Power Management Integrated Circuits
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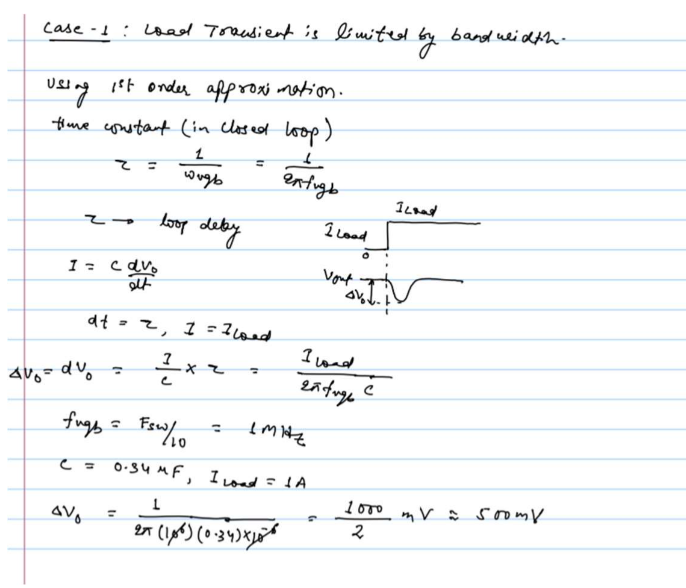
Lecture – 65
Choosing 'C' Depending on Factors that Limit the Load Transient Response

From LC product, output capacitor value we got as 0.34 μF. Now we have to see whether this cap value will meet our transient response or not.

There are two different cases we need to consider when you are looking at transient response. You need to check whether transient response is limited by bandwidth or by your inductor current slew rate.

Inductor slew rate will be the best case because you have stretched your duty cycle all the way to 100% and inductor will keep rising with the slope of $\frac{V_{in}-V_{out}}{L}$. So, you just turn on that high side switch permanently, until your current reaches to the I_{load}, and then loop will try to recover after that. It happens if you have a non-linear control because your bandwidth is infinite; it is not limited by bandwidth.

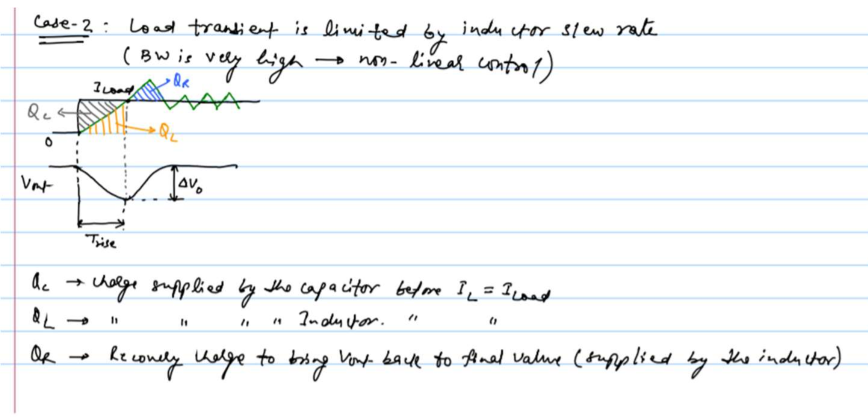
Case 1: Using first order approximation the formula for undershoot or overshoot is derived below, when your load transient is limited by bandwidth.



If you are limited by bandwidth then it is true for any system. So, you can apply this formula for LDO also.

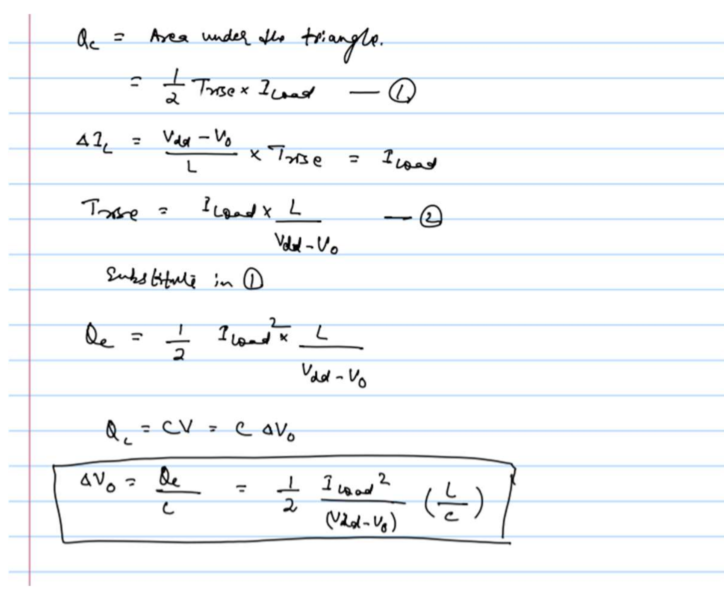
So, with 0.34 μF cap value we are getting undershoot of 500 mV which is too high. Usually specification for undershoot or overshoot is less than 5% of V_{out}. For V_{out} equal to 1.2 V, undervoltage or overvoltage should be less than 60 mV. So, the cap requirement will be approximately 10 times. So, capacitor requirement will be 3.4 μF.

<u>Case 2:</u> Load transient is limited by inductor current slew rate



Q_R is the recovery charge to bring the V_{out} back to final value and it is supplied by the inductor.

In principle all three charges Q_R, Q_L and Q_C should be same. The formula for ΔV_o is derived in below figure.



Student: Sir, in last class we feel that ΔV_{out} was going up to 500 mV. So, this 1st order approximation is valid because there we are assuming ΔV_{out} as small signal.

