Analog Electronic Circuits
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Lecture - 25
The Incremental Voltage-Controlled Voltage Source The Common-Drain Amplifier-Incremental Picture

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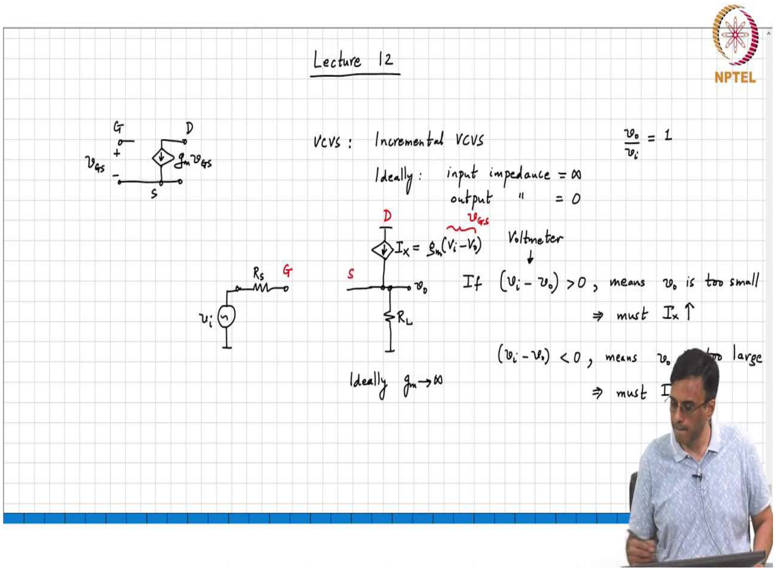

Good morning and welcome to Analog Electronic Circuits. This is Lecture 12. So, in the last class, we basically concluded by saying that we know that, in principle, the transconductance of a MOS transistor operating in saturation Actually, I think I have been using the notation "small v" capital G_S in principle because g_m can be, you know, as large as possible.

So, a MOS transistor operating in saturation behaves like an incremental voltage-controlled current source where, in principle, the transconductance that relates the incremental drain current to the incremental gate source voltage can be as large as possible because, in principle, we can, you know, burn arbitrarily large amounts of current in the transistor and therefore get a large g_m.

In practice, of course, as several of you pointed out, there are real problems in the sense that you know the transistor may get too hot, burn, and so on. But they are what we would call practical problems in principle; you know you can still have as much transconductance as you want. So, using this as a building block, let us now try and build the four controlled sources that you are familiar with from basic circuit theory. The voltage-controlled voltage source, the voltage-controlled current source, the current-controlled voltage source, and the current-controlled current source

We will start with this with the voltage-controlled voltage source, and because we are talking about incremental signals here, the voltage-controlled voltage source is basically going to be an incremental.

Voltage-controlled voltage source, ok. In other words, the controlled source is a linear element, and the transistor as such is non-linear. So, we can only talk about incremental signals. So, any building block that we come up with using transistors that claims to be linear is only linear for small signals, right?

Now, let us recall: what is the input impedance of VCVS?

Student: Infinity.

Infinity. Output impedance?

Student: 0.

Is 0 and therefore, when you say we have a voltage-controlled voltage source the only number you have to specify therefore, is the?

Student: Gain.

Is the gain between the output and the input, v_o / v_i, correct? Now, let us choose the simplest case, namely v_o / v_i, which is equal to 1. We will reflect on why we chose 1 later on, but at this point, 1 is as good as any other number. So, let us try to implement a voltage-controlled voltage source with a gain of 1.

And what we would like to do is to also recognise that the transconductance, while large, is actually quite dependent on the operating point, threshold voltage, and all this other stuff.

So, what we would like to do is build an incremental voltage-controlled voltage source where the properties of the VCVS are largely independent of the properties of the transistor. In this case, the only property we are talking about is the incremental I mean, it is the transconductance of the transistor, alright?

So, in other words again let us derive this from first principles. What we are going to do is basically first come up with a plan that we verbalize. Once you know what you want you can always build an electronic circuit to do it right. So, the problem statement therefore, is we have a voltage v_i and we have some load resistance R_L and we would like the voltage across the load which is, v_o to be equal to v_i.

Student: v_i.

