Calculating Optimum Snubbers

Jim Hagerman, Hagerman Technology
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Introduction

I was reading my first issue of *Audio Amateur* when my eye caught the letter from Scott Morovich (*TAA 3/94 p.46)* regarding snubber design in power supply diode circuits. I've been working recently on snubber design and everything he said was right on the money. Rick Miller's reply suggested using capacitors only as snubbers, but these may not have the effect he expected and the impedance of the circuit may not be as low as he thinks. A similar letter *(p.49)* gave me the impression that there may be a lot of misunderstanding out there about how snubbers work. I thought perhaps I could help by sharing my analysis of snubbers in power supply circuits. The results show that snubbing the parasitic RF oscillations is relatively straightforward without having to resort to exotic diodes.

The basic snubber type in this analysis is a series resistor and capacitor usually placed across the power supply rectification diodes. Many readers have tried this, but coming up with values for the components can be a crapshoot. This analysis (once you get through the math) results in a few simple equations (boxed) allowing direct calculation of optimum values. At a minimum they provide a starting point for the all important listening tests.

The Problem

A snubber is needed when an oscillatory circuit must be damped. Oscillatory circuits come in many forms but can often be reduced to a simple LC circuit commonly known as a "tank", see Figure 1. This circuit has a natural oscillation frequency given by

$$f_n = \frac{1}{2\pi\sqrt{LC}}.$$

When damped by the addition of a resistance the natural oscillation frequency remains unchanged but the amplitude of the oscillation will decay in time to zero. Figure 2 shows a typical output when excited by an impulse.

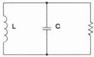

Figure 1. RLC tank circuit.

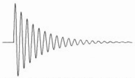

Figure 2. Voltage output of RLC circuit.

Damping can occur at a much greater rate than the frequency so that no oscillation or "ringing" is seen. Conversely, insufficient damping allows oscillation to continue for a long time.

Equivalent Circuit

To get a better understanding let us redraw Figure 1 adding a zero impedance voltage source in series with the inductor. It will have the same AC characteristics and we can drive it with any stimulus function we choose. We could put the voltage source anywhere in the circuit but this position will become convenient later in the analysis.

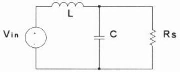

Figure 3.

If we define the output as the voltage across the capacitor we can calculate the output/input transfer function. It is simply a voltage divider given by

$$H(s) = \frac{\left(\dfrac{R_s \cdot \dfrac{1}{sC}}{R_s + \dfrac{1}{sC}}\right)}{\left(\dfrac{R_s \cdot \dfrac{1}{sC}}{R_s + \dfrac{1}{sC}}\right) + sL}$$

which reduces to

$$H(s) = \frac{\left(\frac{1}{LC}\right)}{s^2 + s\left(\frac{1}{R_s C}\right) + \left(\frac{1}{LC}\right)}.$$

Many will recognize this as having the form of a second order response. The general form given by

$$T(s) = \frac{\omega_n^2}{s^2 + s(2\zeta\omega_n) + \omega_n^2}$$

where ζ is the damping coefficient and ω_n is the natural frequency in radians. Many systems in real life can be approximated by this function, especially the step response of an amplifier. Figure 4 shows various step responses of a second order function for ζ varied from 0.3 to 0.9. The smaller the damping, the greater the ringing.

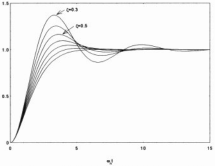

Figure 4. Step responses of second order function.

Equating the previous two equations we get

$$2\zeta\omega_n = \frac{1}{R_s C}$$

and

$$\omega_n^2 = \frac{1}{LC}.$$

The latter becoming the familiar description of the natural oscillating frequency

$$\omega_n = \sqrt{\frac{1}{LC}}$$

or

$$\boxed{f_n = \frac{1}{2\pi\sqrt{LC}}}.$$

The other equation is solved for damping as

$$\zeta = \frac{1}{2\omega_n R_s C}.$$

But what we really want is to calculate the value of resistance which "snubs" the circuit to our desired response. This is solved as

$$\boxed{R_s = \frac{1}{2\zeta\omega_n C} = \left(\frac{1}{2\zeta}\right)\sqrt{\frac{L}{C}}}.$$

Notice in Figure 4 a reasonable damping occurs at a ζ of 0.5. Too little damping allows the oscillation to continue and too much damping results in high resistor power dissipation. So using a damping of 0.5 our equation reduces to

$$\boxed{R_s = \sqrt{\frac{L}{C}}}$$

which is exactly what the Cornell Dubilier application note suggests. It is the characteristic impedance of our circuit.

