DESIGN SOLUTIONS

POWER

Correct Snubber Power Loss Estimate Saves the Day

Introduction

Your customer is worried. He believes the resistor in your voltage regulator's snubber network is overheating and suspects it is causing reported field failures. At stake are millions of products already in the field. Now the customer is at your door step asking for help. Should a recall be issued? What are you going to recommend?

Why Use a Snubber?

First, let's look at the theory behind the use of a snubber. Figure 1 shows a typical buck switching regulator with an RC snubber network. Without the snubber, ringing can occur. This can happen during the deadtime between one transistor turning off and the next transistor turning on. During this period, the output loop is closed only by the parasitic series inductances and the parallel capacitors of the MOSFETs. In theory, the subsequent ringing could be twice as high as the input voltage. Poor PCB layout can also be a strong contributor to ringing. The ringing causes electromagnetic interference (EMI) and system noise interference and may exceed the power train transistors' breakdown ratings, resulting in catastrophic circuit failure. The snubber network reduces the ringing down to safe values, at the cost of power dissipated in the resistor.

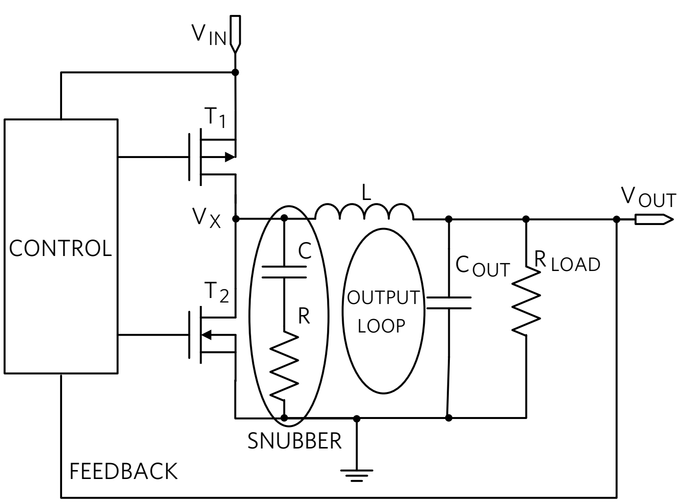

Figure 1. Buck Switching Regulator with an RC Snubber Network

Debugging

Now, back to our story. You visit the customer's lab and look at the crowded PCB housing the voltage regulator. The small external SMD 4.7Ω, 2mm × 1.2m x 0.45mm resistor (0805) is barely visible. Could it have been degraded and be compromising the operation of the circuit? The customer explains the source of the concern. The resistor is rated at 1/8 Watt (125mW), and calculations show that it is dissipating more than its rated power. He states that the calculation for an RC network under a square-wave voltage, V, and frequency, f, is simple enough:

$$P = CV^2f = 680pF \times 19.5^2V \times 500kHz = 129mW$$

The issue is not just that the power dissipation is slightly (4mW) above the resistor rated power. His golden rule is to size the resistor power rating at twice the power dissipation to provide adequate design margin. Hence, the resistor power rating is off by more than 100%. Or is it?

CV^2f Derivation

One of the most popular formulas in the electronics industry is CV^2f. To understand it, it helps to go through the derivation. Figure 2 shows the Vx node of Figure 1 represented by a voltage source and the snubber circuit with the indicated values.

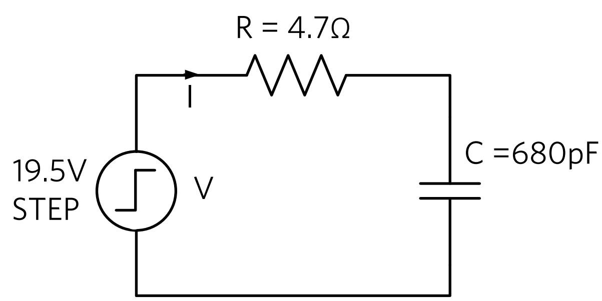

Figure 2. Simplified Snubber Network Circuit

Under a positive step voltage, the current in the snubber circuit is:

