Power Management Integrated Circuits

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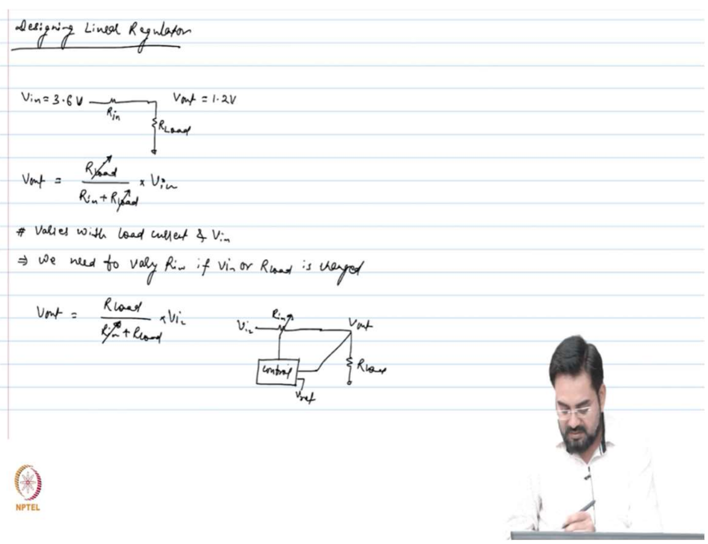
Lecture – 12
Designing a Linear Regulator
Negative and Positive Feedback

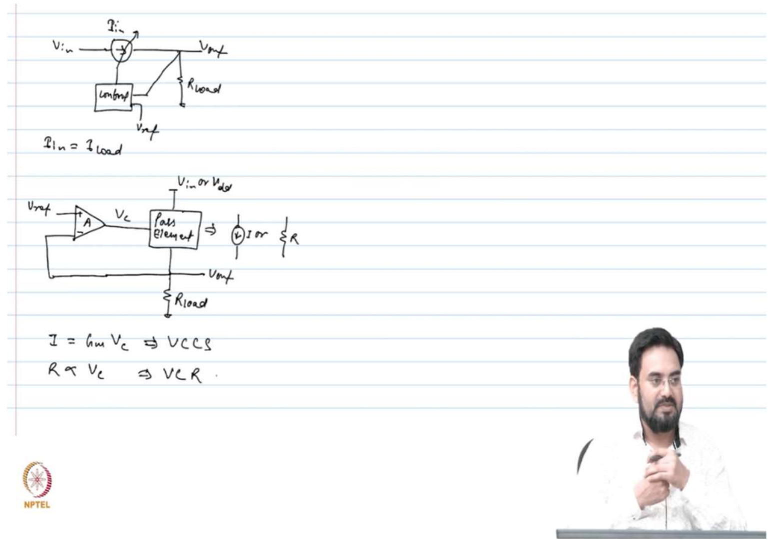
For example, to get V_{out} as 1.2 V from 3.6 V input supply; you just add a series resistor (R_{in}) in the supply and we can drop the voltage. If I drop 2.4 V across the R_{in} then my output voltage which is across R_{load} will be 1.2 V as shown in below figure.



If R_{load} is changing, then V_{out} will not remain constant. So, V_{out} varies with load current and with V_{in} also. This implies that we need to vary R_{in} if V_{in} or R_{load} is changing.

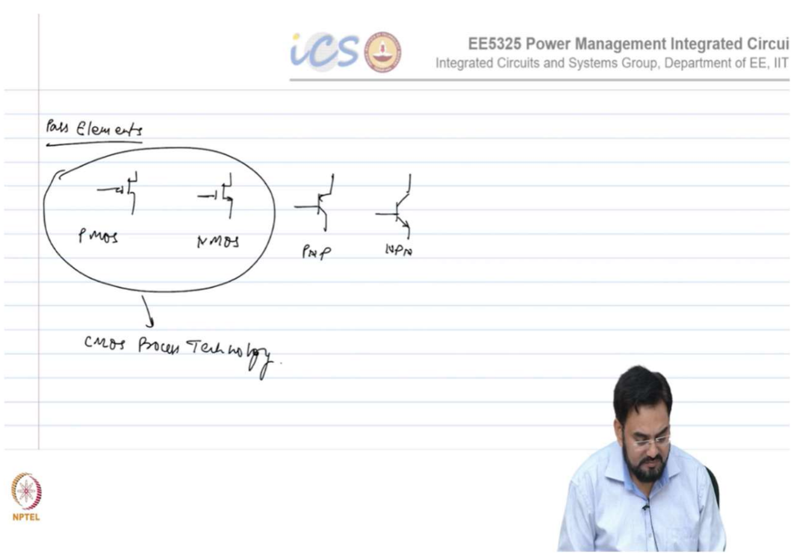
If I find the mechanism so that I can control the R_{in}, then I can regulate my output. So, to control this R_{in} I need a feedback as shown in above figure. This control will compare this V_{out} with V_{ref} and accordingly it will change the R_{in} to make sure your V_{out} is regulated.