Snubber Capacitor

Using only a resistive snubber as in Figure 3 will result in excessive power dissipation. To cure this a capacitor C_s is placed in series with R_s. Its value must be large enough so that the ringing frequency is easily passed but all lower frequencies and DC are blocked. We know that the -3dB corner frequency of the snubber is given by

$$f_o = \frac{1}{2\pi R_s C_s}.$$

However we don't want to be 3dB down or our chosen value of ζ won't be achieved. We need a corner frequency about 10 times lower. For convenience it is nice to choose a frequency that is 2π (about 6.3) times lower. This gives us a nice, simple equation for determining the snubber capacitor.

$$\boxed{C_s \approx \frac{1}{R_s f_o} = \frac{2\pi\sqrt{LC}}{R_s}}.$$

Determining Values

One problem is that the equivalent parasitic inductance and capacitance are not always known, but there are ways to measure them.

Inductance can be measured on some of the newer DMMs. It is the leakage inductance of the secondary that will cause the parasitic RF oscillation. Leakage can be determined by shorting the primary and measuring the inductance of the secondary (out of circuit, of course). This is also a good way to calculate the coupling coefficient of a transformer defined as

$$k = \sqrt{\frac{L_{oc} - L_{sc}}{L_{oc}}}$$

where L_{oc} is the open circuited inductance and L_{sc} is the short circuited (leakage) inductance.

Transformers also have a lot of inter-winding capacitance. This can be approximated as a single lumped capacitor in parallel with the inductance. Measuring the capacitance directly is difficult but can be done with a bridge type impedance analyzer. Not exactly something everyone has lying around. Another method uses a sinewave generator and an oscilloscope. Connect the output of the generator through a series resistor and the coil. Measure the voltage across the coil while varying frequency. The lowest frequency which gives a peaked reading is probably the natural resonant frequency of the coil. Using our formula and knowing the inductance you can calculate the equivalent capacitance.

The diode capacitance depends on the amount of reverse bias and is nonlinear. An approximate zero bias value can be measured using a DMM. Try both polarities to see if you get the same answer. This information can also be obtained from a data sheet.

I tried these techniques on a 1A, 12.6VAC filament transformer. My readings showed a secondary leakage inductance of 0.133mH and an inter-winding capacitance of 550pF. A 1N4004 diode measured about 45pF (data sheet specifies 50pF). As I will show later the transformer and diode capacitances are in parallel. Applying these values to our formulas we get a natural frequency of 560kHz and a characteristic impedance of 470 Ohms.

Sometimes the parasitic inductance or capacitance is difficult to determine. We can replace one of those parameters with the frequency or period of oscillation which can be measured on an oscilloscope of spectrum analyzer. By combining and solving the above equations for different cases we get

$$\boxed{R_s = \frac{\pi f_n L}{\zeta} = \frac{1}{4\pi\zeta f_n C} = \frac{\pi L}{\zeta T_n} = \frac{T_n}{4\pi\zeta C}.}$$

Not just any type of resistor will work well. Wirewounds should be avoided because they themselves are inductive. Carbon composition resistors work the best. However any decent non-inductive type is suitable. Pay attention to power and voltage ratings.

DC-DC Power Supplies

Analyzing DC-DC supplies is easy since the input consists of square pulses and not sinewaves. A typical converter can be reduced to the equivalent circuit of Figure 5. If we ignore the ESR of the output capacitor and inductor, then the parasitic tank circuit becomes the same as Figure 1 (assuming the output capacitor is large and bypassed at RF). The snubber is usually, but not necessarily, placed across the diode. It can be seen in the equivalent circuit that the diode capacitance is in parallel with the coil capacitance so they are additive. Since the snubber resistor must be in parallel with both the inductance and capacitance, it can be placed across either the diode or the coil.

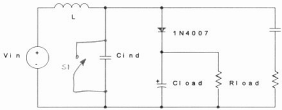

Figure 5. Equivalent circuit of DC-DC converter.

The power dissipated in the resistor is determined by dividing the energy stored in the capacitor by time. The energy is given by

$$E = \frac{1}{2} C_s V_p^2$$

where V_p is the peak voltage stored on the capacitor between pulse edges. A DC-DC converter switches at a typical frequency f_s or period T_s. For each cycle there are two edges or transitions. During each transition all of the energy stored in the capacitor is dissipated in the resistor. Power dissipation is given as

$$\boxed{P = \frac{2E}{T_s} = \frac{CV_p^2}{T_s} = Cf_s V_p^2.}$$

It is important to note that the power dissipated in the snubber resistor is a function of the snubber capacitance, so it helps to make the capacitor as small as possible.