And that is because we wanted to shoot for an incremental gain of 1. So, let us imagine you are in a lab, and let us, for argument's sake, also assume that there is some source resistance for the input. So, this is our R source. We have a voltage of v_i with an internal resistance of R. We are in a lab, and we would like to make the voltage across a load R_L exactly equal to v_i.

Student: v_i.

Ok. So, in principle, what would we do and what equipment would we need?

Student: Volt meter.

So, let me you know let me kind of track back a little and say well you want $v_i = v_o$ why not I just shot v_i with v_o. Yes, it is a smart idea or a stupid idea.

Student: Stupid idea.

Why? Well, that is a terrible idea because you know there is of course, a voltage drop and as you keep changing R_L. The voltage will keep changing at the output. So, that is no good.

Right. So, we can dismiss that right away. So, what we need therefore, what we need?

Student: A voltmeter.

Student: And next one we need a variable method v_0.

So, basically one way of doing this is to say well we have a variable voltage source. And what do we do?

Student: Connect voltage.

Connect which with?

Student: Circuit and joint sir.

So, basically, the idea is to say, "Well, take a voltmeter, which measures, say, the voltage between the positive terminal and the negative terminal, and now what do we do?" You read the reading on the voltmeter, correct? And what is the reading on the voltmeter? By the way, what is the impedance of the voltmeter?

If you have an ideal voltmeter, the internal resistance of a voltmeter is infinite. So, what exactly is the voltmeter actually the reading on the voltmeter therefore, represents?

Student: v_i.

Very good. So, the voltmeter therefore, reads v_i - v_o. So, if the voltmeter reading is greater than 0 what does it mean? What does it mean? Then we figure out what to do? It means that what v_i is? You cannot say it is too little or too high. It is v_o's job to follow v_i.

Student: v_i.

So, it basically means if v_i - v_o is greater than 0 it means that?

Student: v_o is too small.

Means v_o is too small. What must I do therefore,

Student: Increase V_X.

Must increase V_X alright. Now, let me ask you a question if you want to increase the potential of a node. In this case we are taking the variable voltage source and simply yanking its potential up and down. Can you think of another way of increasing or decreasing the potential of a node without using a voltage source?

Yeah. So, there are two ways of changing the potential of a node, one is of course, use a variable voltage source to go and move the potential up and down the other way is to?

Student: Pump a current.

Pump a current, alright. And why are we interested in pumping a current? Because that transistor is a?

Student: Voltage.

It is a variable, I mean it is an electronically variable.

Student: Current source.

Current source, correct. So, therefore, we would like to use a variable current source because we are talking about eventually using transistors. So, now, if we wanted a variable current, instead of using a variable voltage source here. If you had to use a variable current source what would we do? So, basically you need to connect a current?

Student: Current pump current.

Which pumps current there, some I_X correct. So, if the voltmeter reading is greater than 0, it means that v_o is too small again, but what must we do now? So, what we must do therefore, is to increase I_X, does it make sense? Alright. Now, if on the other hand v_i minus v_o is less than 0, what does it mean?

Student: Large.

What does it mean?

Student: v_o is too large.

v_o is too large and therefore, we must reduce I_X.

Student: Reduce I_X.

Does it make sense to people? Alright. So, therefore, we can see that I_X is a current source which is controlled by which voltage?

Student: v_i - v_o.

v_i - v_o. So, it is controlled. So, it is therefore, proportional to v_i - v_o alright. And the constant of proportionality will therefore, the output is a current the controlling quantity is a?

Student: Voltage.

Voltage. So, the constant of proportionality will have dimensions of?

Student: Conductance.

Conductance, right. So, that is what we will simply call g_m, correct. Is a sign of gram positive or negative?

Student: Positive.

Why?

Student: Because if v_i is greater than v_o, I_X must be positive.

So, alright. So, in other words, remember that the general notation for a current source is actually that, alright. So, now can somebody recognize the transistor, the terminals of the transistor in this picture.

Student: Yes sir.

Or by the way so, basically I_X produces a current which is proportional to v_i - v_o. And what if you want v_o to be exactly equal to v_i, what comment can you make about the transconductance g_m?

How much do we need?

Student: Infinite.

Why? Because you ideally want g_m must tend to infinity because even if you see an infinite simile small difference between v_i and v_o you must go and kick that node v_o so hard so that its potential becomes exactly the same as that of v_i.

