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Correct Snubber Power Loss Estimate Saves The Day

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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 doorstep asking for help. Should a recall be issued? What are you going to recommend?

In this article we present a case study that allows us to examine the common assumptions designers make when choosing the rating for a resistor in an RC snubber network. We start with the familiar formula $P = CV^2f$, which most designers rely on to determine the resistor's power dissipation. We then go back and rederive this formula, explaining as we do so, what assumptions are being made about circuit operating conditions.

Specifically, we'll notice that it has been assumed that a step function or perfect square wave voltage is being applied to the snubber. However, a closer inspection of the switch-node waveform in our design example reveals that the applied voltage is not a perfect square wave with infinitely fast edges. So we derive a revised formula for power dissipation that contains a term to correct for the finite rise and fall times of the switch-node voltage.

We use this new formula to determine whether the resistor in our case study was sufficiently rated for the average power it sees in the voltage regulator circuit. Finally, we run SIMPLIS to verify our results. But before we introduce the case study or derive any formulas, we'll review the reasons we need a snubber network in the first place.

Why Use A Snubber?

First, let's look at the theory behind the use of a snubber. Fig. 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 capacitances 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)—both radiated and conducted—and may exceed the power train transistors' breakdown ratings, resulting in catastrophic circuit failure. The RC snubber network reduces the ringing down to safe values, at the cost of power dissipated in the resistor.

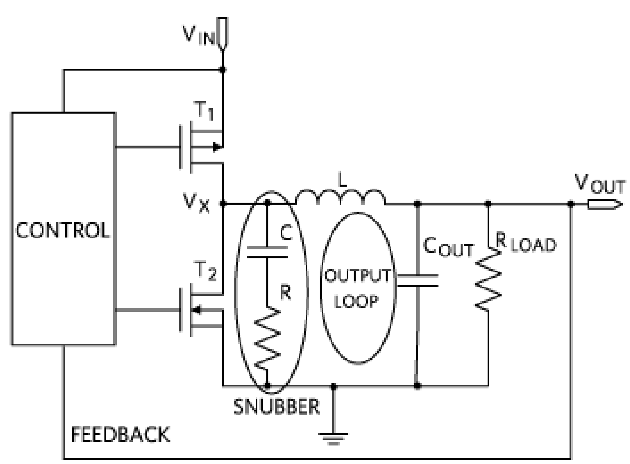

Fig. 1. Buck switching regulator with an RC snubber network.

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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 4.7-Ω, 2-mm x 1.2-mm x 0.45-mm surface-mount resistor (0805 case size) 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, following the product data sheet, is rated at 1/8 W (125 mW), and calculations show that it is dissipating more than its rated power. He states that the calculation of power dissipation for an RC network under a square-wave voltage, V, and frequency, f, is simple enough.

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

The issue is not just that the power dissipation is slightly (4 mW) above the resistor's 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. Fig. 2 shows the V_X node of Fig. 1 represented by a voltage source and the snubber circuit with the indicated values.

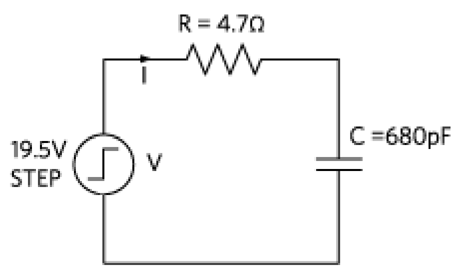

Fig. 2. Simplified snubber network circuit.

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

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

where V is the 19.5-V step amplitude. The power dissipated in the resistor is defined by the following equation.

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

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.

$$\int_{0-}^{+\infty} P(t) * dt = \frac{1}{2} C V^2$$

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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 falling edges (a step function). How true is this hypothesis in our case?

Finite Rise And Fall Time Derivation

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

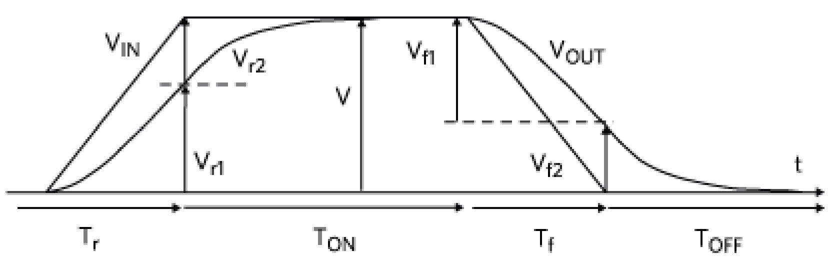

Fig. 3. Ramp waveforms.

