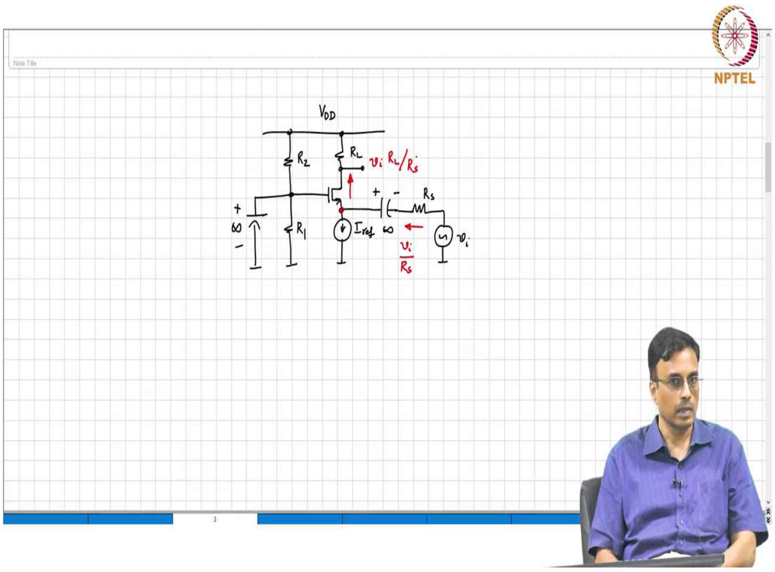
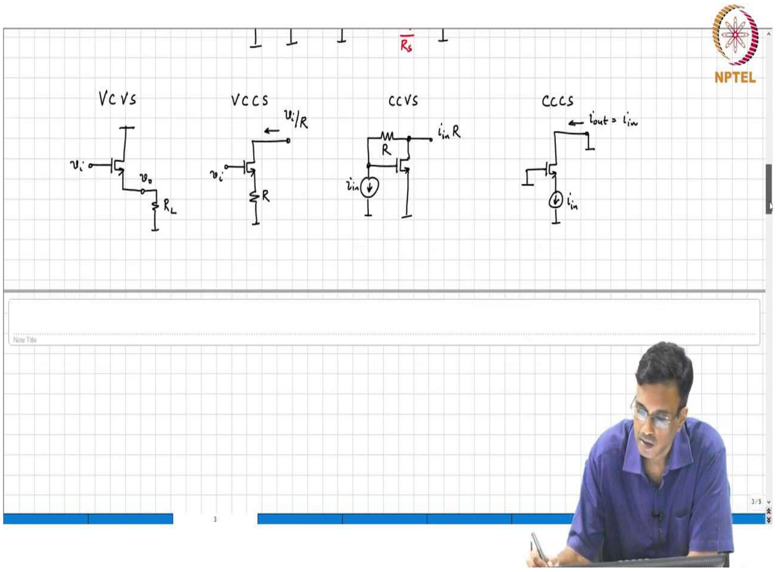
Analog Electronic Circuits
Prof. Shanthi Pavan
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 32
Summary of controlled Sources and Finite Output Impedance of the Transistor

(Refer Slide Time: 00:19)



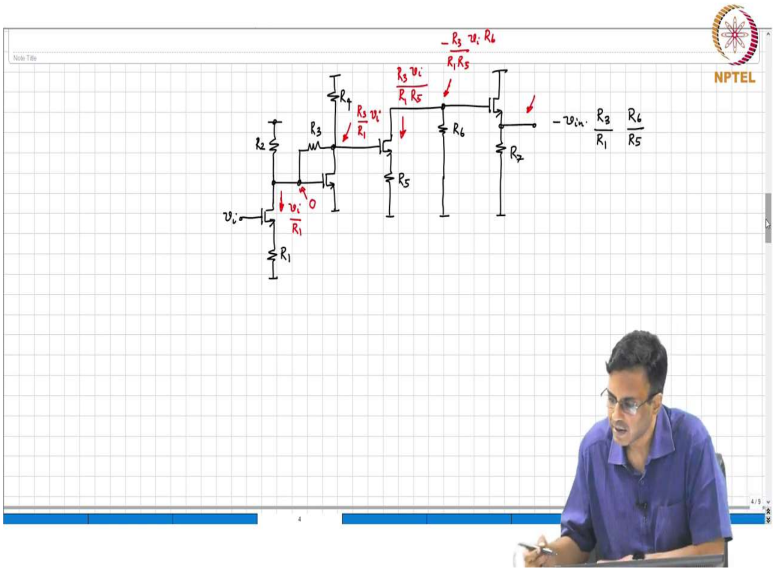
(Refer Slide Time: 00:40)