AC-DC Power Supplies

DC-DC switching power supplies are rarely used in audio equipment. Although extremely efficient they regulate by either modulating their switching frequency or duty cycle. Modulation can occur at low frequencies, especially in the audio band, so there is a good chance of switching interference in low level audio circuits. High power car amplifiers is one application that requires their use because the battery voltage is insufficient.

Ringing occurs in AC-DC supplies when the diode is just turning off. Using the 1A, 12.6VAC transformer of the previous example we had a natural ringing frequency of 560kHz. This is much higher than the audio band. However, it is modulated by the power line frequency. A half-wave bridge will "buzz" at the line frequency and a full-wave bridge at twice the line frequency. The ringing frequency acts as a carrier to couple with other circuits. To make matters worse the capacitance of the diode is nonlinear so the ringing frequency will contain plenty of harmonics well into the MHz region. Another problem is that the circuit is physically large consisting of a power transformer, diodes, and output capacitors resulting in a significant loop area. Coupling mechanisms to other circuits are both magnetic and capacitive. It is no wonder audio designers often build the power supply on a separate chassis.

Judicious attention to wiring, loop area, components, and shielding will reduce the ability of the oscillation to couple with other circuits. However, this only attacks the symptoms, not the cause. This is where snubbers come in.

A typical power supply circuit is shown in Figure 6. It can be reduced to the equivalent circuit of Figure 7. The primary to secondary turns ratio is replaced by a voltage source of the appropriate value. Accuracy of the model is improved by the addition of transformer secondary and output capacitor ESR (combined in R_t).

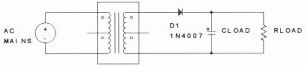

Figure 6. AC-DC power supply.

As suggested in the letters I added C_x, a purely capacitive snubber. A full-wave bridge can be reduced to the same circuit but with two diodes in series. This will effectively cut the diode capacitance in half and the analysis is still valid.

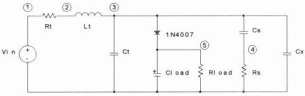

Figure 7. PSPICE circuit.

The above circuit was simulated using PSPICE (see Appendix A for a listing). I modeled the 1N4007, a commonly used 60Hz rectifier, using data sheets from Motorola. Figure 8 shows the simulation without the snubber components, R_s, C_s, & C_X. A load of about 100mA was added so the diode always conducted during each cycle. Initial conditions set the output voltage to zero, consequently the first sinewave pushed the output up to near final value. The second peak more clearly shows the steady state conditions. It is difficult to see in the figure but near both 5ms and 22ms the diode turns off and there is a burst of ringing.

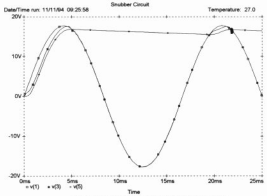

Figure 8. PSPICE simulation of Figure 7.

To see what it really going on we zoom in on the ringing near 22ms. Figure 9 clearly illustrates the problem. The oscillation should be approximately 560kHz as we calculated.

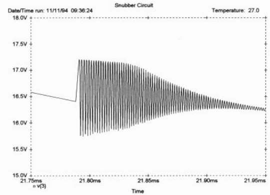

Figure 9. Ringing of standard circuit.

Derivation of snubber values is a little different than before because of R_t. The solution, skipping the mathematical derivation, is given by

$$\boxed{R_s = \frac{\omega_n L_t}{2\zeta - \left(\dfrac{R_t}{\omega_n L_t}\right)} = \frac{L_t}{2\zeta\sqrt{L_t C_{eq}} - R_t C_{eq}}}$$

where

$$C_{eq} = C_t + C_d + C_x.$$

As R_t goes to zero the equation is the same as we had before. In practice R_t is so low that it may not effect the outcome significantly, although if large enough it would act as a snubber itself. Targeting a damping of 0.5 we calculate our snubber values as

$$R_s = \sqrt{\frac{L_t}{C_{eq}}} = \sqrt{\frac{0.133mH}{600pF}} = 471\Omega$$

$$C_s = \frac{2\pi\sqrt{L_t C_{eq}}}{R_s} = \frac{2\pi\sqrt{(0.133mH)(600pF)}}{471} = 3800pF.$$

Using standard values of 470 Ohms and 3900pF the circuit was simulated and results shown in Figure 10. Ringing is almost completely damped out except for the initial pulse. Overshoot is consistent with a damping of about 0.5.