The equations below describe the energies, E_{r1} and E_{r2}, associated with rise time T_r and T_{ON}, respectively.

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

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

$$E_{r2} = \frac{1}{2} C V_{r2}^{\,2}$$

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

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

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

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

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

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

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

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

However, 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 Fig. 2 is that the snubber RC time constant is small compared to the rising edge duration, T_r, and that the rise and fall times are identical.

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

and

$Tr = Tf$

This allows for the simplification of the ramp power expression.

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

where the correction term α is simply defined as follows.

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

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

P ≃ 129 mW x 0.43 = 56 mW

This result is within an accuracy of approximately 1 mW compared to the exact calculation. Accordingly, the 1/8-W 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.

Consider a case where $Tr \ll \tau$:

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

then the correction term would be as follows.

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

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In other words, here is where the step-function formula works best. Finally, for $Tr \simeq \tau$ the approximation that works best is $\alpha" \simeq 1/3$.

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.

Fig. 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 81 W, which accounts for its unfavorability. The label Power(R1) (Y2) in the middle of Fig. 4 also reports the average power dissipation: 129.28876 mW, in agreement with the previous calculation.

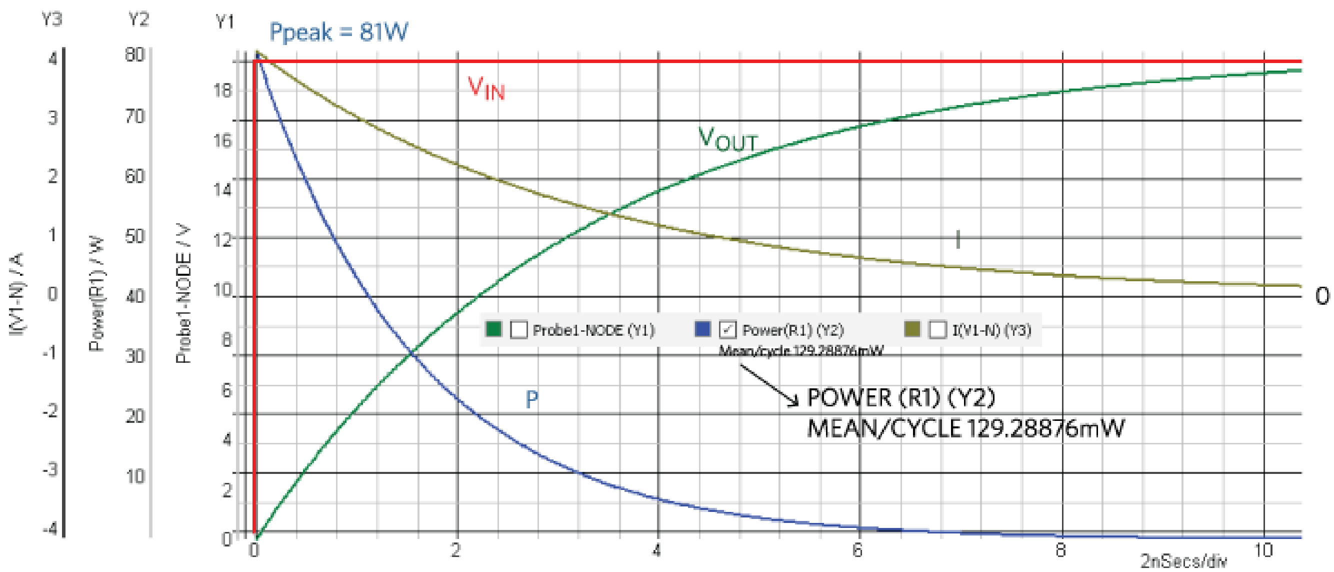

Fig. 4. Snubber Simplis simulation with step-function input voltage.

Fig. 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 7.5 W which accounts for its favorability. The label Power(R1) (Y2) at the top of Fig. 5 also reports the average power dissipation: 57.383628 mW, within about 1 mW of the approximate calculation.