$$I = \frac{V}{R} \times e^{-t/RC}$$

where V is the 19.5V step amplitude. The power dissipated in the resistor is:

$$P(t) = R \times I^2 = \frac{V^2}{R} \times e^{-2t/RC}$$

Going from instantaneous power to average power requires integration over time, namely calculation of the energy. Note that integration over the half-period, T/2, of a repetitive square wave would produce practically the same result as RC<<T:

$$\int_{0-}^{+\infty} P(t) \times dt = \frac{1}{2} CV^2$$

For a square-wave voltage source, the same amount of energy is dissipated during the 'low' time of the voltage source, hence the total energy dissipated in one period is doubled:

$$E = CV^2$$

The average power dissipated is the energy, E, divided by the period, T:

$$P = \frac{CV^2}{T} = CV^2 f$$

where f is the square wave voltage source frequency.

The important thing to notice here is that the formula's underlying assumption is that the snubber input voltage is a square wave with perfectly vertical rising and fall edges (a step-function). How true is this hypothesis in our case?

Finite Rise/Fall Time Derivation

A voltage probe on the snubber input node (Vx in Figure 1) reveals that the rise and fall times appear to indeed be quite fast. They ramp up and down the 19.5V excursion in 10ns. Does that make a significant difference? Going back to square one, we repeat the same calculations as above, but this time with ramped edges (Figure 3) instead of step-function edges.

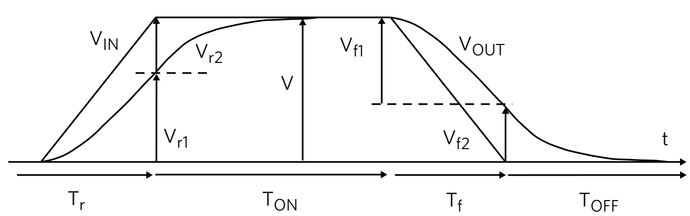

Figure 3. Ramp Waveforms

The equations below describe the energies, Er1 and Er2, associated with rise time T_r and T_{ON}, respectively:

$$E_{r1} = CV^2 \frac{\tau}{T_r} \left(T_r - \frac{3}{2}\tau + 2\tau e^{-\frac{T_r}{\tau}} - \frac{\tau}{e} e^{-\frac{2T_r}{\tau}}\right)$$

$$V_{r1} = \frac{V}{T_r} \left[T_r - \tau(1 - e^{-\frac{T_r}{\tau}}) \right]$$

$$E_{r2} = \frac{1}{2} CV_{r2}^2$$

$$V_{r2} = V - V_{r1}$$

A similar set of equations is derived for the falling edge:

$$E_{f1} = CV^2 \frac{\tau}{T_f} \left(T_f - \frac{3}{2}\tau + 2\tau e^{-\frac{T_f}{\tau}} - \frac{\tau}{e} e^{-\frac{2T_f}{\tau}}\right)$$

$$V_{f1} = \frac{V}{T_f} \left[T_f - \tau(1 - e^{-\frac{T_f}{\tau}}) \right]$$

$$E_{f2} = \frac{1}{2} CV_{f2}^2$$

$$V_{f2} = V - V_{f1}$$

The total average power dissipation is the sum of the four energies times the frequency of the voltage source:

$$P = (E_{r1} + E_{r2} + E_{f1} + E_{f2})f$$

We find out the hard way that the power loss equations in the ramp case are a bit more complicated.

Simplification

A saving grace in the case of Figure 2 is that the snubber RC time constant is small compared to the rising edge duration, Tr, and that the rise and fall times are identical:

$\tau = RC = 4.7 \times 680n = 3.2nsec < Tr = 10nsec$, hence $e^{-Tr/\tau} \ll 1$

and $Tr = Tf$

This allows for the simplification of the ramp power expression to:

$$P \approx CV^2 f\alpha$$

Where the correction term α is simply:

$$\alpha = 2\frac{\tau}{Tr}\left(1 - \frac{\tau}{Tr}\right) = 0.43$$

Hence, the real power dissipated in the RC network is less than half of that predicted with the step-function assumption:

$$P \approx 129mW \times 0.43 = 56mW$$

This result is within an accuracy of approximately 1mW compared to the exact calculation. Accordingly, the $1/8^{th}$ Watt resistor is indeed sized to take more than twice the power dissipated, adhering to your customer's golden rule after all. You get to live another day.