Alright. So, let us quickly summarize the 4 controlled sources. The first thing that we saw was the incremental voltage controlled voltage source and that is the common drain amplifier v_i, v_o. Then, we saw the voltage controlled current source that is the transconductance amplifier. So, this is R, this is v_i. And this is; what is the trans conductance if g_m is very large? And, this current is v_i/R.

The current controlled voltage source, what is the incremental output voltage? i_{in} R and the current controlled current source, this is i_{out} equals. Is this clear people? Alright. So, now once you have these individual building blocks whose behaviour you all understand, it is straightforward to come here to put many of these together right to do stuff for example.

(Refer Slide Time: 02:55)



This is the incremental diagram, alright, ok. So, now, I mean the circuit looks pretty complicated, right. But you should be able to stare at it and tell me assuming that g_m is large, what is the output voltage? v - v_{in}.

Student: R_3 R_6/R_1 R_5.

Very good. Let us see if this makes sense, alright. So, what comment can you make about the incremental current there?

Student: v_i/R_1.

So, what is the next stage following? What kind of control source is that?

Student: Current controlled voltage impedance.

What is the input impedance? g_m is infinite. What is the input impedance? Come on.

Student: 0.

0. So, where will all that current v_i/R_1 flow? It will flow into?

Student: R_3.

Why not R_2? What is the incremental voltage at this node there? Come on people.

Student: 0.

0. Why?

Student: g_m is infinite.

g_m is infinite, so that incremental voltage is 0. So, what will be the current flowing through R_2?

Student: 0.

0, correct. So, all the current v_i/R_1 must flow through?

Student: R_3.

R_3. So, what is the incremental voltage there?

Student: R_3/R_1 v_i.

And What about R_4? Does it affect the voltage there? Why does R_4 not affect the voltage at that node? So, it is said that g_m is infinite, so it is a current controlled voltage source.

So, loading it will not change the voltage. So, R_4 has no influence on the output. So, what comment can you make, therefore, about this current situation?

v_i/R_1 R_5, ok. So, what comment can you make about this voltage here? Current flowing into it is - R_3 I R_1 R_5 v_i R_6, ok. What about this voltage? What kind of control source is the last one? It is a common drain amplifier. So, what comment can you make about the output?

Student: Same as the input.

Same as the input. So, basically that is ok. But if you are thorough with this, you will be able to stare at this and then simply say, right. What is it? R_6/R_3 R_6/R_5 times R_3/R_1 with a negative sign, correct.