Instead of a resistor if I have a current source, then your feedback controls that current. It compares V_{out} with V_{ref} and we will achieve the same result. Which means your I_{in} equal to I_{load}. If your I_{in} is varied based on whatever the load current you require, then it will supply the same load current and your output will remain constant.



So, the whole concept behind your regulator is you have to build this variable resistor or variable current source. And we do it by using a pass element. Pass element is nothing but your current source or resistor as shown in above circuit. Control voltage (V_c) will control your pass element and that will in turn control your R or I.

You can use resistor or current but most of the time we use current. If you operate your MOSFET in a triode region, it will behave like a resistor and if you operate in saturation region, it will behave like a current source. But most of the time we use in saturation region. The obvious region is your PSRR. And these pass elements could be your PMOS, NMOS, PNP or NPN.



Since we mostly use CMOS technologies where we do not get freedom of having active bipolar devices and we only get these parasitic bipolar. That’s why we do not have the freedom to use bipolar.

In some high voltage process, we have BCDMOS where we call bipolar-CMOS-DMOS devices, there we get these bipolar. If you have that special process then you can use bipolar, otherwise in a standard CMOS process technology we use PMOS or NMOS. And PMOS is the commonly used pass element and there are some places where we use NMOS also. Both have their own advantages and disadvantages. So, we will talk about both PMOS LDOs and NMOS LDOs.

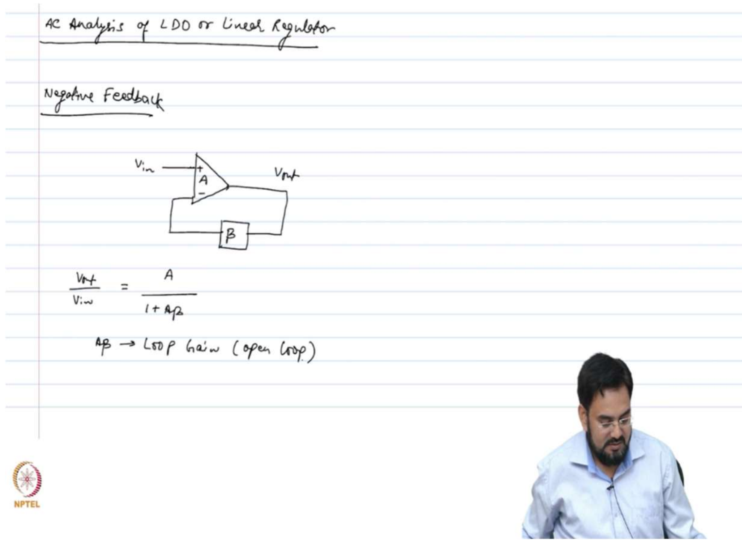
In order to design a linear regulator or LDO, we require a pass element, error amplifier and we have a load. Error amplifier is nothing but your op-amp; it could be single stage or two stage depending upon your gain requirements. And since it's connected in a feedback loop, we have to analyze the stability behavior and which is done using AC analysis. So, you have to do a small signal or AC analysis of your LDO to make sure that it is stable.

In order to do AC analysis, we require the knowledge of Bode plot. So, first you need to understand the concept of negative feedback because any stable system is designed using negative feedback. We never want our feedback to become positive otherwise it will become unstable. What happens if the system is unstable?

Student: The output is uncontrollable.

Which means, it may oscillate or may not oscillate. Some people say unstable means it's oscillating but that is not true. If output is not bounded, then it's unstable. So, it may have oscillation, or it may saturate to your V_{dd} or ground. One classic example of your unstable system which is not oscillating is your Schmitt trigger. In the Schmitt trigger your output is a square wave.