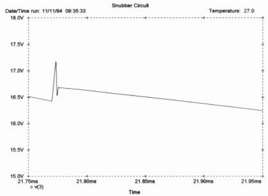

Figure 10. Ringing with RC snubber.

It is interesting to see what happens when only a capacitor is used as a snubber, as is commonly recommended. A value of 0.01uF was added for C_x and then simulated. Figure 11 shows the results.

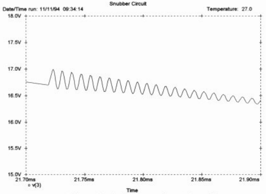

Figure 11. 0.01uF capacitor only snubber.

Ringing is still evident, no damping or snubbing has occurred, however the frequency is much lower. The new frequency should be

$$f = \frac{1}{2\pi\sqrt{L_t C_{eq}}} = \frac{1}{2\pi\sqrt{(0.133mH)(0.0106uF)}} = 130kHz.$$

Obviously the improvement in sonic quality or reduction of noise occurs because the ringing frequency is so much lower that the ability to couple to other circuits is reduced. In fact, the larger the capacitor, the lower the frequency. All of this very much depends on the quality of the components and the transformer involved. It should come as no surprise that each power supply must be individually tuned for optimum performance.

So what happens if both types of snubbers are combined? Keeping C_x we recalculate values for R_s and C_s getting 110 Ohms and 0.068uF respectively. Again a simulation was performed and is shown in Figure 12.

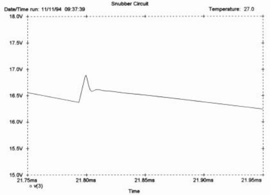

Figure 12. RC & C snubber.

This solution may be the best of all. Not only is ringing snubbed by the R_s & C_s but the frequency of the initial pulse is lowered by C_x.

Calculating the power dissipation in the resistor can be done knowing the input rms voltage V_{rms} (and a lot of math). Power is given and approximated by

$$\boxed{P_{R_s} = \frac{V_{rms}^2\left(2\pi f_{ac} R_s C_s\right)^2}{R_s\left[1+\left(2\pi f_{ac} R_s C_s\right)^2\right]} \approx R_s\left(V_{rms} 2\pi f_{ac} C_s\right)^2.}$$

For our final case we get

$$P_{R_s} \approx (110)[(12.6)(2\pi)(60)(0.068uF)]^2 = 12\mu W.$$

Not very much power is dissipated in the resistor because the power line frequency is relatively low.

Reader Feedback

Of course all of this theory may be hogwash. The real test is how these snubbers actually perform in real circuits. I have tried them in several DC-DC switching power supply circuits with excellent results. In fact none of them required tweaking after calculation of the original values.

I encourage readers to try these snubbers in their audio equipment. Improvements in sonic quality could range from nothing to quite dramatic. If anything there should be a reduction in power line buzz. Good luck!

Appendix A: PSPICE Listing of AC-DC Snubber Circuit

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Snubber Circuit, Jim Hagerman, 11/11/94

Vin 1 0 sin(0 17.8 60 0 0)

Rt 1 2 0.5
Lt 2 3 0.133mH
Ct 3 0 550pF
D1 3 5 _1n4007
Cload 5 0 1000uF
Rload 5 0 180
;Rs 4 0 470 ;110
;Cs 3 4 3900pF ;0.068uF
;Cx 3 0 0.01uF

;.tran 0.01m 25m
.tran 0.001m 25m 20m
.probe
.option ITL5 10000

* Jim Hagerman
* 11/7/94 typical
.model _1n4007 d
+ (
+   n   = 1.57
+   is  = 6.1e-10
+   rs  = 0.044
+   tt  = 7.2e-6
+   cjo = 50e-12
+   m   = 0.25
+   vj  = 0.31
+   eg  = 1.11
+   xti = 3.0
+   bv  = 1000
+   ibv = 1e-6
+ )

.end
```

References

. Rick Miller et. al., *TAA* 1/94, 26-27; *TAA* 3/94, 46,49.
. G. Chryssis, "High-Frequency Switching Power Supplies, Theory & Design," 138-140.
. "Designing an RC Snubber", *Cornell Dubilier Snubber Capacitors*, 14-16.

Biography

Jim Hagerman obtained a BSEE from the University of Minnesota in 1982. His professional career has been designing circuits for CRT based displays and pursuing the "art of analog". He has published several technical articles and has several patents pending. In the future he hopes to offer tube-based audio equipment DIY kits.