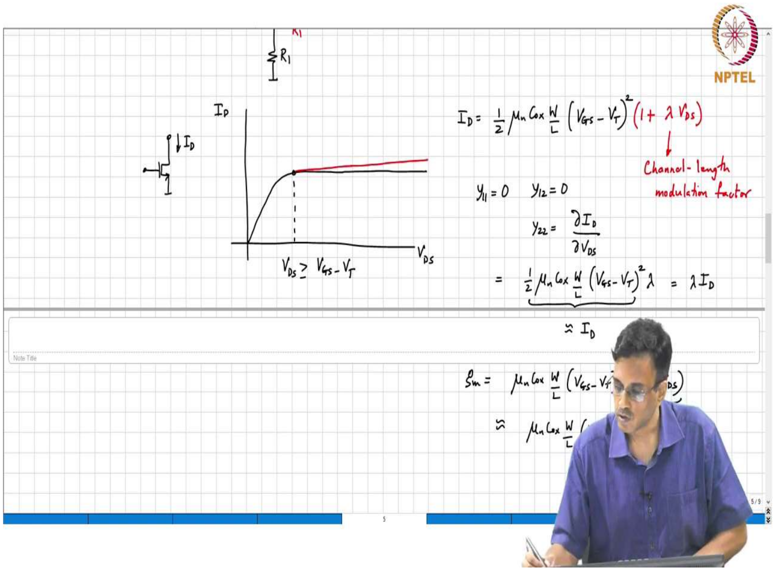
And now, I mean if I now add the biasing to all this, I mean it looks really complicated. But even then, you should simply be able to take a look at it and say this is the gain, correct. What is the input impedance? Infinite. What is the output impedance? Output impedance is 0. All this is assuming that the g_m you know everywhere is considered large. Is that clear? Alright. So, I mean the bottom line is this. So, when you I mean this is now putting these are the 4 building blocks, then you know you can just like Lego, you can put various things together in various fashions. And you know, build all sorts of circuits, ok.

And in the exam if you or you know in your professional practice if you see some circuit, you know the first thing is not to panic, right. It is not very likely that you know you have seen the circuits before, right in your exam as well as in your job, right.

But there is nothing to panic about, right? Basically, with careful analysis, you will be able to identify these building blocks, and then you know from there you should be able to figure out what is going on, ok.

Lastly, you know that in electrical engineering, everything must obey KCL and KVL, right? So, you basically run through the algebra, right. If you find that you have 0 intuition about the circuit, then you run through the algebra which will take you forever, right? But you know that there is nothing deeper than that, alright.

(Refer Slide Time: 10:22)



So, the next thing that I would like to talk about is, so far we assume that the IV characteristic of the transistor. So, the output characteristics of the transistor, right we assume to be the drain current I_D. In saturation, we assume that the current is independent of?

Student: V_{DS}.

V_{DS} provided, V_{DS} is greater than some V_{DS} minimum which is V_{GS} - V_T. Unfortunately, it turns out that I lied. So, in reality, the slope of this line I mean saturation which is what we said was 0 is not quite 0. There is a small slope, something like that, ok. So, the red curve is the true characteristic and the black one is the idealized one we have been seeing so far, ok.

So, the ideal characteristic, we said, was that the I_D was 1/2 μ_n C_{ox} W/L $(V_{GS} - V_T)^2$ correct. Now, it is not quite that. So, you know what you think you can do? What do you think we can do? We have to fetch the characteristic, fetch the equation, so that it matches the curve, right. And it does not take a genius to figure out that it is. I mean it looks like a straight line, right. It is proportional to V_{DS}. So, it is some $(1 + \lambda)$ times some constant times V_{DS} that turns out to be that this parameter is called λ, alright. What are the units of λ?

Student: Per volt.

Per volt, ok. And this is often this I mean those you have done device switch class before this is called?

Student: Channel length.

Channel length modulation factor, ok. I mean if you do not know how that came about, do not worry about it. It is some minor detail as far as from the physics of the transistor. But at any rate you measure the transistor characteristic. This is what you see. And this equation models the characteristic pretty, ok, alright.

So, the equation for the transistor is evidently changed. So, therefore, what comment can we make? What are the consequences of the equations changing?

Student: Output.

The model will change, right? So, earlier, so Y_{11} was and is still 0, the gate current is still 0 and therefore, Y_{11} and Y_{12} are 0. Y_{22} which was earlier 0, what is Y_{22}?

Student: $\frac{\partial I_D}{\partial V_{DS}}$.

Which was earlier 0 is now going to be $1/2\ \mu_n C_{ox} W/L (V_{GS} - V_T)^2 \lambda$, ok.