Yeah, we are just looking at whether ΔV_o is more than whatever you require 5% or not. That 500 mV is telling you that the capacitor requirement is higher than this. But initially, you do your hand calculation, and check whether it is meeting your transient requirement of 60 mV or not. After that check your transient response from the simulation because your hand calculation is based on first order approximation.

The formula $\Delta V_o = \frac{I_{load}}{2\pi f_{ugb} C}$ is only valid for a small signal because bandwidth is only for the small signal not for the large signal. For the large signal your system will be more like a non-linear. So, for the large signal this one ($\Delta V_o = \frac{1}{2} \frac{I_{load}^2}{(V_{dd} - V_o)} \frac{L}{C}$) will be valid because let's say your control voltage goes very high and it reaches to your V_m (100% duty cycle), then you are looking at a large signal.

But anything within your sawtooth amplitude (V_m), you can approximate it as a small signal because your system behaves linearly for that. You can call it non-linear when your circuits are saturated. Let's say your amplifier is saturated or your control voltage is saturated to V_m , only then you can call it non-linear.

But for 500 mV kind of undershoot or overshoot, most likely small signal-based formula won't valid because when you give a 500 mV error, your error amplifier may get saturated. In that case transient response limited by inductor current slope may valid. So, you may find that for a small portion; when your amplifier is saturated and your duty cycle is stretched to 100%, then transient response limited by inductor current slope may get valid. And when your output is approaching near settling, then the other formula will be valid.

We are calculating the worst case and in the worst case you may require 3.4 μF. If you keep 3.4 μF, then you will be safe because you will always get a better transient response.

If you are not limited by bandwidth, then the worst case is when you are operating at maximum V_{out} because the voltage across the inductor will reduce. That's why when you are closer to 100% duty cycle, you will get very bad transient response.

For example, consider V_{out} equal to 1.2 V. And we know that your $I_{LOAD} = 1$ A , L = 165 nH and $V_{dd} = 1.2$ V. So, with 0.34 µF we are getting ΔV_o as 400 mV.

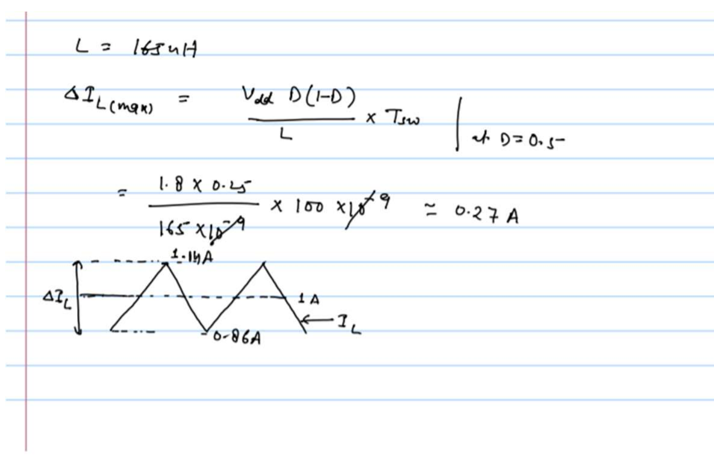
$$\Delta V_o = \frac{1}{2} \frac{I_{load}^2}{(V_{dd} - V_o)} \frac{L}{C} = 0.5 \text{ x } \frac{1}{0.6} \text{ x } \frac{0.165}{0.34} = 400 \text{ mV}$$

Which means even if you stretch your duty cycle to 100%, this cap value is not sufficient. So, you have to increase the cap. And at 1.6 V output voltage, this will get even worse because your inductor will charge very slowly. In that case it does not matter how much bandwidth you have; you will be limited by inductor slew rate.

So, always you have to calculate your capacitor value based on the worst case. In this case the worst case is bandwidth limited because we were getting 500 mV. And here we are getting 400 mV.

When you are applying the load then the undershoot will be worse, if you are operating at higher duty cycle because inductor current rising slope is small. In the same way when you are releasing the load then the overshoot will be worse, if you are operating at lower duty cycle because inductor current discharge rate will be much slower. Undershoot and overshoot will be same at 50% duty cycle. When you are operating at lower or higher duty cycle, one will improve and other will degrade.

So, for L equal to 165 nH, what will be the ΔI_L? We know that ΔI_L will be maximum at 50% duty cycle. So, $\Delta I_{L,max} = 0.27$ A and the inductor current is drawn in below.



So, we will hit the DCM if load current is $\frac{\Delta I_L}{2}$, which is roughly 140 mA.

This inductor current ripple (ΔI_L) is not very high compared to the 1 A load. The peak of inductor ripple is only 14% percent of the load and peak-peak is 28% of your load. Usually we look for inductor ripple of 50% or so.

In some cases, your peak-peak inductor ripple current could be same as your load current. But then you will hit the DCM boundary much early and you may start entering the PFM mode even at a high load.

Let us say you hit the DCM at 500 mA. When you start reducing the switching frequency at higher load current then your peak current will increase, output ripple will increase and your RMS losses may increase. So, you have to do some kind of analysis on what should be the proper load current to enter the PFM mode and based on that you can decide the inductor value.

But in some cases, you may have to increase the inductor value. Let's say you are operating at very low load current and you have very tight spec on the output ripple for a small range of load, then you are forced to operate in CCM. So, you can't choose a very small value of inductor in that case, you may have to choose a higher value. It all depends on what kind of ripple requirement you have. And then considering the rms losses you have to back calculate the efficiency and see whether it is meeting your requirement or not.