Student: v_i.

Is that clear alright? So, now, what comment can you make, can you now recognize the terminals of the transistor here? Stare at this picture I mean in this picture this is the gate, this is the source, this is the drain. So, stare at the two pictures and tell me which terminal is which?

Student: Gate source.

So, this gate is the input.

Student: Source is the output.

Source is the output and the other end of the current source is drain.

Student: Drain.

Drain right, because you simply recognize this as being the incremental V_{GS}, does it make sense?

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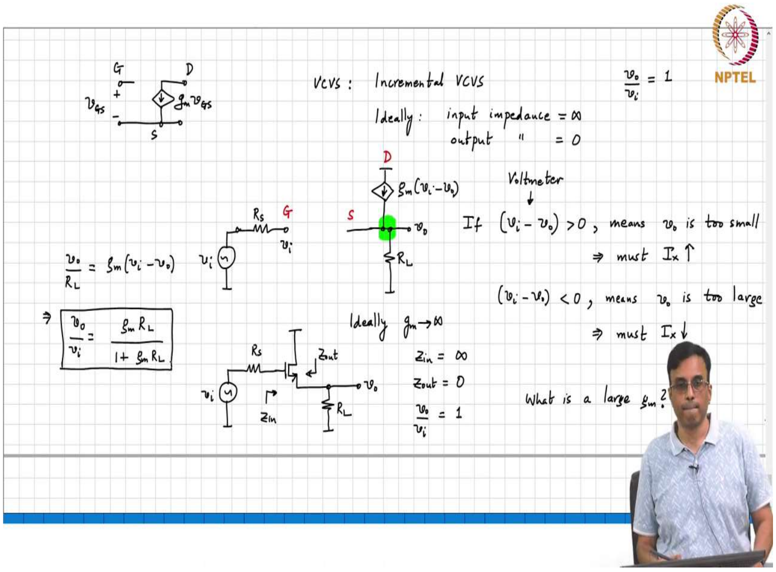

And therefore, the circuit, when you recognise the transistor, becomes vi R_S; this is R; this is v_o alright. Ok. So, let us tabulate the properties of the voltage-control current. This is the incremental picture, ok? It does not mean that, again, let me retrain that, it does not mean that you take a transistor connected up like this and magically you will get v_o equal to v_i; this only works when the transistor is operating in the saturation region. So, for that, you have to act appropriately.

Student: Bias.

Biasing the transistor, you already know at least 5 or 6 ways of biasing the transistor; you can pick your favorite way to bias the transistor. Once you bias the transistor, you also know how to get rid of elements that you do not want and keep elements that you do want, and so on, by adding infinite inductors and infinite capacitors, and then you must make sure that the incremental circuit looks like this one.

So, before we actually build the real circuit, let us tabulate what we will get as far as the input impedance is concerned. What is the input impedance?

Student: Infinity.

This is infinity because the incremental gate current is 0, that does this depend on g_m being infinite or not?

Student: No.

It is independent of g_m correct. What about Z_{out}? You know g_m is infinite. The easiest way is to figure out that well if you go and change R_L, what comment can you make about the output voltage?

Student: It remains the same.

It remains the same, alright and therefore, this basically means that the output resistance seen is 0 if g_m tends to infinity. What comment can you make about v_o / v_i this we knew already, if g_m tends to infinity the incremental gain is 1. Does it make sense to people? Alright. So, now, ideally g_m must be infinite in reality. Well, we can say we cannot get g_m is infinity after all g_m must be very large now the question is what is a large g_m? Alright, again this is context dependent and we have to figure out what the context in this particular case is and how do you propose to figure out what it means to have a large g_m? How do we figure it out? We know that g_m must be large.

Student: We can put the output or the g_m send it

Any ideas? Ok. So, equivalently you can say that there are multiple ways of doing this.