Now, you know as I said I mean this is going to be if you had to try and remember we like to write the g_m as a function of you know the bias current, right. So, now if you have to put that in here you can see that the equation is very messy, alright, ok. Because to solve this, right now it becomes a bit messy. So, as you know when the going gets tough, engineers start to make approximations.

So, that λV_{DS} we assume that is a, I mean, what comment can you make about that λV_{DS}? You hope that you have a good transistor, so that λV_{DS} must be?

Student: Small.

Small, compared to what?

Student: 1.

1. So, if that λV_{DS} is small compared to 1, what comment can you make about this guy? This is approximately I_D. So, this is nothing, but λI_D, alright. Dimensionally also you can see it is consistent because I_D is λ is reciprocal volts, so that is conductance, ok. And what about g_m? Well, for g_m you know the g_m, true g_m as per this equation is nothing, but $1/2\ \mu_n C_{ox} W/L (V_{GS}$

$-V_T$) (1 +λ) V_{DS}. But again, this being very close to 1, simply continue, at least for hand calculations you just basically say that this is μ_n C_{ox} W/L (V_{GS} -V_T), ok.

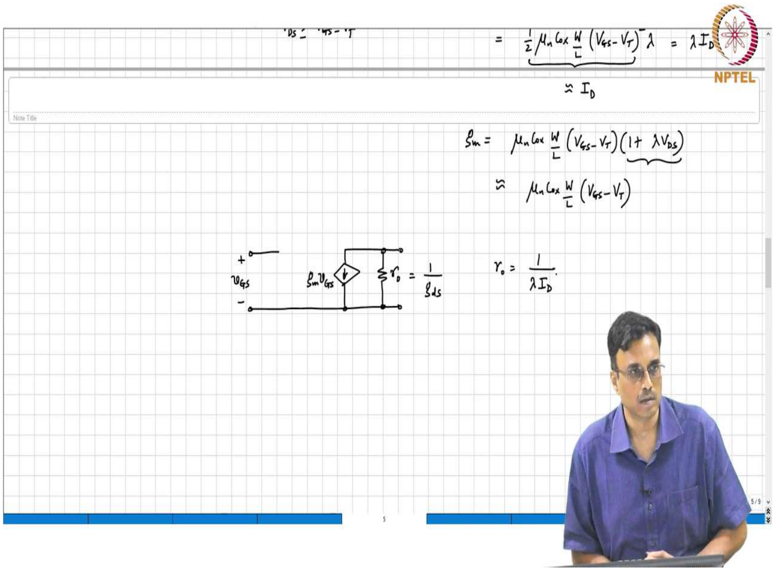
In any case, to get the exact operating point and the g_m and all those of you who have done a device course know that all these toy equations are only there for the textbook. A real MOSFET will have much more complicated behaviour which is you know almost impossible to figure out T, I mean unless you have a computer.

So, anyway you need to know you anyway you need a computer. So, for hand calculations, what is the point you know breaking your head over a model which is complicated and inaccurate, correct?

It makes sense to spend time you know with complexity, if you know that you are going somewhere, right. If you know this is wrong you know anyway, what is the hand you have to anyway go to a computer you know why break your head, right. So, that is the philosophy.

You basically, say, well, I will continue with my old you know g_m equation because it is not worth it and likewise the output resistance is just simply λ I_D right. All this is good enough for hand calculations. For a detailed calculation you anyway go to a computer. I mean and all of you have no doubt heard of spice, yes, right, ok, alright. So, if you put all this into a simulator and hit the run button and you get all the answers that you are looking for.

(Refer Slide Time: 17:55)



$$= \underbrace{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)}_{\approx I_D}\lambda = \lambda I_D$$

$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)\underbrace{(1+\lambda V_{DS})}$$

$$\approx \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)$$

$$r_o = \frac{1}{\lambda I_D}$$

So, our model now is only slightly modified. So, this is g_m times V_{GS}. This is often called r o. It is also sometimes called g_{ds}. The conductance is called g_{ds}, right because it is between the drain and the source, right. And g_m expression is known, $r_o = 1/\lambda\ I_D$.