Power Management Integrated Circuits
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Lecture – 64
Choosing Inductance and Capacitance Values

So, we decided 10 MHz switching frequency. Now, we will choose L and C values based on the output ripple specification. Output ripple formula for buck is shown in below.

$$F_{sw} = 10\ MHz$$

$$\Delta V_o = \frac{V_{dd} \cdot D \cdot (1-D)}{8 L C F_{sw}^2} = \frac{1.8V\,(0.5)(0.5)}{8 L C F_{sw}^2}$$

Assume $\Delta V_o = 10mV$ (max)

$$LC = \frac{1.8(0.25)}{8 \times (10 \times 10^6)^2 \times 10mV} = \frac{0.45}{8 \times 1\cancel{00} \times 10^{12} \times \cancel{10^{-2}}}$$

$$= \frac{0.45}{8 \times 10^{12}} = 5.6 \times 10^{-14} \left(\frac{sec}{rad}\right)^2$$

Maximum output ripple 10 mV means, in the worst case you should have 10 mV ripple. Which means including the tolerances in L and C, it should not be more than 10 mV. So, when you design at a typical corner you should have some margin. Usually in typical case you will target 5 mV or so. Because your L and C will have some tolerances and those tolerances maybe ±20% or so.

So, this LC product may see a huge variation and then you also have to consider the variation in the switching frequency (F_{sw}) because you will be designing an on-chip oscillator. That oscillator may also vary across process, voltage and temperature.

Now, we know the LC product. From this LC product, one you have to fix and calculate the other. So, how do we choose L? One thing we know that choosing smaller L and higher C for the same LC product will give you a better transient response, but it will increase your inductor ripple current.

So, you have to go back and calculate your RMS losses. So far we have been considering that your ripple is small, and we are not taking the RMS effect, we are only taking the DC. If inductor ripple current becomes larger, then your RMS losses will be much higher, and it will start dominating. So, if you are choosing a very small L then you have to make sure that you go back and calculate your RMS losses and make sure that your efficiency is not hampered that much.

What do you think the L should be at 10 MHz switching frequency?

So, if you look at any products; you will find the design trend, actually the inductor size. This comes from the experience actually. So, typical output voltage of Lithium-ion battery is roughly 3.6 V. For Lithium-ion battery, we choose L as 3.3 μH for 1 MHz switching frequency. Which means, if your F_{sw} is 3 MHz then L will become roughly 1 μH. When you go to 6 MHz, it will become 0.5 or 0.47 μH and that is how it scales actually. If you pick any product you will see the similar numbers.

And the reason is, this is the optimum value for the range of voltages you are looking for. Your Lithium-ion battery maximum voltage will be 4.6 V or so. 3.6 V is the typical, but usually they are designed for maximum voltage of up to 5.5 V. Considering all those factors, 3.3 μH for 1 MHz will give you the optimum value for which you get a decent efficiency like you can achieve 90% or so. Which means your RMS loss would not be that much and you can still achieve a decent efficiency.

But now we are looking at 1.8 V. This 3.3 μH for 1 MHz is for 3.6 V. I am considering 3.6 V because Lithium-ion batteries spend most of the time at 3.6 V and that is where you actually optimize your efficiency. To have the same output ripple at 1.8 V, inductor value needs to be scale down by a factor of 2, which means 1.65 μH for 1 MHz. For 10 MHz you can choose inductor value as 165 nH to maintain the same ripple.

Now, we know the LC product and we know L value. So, C value turns out to be 0.34 μF.

Do you think this capacitance will be enough to meet the transient? You can meet the ripple spec, but for the transient you have to calculate. So, let's calculate the worst-case transient response. The worst-case is your inductor does not supply any current during transient and all the current is supplied by your capacitor during the rise time of the inductor current.

Let us say load current is 1 A and you know the inductor value. For 50% duty cycle you are looking at V_{in} = 1.8 V and V_{out} = 0.9 V. So,

$$\text{Slope} = \frac{V_{in} - V_{out}}{L} = \frac{0.9}{165n} = 5.45\,\frac{mA}{ns}$$

Let's say during transient, you stretched your duty cycle to 100% (true for transient response limited by inductor slew rate not on the loop bandwidth). So, in 100 nanoseconds inductor current will rise to 545 mA. But if you want to calculate the exact number, then you have to look at the triangular waveform (inductor current); how much charge is supplied by the inductor and how much capacitor is supplying. Because your inductor current will be rising but not at the same rate at which load is rising. Because load can change instantaneously, but this inductor current will have some finite slope. So, that difference will be supplied by your capacitor.

If you want to limit transient response by your loop bandwidth, then you can make your loop delay as 1 over bandwidth and from there you can calculate undershoot and overshoot. Let's say bandwidth is 1 MHz for 10 MHz switching frequency. So,

$$\text{bandwidth} = 2\pi \text{ x } 10^6 = \frac{1}{t_{delay}}$$

$$t_{delay} = \frac{1\mu}{2\pi} = 159 \text{ ns}$$

If you are not limited by loop bandwidth, then you will be limited by inductor current slope. Inductor current slope means you have an instantaneous change in the duty cycle. I mean whenever your load change happens, in the next cycle you will stretch your duty cycle to 100% right away.

But that is not true if you are limited by bandwidth because it will not change your control voltage instantaneously to make your duty cycle to go from 50% to 100% because of finite bandwidth. So, control voltage won't change right away in the next cycle, it will take some time because of the compensator.

But if you have some other control technique like non-linear, then it is possible. In the next cycle it can provide 100% duty cycle, then you would not be limited by bandwidth, but you will be limited by the inductor current slope.

So, your transient will be better if you are using a non-linear control technique. But here you are limited by bandwidth. So, your capacitor requirement might be larger here. Usually the cap requirement is 10 times of your inductor value and usually that is how you keep.

For example, if you have a 1 μH inductor then you try to keep your capacitor value 10 μF or so, and then on top of that you have to consider ±20% tolerances. Let's say your inductor has increased by 20% and capacitor has decreased by 20%. It is quite possible, since your tolerances are random, one may increase and other may decrease. So, that will be the worst case. So, you have to consider the worst case and on top of that keep some margin. So, whatever the capacitor you got from your theoretical calculation, usually keep 2 times of that cap.

If your theoretical calculation says 1 μF then you just choose 2 μF, so that you will still get 1 μF considering all those tolerances and other variations.