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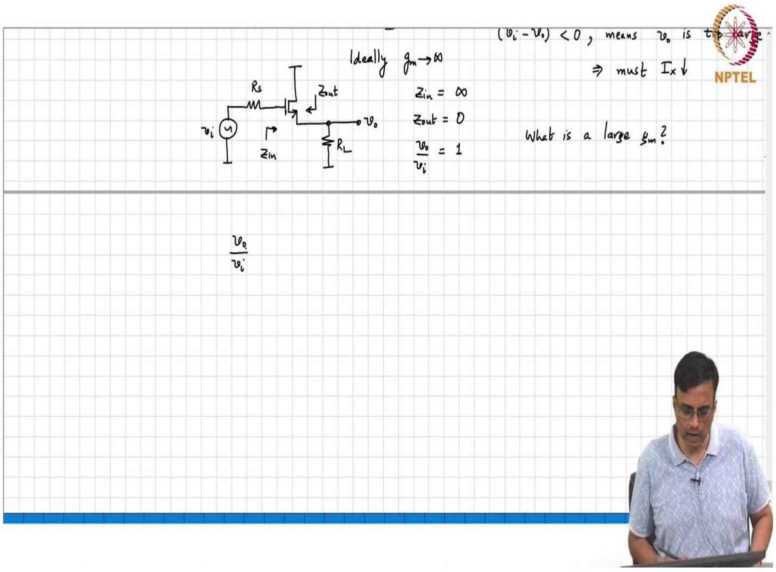

One is to simply compute v_o / v_i when g_m is finite and stare at that expression and figure out for what values of g_m that expression will tend to 1.

Student: 1.

Alright and to do that well we go back to our circuit here this is $g_m(v_i - v_o)$. What are the unknowns? What is the incremental gate voltage?

Student: v_i.

v_i that there is no. So, what is the only unknown?

Student: v_o.

v_o. So, how will you figure out v_o? Right KCL at the output node. So, v_o / R_L that is the current flowing downwards is nothing, but g_m v_o (v_i -v_o) and therefore, v_o / v_i is nothing, but g_m R_L / (1 + g_m R_L), alright. So, therefore, staring at this expression, what comment can we make about what constitutes a large g_m?

Student: R_L considered as g_m.

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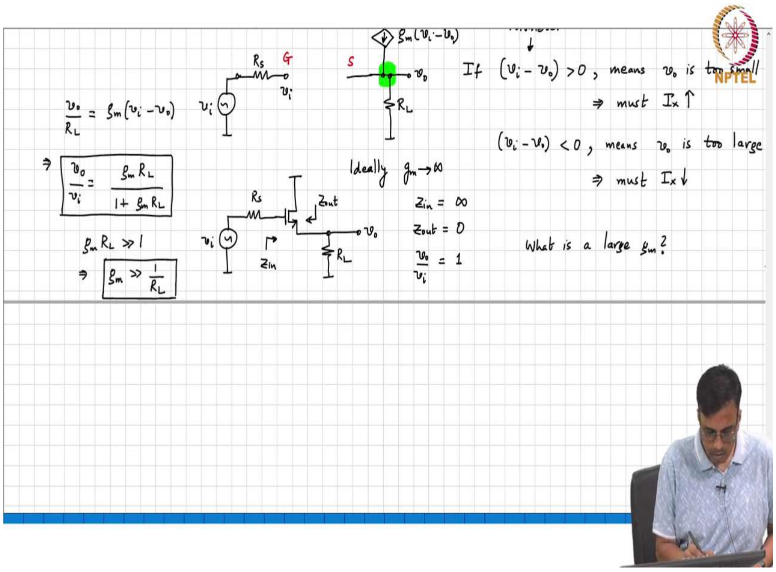

g_m R_L must be much much greater than 1. Alright or equivalently the meaning of g_m a large g_m is that it is much much greater than 1/ R_L. So, to find output impedance, this is the gain with the finite g_m. What comment can we make about the output resistance? How will we figure it out?

How will we find out the output resistance?