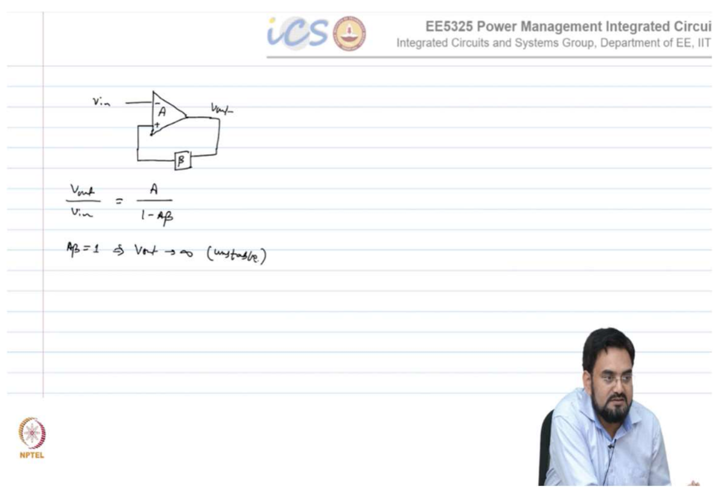
So, instead of behaving like a linear system, your system becomes non-linear. Non-linear means you do not have input-output characteristics as linear, but it has only two points like it will either go to V_{dd} or ground. So, it completely becomes undefined between your 0 and V_{dd} rail when you change the input. So, there is no such direct linear relationship between input and output. It only acts at a certain threshold just like a comparator.



For the above negative feedback system, we get transfer function as

$$\frac{V_{out}}{V_{in}} = \frac{A}{1+A\beta} \quad \text{where, } A\beta \text{ is the open-loop gain}$$

So, whenever you want to find the loop gain you want to break the loop because it's defined as open loop gain.



Now, if I change the signs of the gain block (A) as shown in above figure (positive feedback system), we get transfer function as

$$\frac{V_{out}}{V_{in}} = \frac{A}{1-A\beta}$$

Is there any condition where this V_{out} will go to infinite in previous case where $\frac{V_{out}}{V_{in}} = \frac{A}{1+A\beta}$?

Student: Aβ = -1

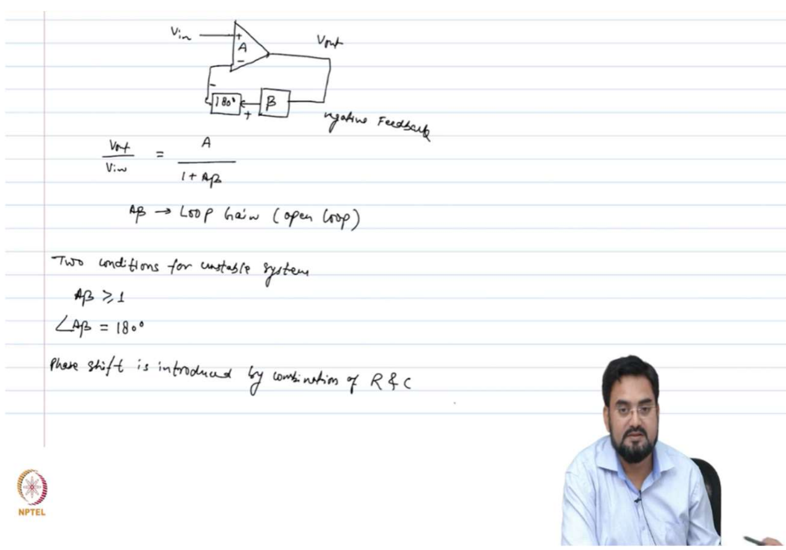
Forget about sign.

Is any positive value of Aβ product which will make it infinite? No values because if Aβ = 0 then it will become open loop system. So, the maximum loop gain you can achieve from this is basically A here. Because the feedback factor β is mostly less than 1. So, in the open loop you get A and when you have Aβ infinite, then $\frac{V_{out}}{V_{in}} = \frac{1}{\beta}$.

In this case ($\frac{V_{out}}{V_{in}} = \frac{A}{1-A\beta}$), is there any value of Aβ which will make the output infinite?

Student: Aβ =1

Which means in order to make the system unstable, it has to be a positive feedback. But we always operate our system in the negative feedback. So, how does it become positive feedback then?



In your loop if you have a 180° phase shift, then it will make your negative feedback into a positive feedback as shown in above figure. And if your gain becomes more than 1, then it will become unstable. There are two conditions for unstable system: Aβ ≥ 1 and angle of Aβ =180°.

Why gain Aβ ≥ 1?

Student: Because it will shift the pole towards right.

That is mathematical. So, you have to look around the loop. What you are doing? You are taking the output and feeding it back and amplifying. If your $A\beta < 1$, just think about every time you multiply by a number which is less than ,1then it will keep decreasing. Let us say 0.9 power infinity, it will become 0. And that is what happens when you travel around the loop.

Even if your phase shift becomes 180° and your gain is not sufficient then your output will not oscillate, or it will not go to V_{dd} or ground. It will converge or your oscillations will die out if it is a second order system. That's why we require $A\beta > 1$ and $A\beta \geq 1$ is the ideal condition.

So, where does this phase shift come from?

Student: Aβ is a function of frequency.

Why it is a function of frequency?

Student: If there are capacitors.

Yeah, phase shift is introduced by the combination of R and C.