In the case that $Tr \ll \tau$, for example:

$\tau = RC = 4.7 \times 680n = 3.2nsec \gg Tr = 0.1nsec$

then the correction term would be:

$$\alpha' = \left(1 - \frac{Tr}{\tau}\right) = 0.97$$

In other words, here is where the step-function formula works best. Finally, for $Tr \approx \tau$ the approximation that works best is

$\alpha'' = 1/3$.

Simplis Verification

What we showed above was first, the exact power dissipation equations, and second, the back-of-the-envelope version of the story. Both required some recollection of the physics and math behind the circuit. With a computer, you can easily simulate the circuit using Simplis and get the answer the easy way.

Figure 4 shows the power, voltage and current waveforms for the step-function case simulated with Simplis. Notice how the peak power dissipation in this case is a hefty 81W which accounts for its unfavourability. The label Power(R1) (Y2) in the middle of Figure 4 also reports the average power dissipation: 129.28876mW, in agreement with the previous calculation.

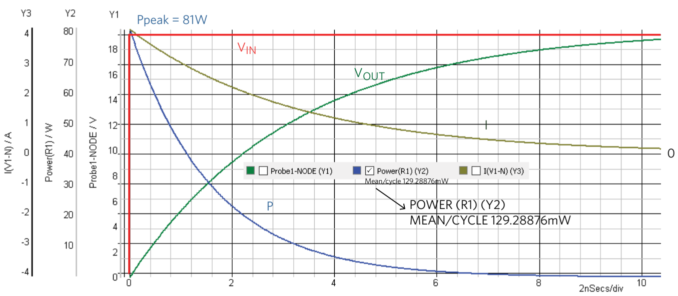

Figure 4. Snubber Simplis Simulation with Step-Function Input Voltage

Figure 5 shows the power, voltage and current waveforms for the ramp case simulated with Simplis. Notice how the peak power dissipation in this case is only 7.5W which accounts for its favorability. The label Power(R1) (Y2) at the top of Figure 5 also reports the average power dissipation: 57.383628mW, within about 1mW of the approximate calculation.

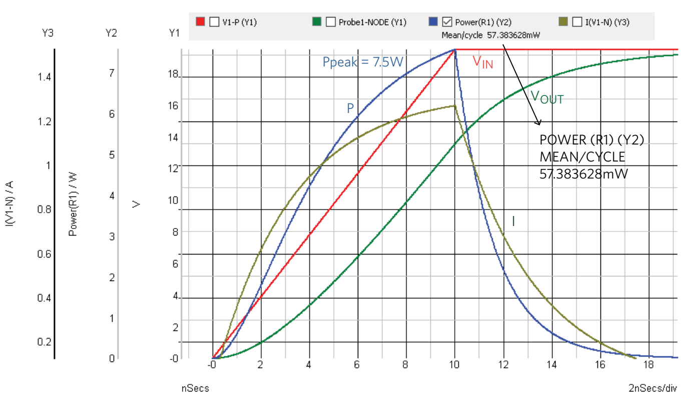

Figure 5. Snubber Simplis Simulation with Ramp Input Voltage

Many switching regulator implementations may benefit from the presence of a snubber network on the Vx output. For practical examples of buck converters utilizing snubbing networks, Maxim's Himalaya family of buck converters are an excellent resource.

Conclusion

We analyzed the power dissipation of a snubber network from several angles and showed different ways to correctly estimate the associated power loss. Going back to our case study, in the end it was revealed that the RC snubber network was innocent, and the field returns were caused by some bad soldering. No recall was needed. As a designer, it's good to have several tools in your toolkit, but more importantly, when the time comes, you must reach for the right tool for the job at hand.

Learn more:

Application Note: R-C Snubbing for the Lab

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