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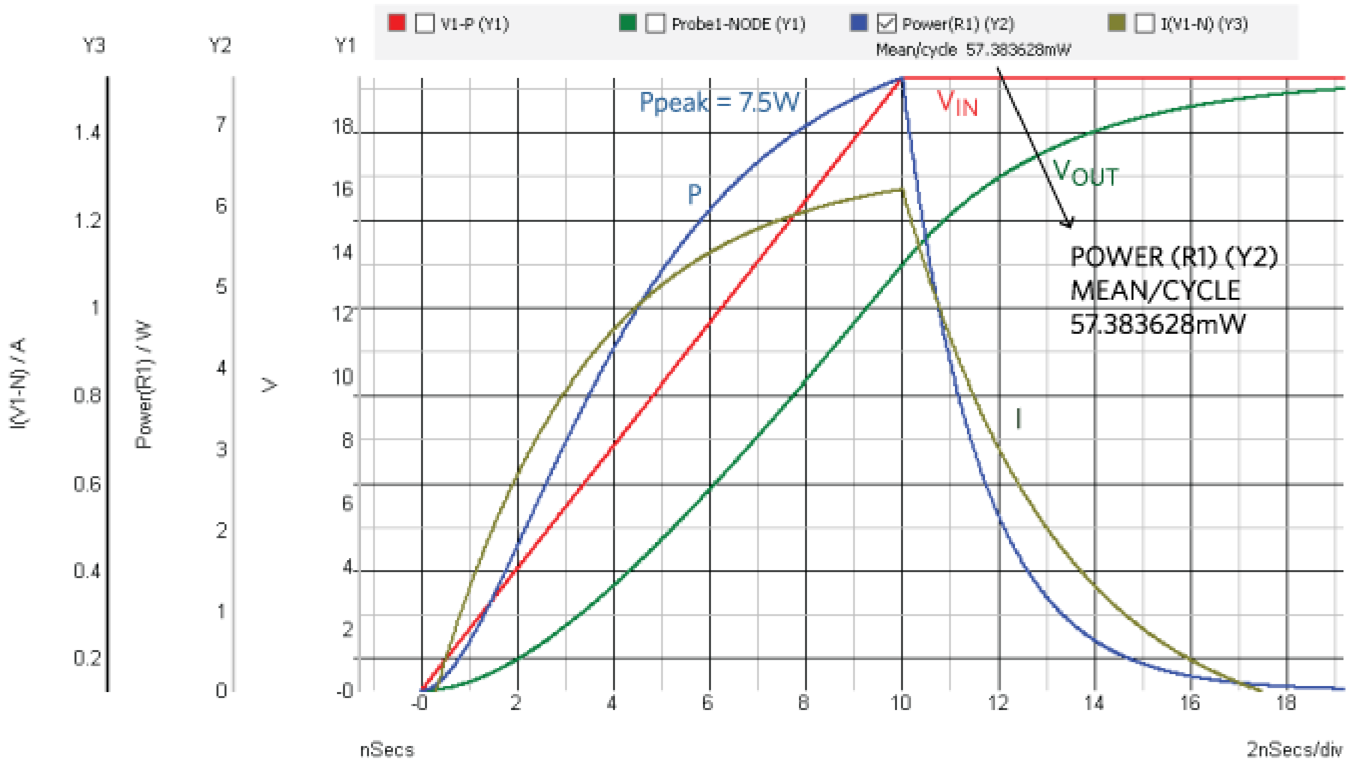

Fig. 5. Snubber Simplis simulation with ramp input voltage.

Many switching regulator implementations may benefit from the presence of a snubber network on the V_X output. For practical examples of buck converters utilizing snubbing networks, Maxim's Himalaya family of buck converters[1] are an excellent resource. To learn more about snubber design, see the application note[2] or the How2Power Design Guide resources cited at the end of the article.

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.

References

1. Himalayas Step-Down Switching Regulators and Power Modules, Maxim Integrated product page.
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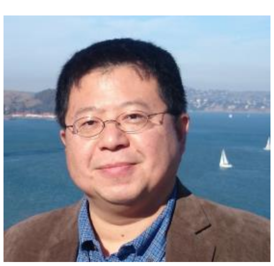
About The Authors



Rayleigh Lan is a senior principle member of Technical Staff at Maxim Integrated. His areas of interest are power management theoretical analysis and applications of analog products and motor drivers. He holds several patents and has published several articles in the field. He received his BSEE and MSEE degrees from National Taiwan University.

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For more on snubber design, see the [How2Power Design Guide](), locate the Power Supply Function category and select Filters and Snubbers.

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