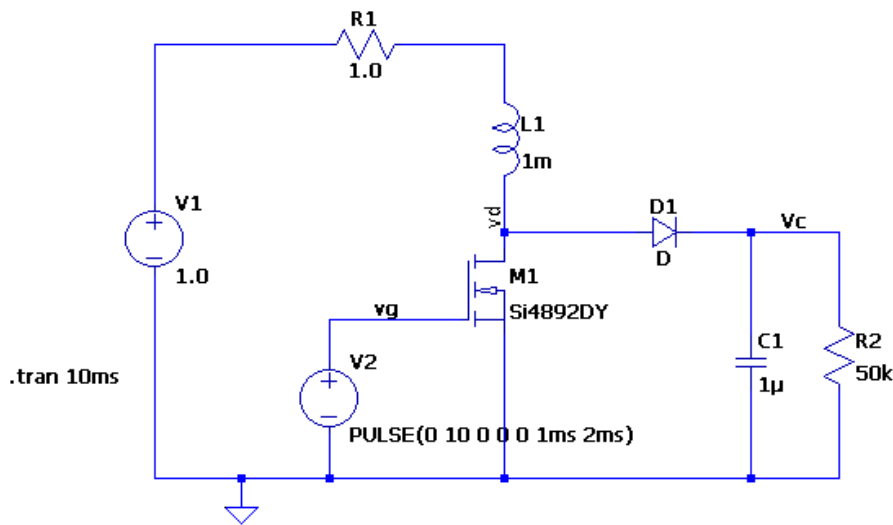


Figure 8: Smoothing the output voltage

Simulate this circuit, plotting also the capacitor voltage  $V_c$ , which you should see does not fall away like  $V_d$ . Annotate your plot and use it to explain when the diode conducts and when it does not, and the shape of the  $V_c$  waveform. Also simulate for longer (Edit the `.tran 10ms` to be e.g. 30ms) and explain the steady state behaviour.

DEMO NOTES: *Diode conducts when  $V_d > V_c$  by about 0.7V (you can see  $V_d$  is clipped to about*

0.7V above  $V_c$  in the simulation). This charges  $C1$ , but when  $V_d$  falls away, the diode cannot conduct in the reverse direction, so  $C1$  remains charged. Successive pulses at  $V_d$  add to the charge in  $C1$ .  $V_c$  ramps downwards because it discharges by passing current through the load  $R1$ . If there were enough time for  $C1$  to discharge all the way, you'd see an exponential decay to zero volts, but the initial 2 ms of this decay is almost linear. Running the simulation for 30 ms shows that eventually  $V_c$  levels out to 35-36 V with a steady ripple.

### 3.4 Efficiency

Ideally, all the power entering a circuit like Fig. 8 would be delivered to the load. Considering just one of the pulses, compare the maximum energy stored in the inductor with the amount delivered to the capacitor [the energy stored in an inductor is  $\frac{1}{2}LI^2$ , that in a capacitor is  $\frac{1}{2}CV^2$ ]. Also note the power lost in  $R1$  and comment on your result. You may find it helpful to use the cursor on the graphs to read values (shown at the bottom of the window).

DEMO NOTES: *Peak current in the inductor is 0.67 A, hence  $2.24 \times 10^{-4}$  J stored. Capacitor steps from 34.8 to 36.25 V, an increment of  $5 \times 10^{-5}$  J (exact values will vary), so the switching process is not completely efficient. Average current in the resistor is about 710  $\mu$ A. Over the 2ms between pulses, it dissipates the  $5 \times 10^{-5}$  J that was put into the capacitor – as it must, to be in a steady state.*

## 4 Flyback converter: output isolation

A disadvantage of the circuit of Fig. 8 is that the output (e.g. 5 V dc USB power) cannot be isolated from the input (e.g. derived from 240 V ac mains). This could be a safety hazard. Now we add a second winding on the inductor to allow us to take power out of it without any electrical connection; the input and output circuits are coupled only by their shared magnetic flux.<sup>2</sup>

### 4.1 Simulating a flyback converter

Convert your model to Fig. 9 (the Cut tool [scissors] is useful for removing circuit elements). Tell LTspice that the two inductors are coupled magnetically by using the Spice Directive button (looks like .op) » Edit text on the schematic » How to netlist = SPICE directive to add the text **K L1 L2 1** in the text box. Place the generated text near the inductors. Notice the reversed direction of the diode. For convenience in plotting, the  $V_c$  and ground terminals have also been interchanged. Run the simulator, and examine how the signals compare to those in the non-isolated circuit of Fig. 8.

If the two inductors are not oriented the same way, as indicated by the circle near one end, only a small  $V_c$  will be seen. Investigate this and explain why.

DEMO NOTES:  *$V = -N \frac{d\phi}{dt}$  applies to both inductors, and the flux  $\phi$  is the same in each of them, owing to the 100% coupling (1) of the K directive, so voltages should be the same. The dominant voltage spike has a certain sign, which has to match the orientation of the diode to make it into the capacitor.*

<sup>2</sup>The term flyback relates to the movement of the electron beam in vintage cathode ray tube televisions; the magnetic flux was used to deflect the electron beam as well as to generate a high voltage.



See if you can get more voltage out of the circuit. Hint: a step-up transformer needs more turns on the secondary than the primary.

DEMO NOTES: Making  $L2$  bigger by a factor  $N$  implies  $\sqrt{N}$  more turns, and correspondingly greater voltage, but to get very far with this, you also need to increase  $R2$ , since the power available is limited by the current in  $L1$  and the switching rate.