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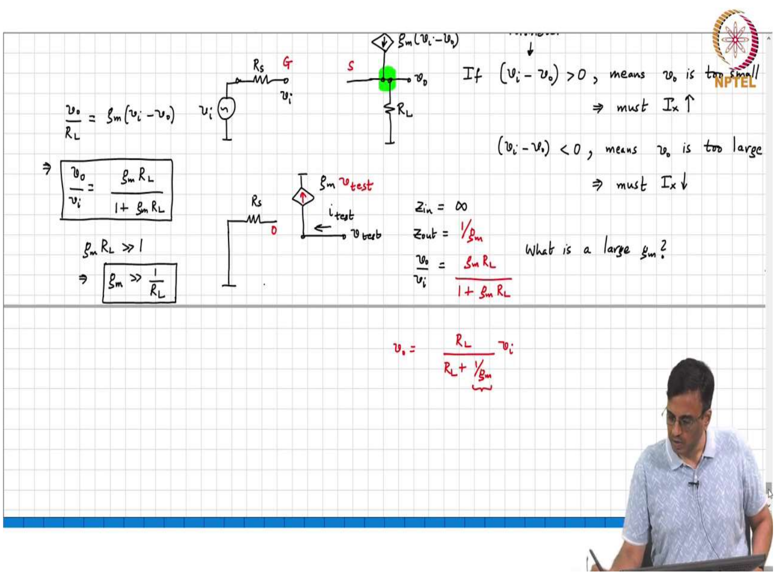

Well, we de-energize all the independent sources so, v_i becomes 0 alright and so, therefore, does R_{SX} you know and we need to find Z_{out}. So, what will we do? We will replace the transistor with this incremental equivalent. So, that is our controlled source for the end right there, we will put a test voltage and measure the test current, what is that, what is the strength of that current source? What is the strength of that current source? What is that current source?

Student: g_m.

g_m times is the incremental V_{GS}, what is the incremental gate voltage?

Student: 0.

0. So, that is basically g_m $(0 - v_{test})$ right. So, that is equivalent to changing the direction of the arrow there and making this simply g_m v_{test}. So, what do we conclude therefore?

What do we conclude output resistance is therefore, $g_m R_L /(1 + g_m R_L)$. I mean another way of doing it without doing this is to basically see that v_o can be written as $R_L /R_L + (1 + g_m v_i)$ and simply staring at this expression you know does this seem familiar?

Student: Voltage divider.

So, voltage divider so, the vertical arm is R_L the horizontal arm is $1 /g_m$ and it is being driven by voltage source v_i. So, it is clear that this must be the output resistance ok. I mean if you can see it this way well and good if you cannot never mind it is not important. The fool proof way of finding output resistance is simply what you call de-energizing all independent sources which means that you shoot all the voltage sources and.

Student: Open sources.

Open it all?

Student: Current sources.

Current sources and then apply?

Student: Test voltage

Test voltage and measure the test current that is something that will always work.

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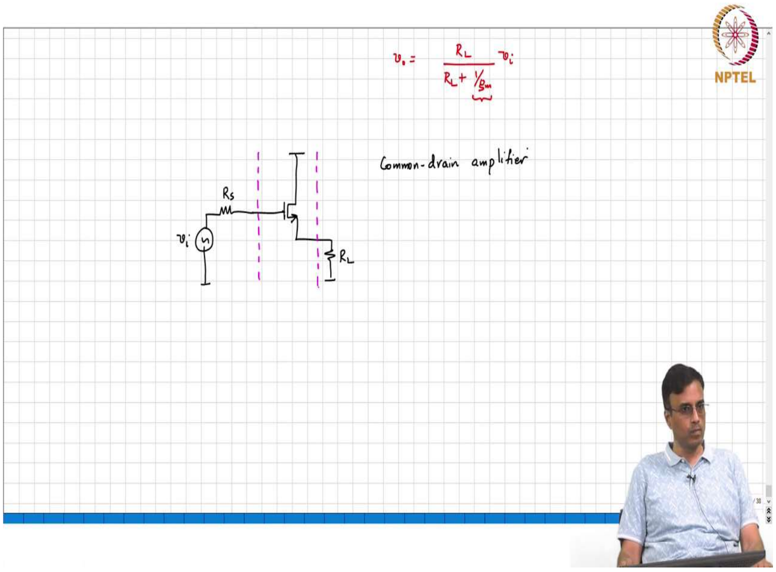

So, with this you know everything that we need to figure out about the amplifier is known. So, basically let me redraw the circuit, this is v_i this is R_S ok and as you can see which terminal of the transistor is common to both the input side and that is the input source as well as the load.

Student: Drain.

The drain right. So, what would you call this? This is the common drain amplifier. And the common drain amplifier is a way of realizing an incremental voltage controlled voltage source with a gain of 1.

Student: 1.

With a gain of 1.