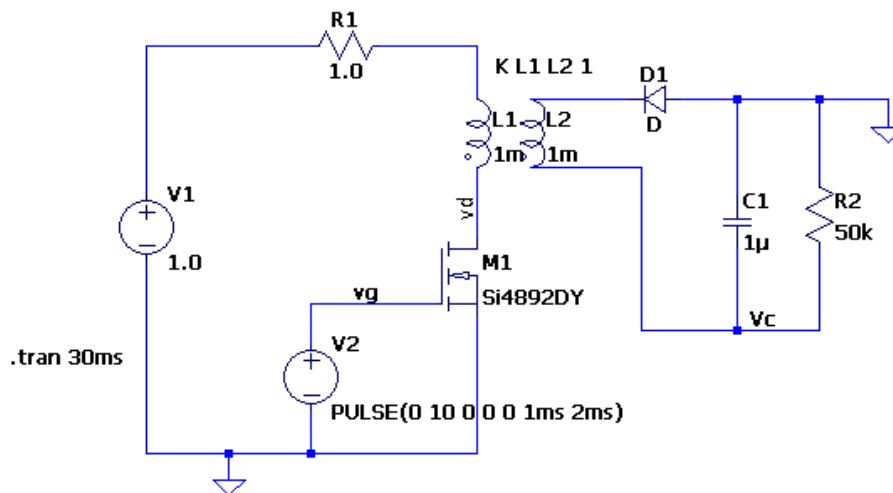


Figure 9: A flyback power converter

## 4.2 How realistic is all this?

In the separate practical “Switch mode power supply” experiment, you can build a circuit very similar to Fig. 9, and use it to generate a few hundred volts from a 1.5 V battery. A real mains power supply uses the same principle, as shown in Fig. 10. You should be able to identify in it all the key elements of Fig. 9, alongside its input power and control circuits.

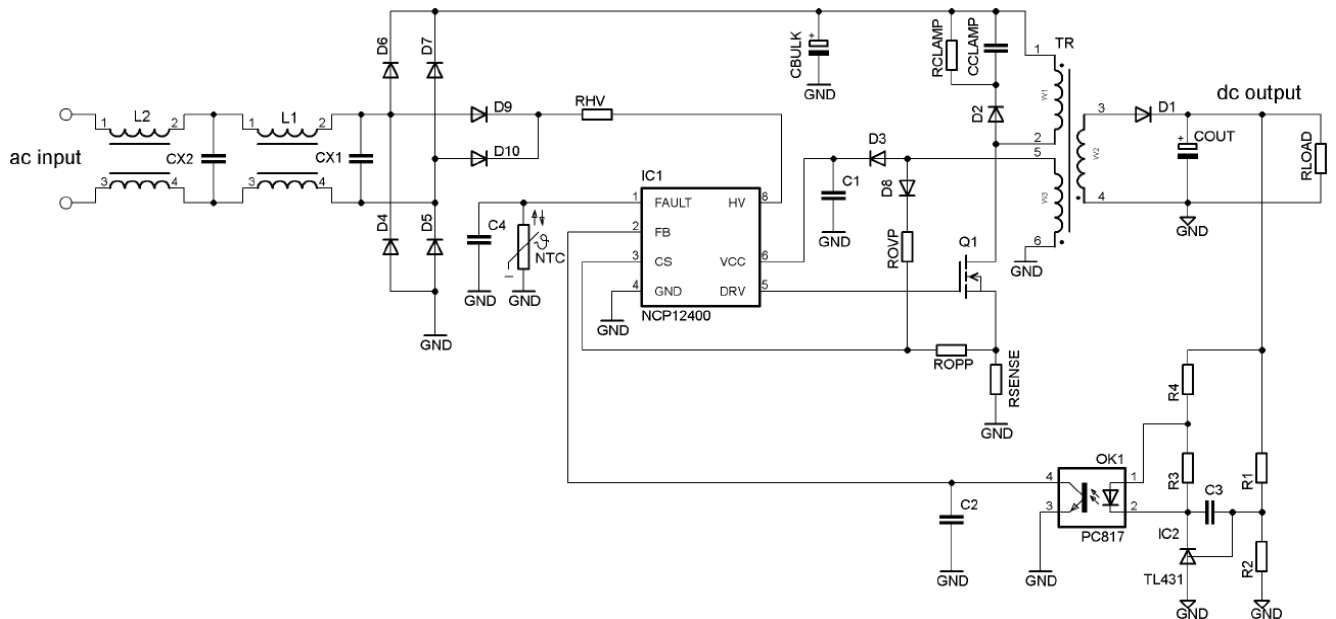


Figure 10: A practical mains power supply (ON Semiconductor NCP12400 data sheet)

DEMO NOTES: *Anyone moving to the switch mode lab experiment after this should go straight to “section 4: Higher voltages” in that experiment.*

*Enthusiastic students should be able to pick out some of the main components of the realistic circuit, thus: Correspondence between Fig. 9 and Fig. 10:*

- *L1, L2 & K - TR*
- *M1 - Q1*
- *D1 - D1*
- *C1 - COUT*
- *R2 - RLOAD*
- *V2 - IC1 and surrounding components*
- *V1 - Everything from ac input to CBULK*

*In case anybody asks: D2 and friends damp the inductor and keep the transient voltage under control. Circuitry around OK1 senses the output voltage and tells IC1 to back off once it is high enough. Notice that OK1 is optically isolated, to avoid breaching the input/output electrical isolation. The bottom winding on TR makes a secondary power supply for the chip (D3, C1).*

## Recreational reading

- <http://www.righto.com/2012/10/a-dozen-usb-chargers-in-lab-apple-is.html>
- <https://spectrum.ieee.org/tag/switching+power+supplies>