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

Lecture - 13
The Common Source Amplifier - Swing Limits

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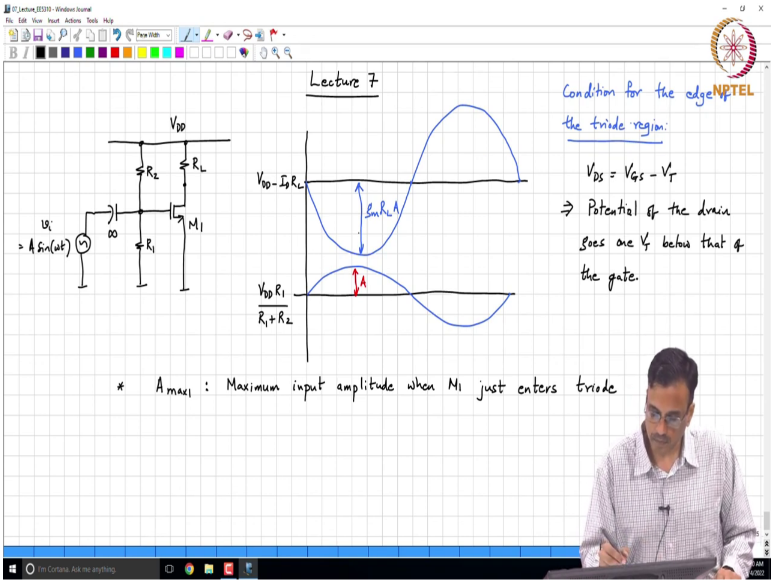

Lecture 7

Condition for the edge of the triode region:

$V_{DS} = V_{GS} - V_T$

$\Rightarrow$ Potential of the drain goes one V_T below that of the gate.

* A_{max1} : Maximum input amplitude when M_1 just enters triode

Good morning and welcome to Analog Electronic Circuits. This is Lecture 7. So, in the last class we were looking at what it meant for a signal to be a large signal and we said that an incremental gate source voltage where the swing is much smaller than twice V GS minus V T it is what is considered a small signal. And then we went on to start looking at what actually happens when the input signal swing is increased. So, v i is nothing but A sin sum omega t.

Omega is assumed to be sufficiently large that input capacitor coupling capacitor is can be considered a short circuit, ok. And we said let us take a look at the absolute waveforms at the gate and the drain. So, at the gate the absolute waveform the total waveform will be the sum of the quiescent quantity and the incremental quantity the quiescent value is V DD times R 1 by.

Student: R 2.

R 1 plus R 2. And on top of it now you are going to have a sinusoid with amplitude.

Student: A.

A, right, ok. And the drain potential is going to be the quiescent value is going to be V DD minus I D times R L. And I D can be found the moment we know the properties of the transistor and the total voltage at the drain is basically the sum of the quiescent and the increment again. The incremental voltage at the drain is what now?

Student: g m.

Minus g m R L times v i. So, this amplitude that distance is A. So, this must be. So, somewhere there, right. So, this distance must be g m R L times A, right. So, in the positive half of the input cycle we see that the transistor is going towards its going towards the triode region, right. And if the input if the input A increases beyond a certain limit what will happen? First of course, the drain potential will go below the gate potential and if you increase the amplitude even further what happens?

Student: (Refer Time: 03:35).

The drain potential will become?

Student: (Refer Time: 03:38).

Yeah. So, remember that the condition for triode is what V DS equals V GS minus V T which in English basically means that the potential of the drain goes one V T below that of the gate, ok. So, now, the question is. So, the first question that we would like to ask is, what is the largest input one can put. So, that the transistor.

Student: Remains in saturation.

Remains in saturation, right. So, A max 1 is the maximum input amplitude when the device when let us call this M 1, just enters triode, ok. How does that look like?

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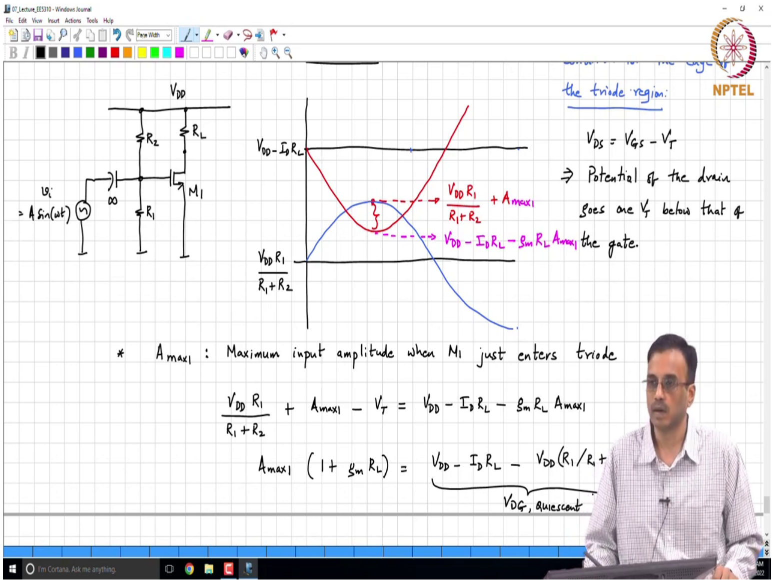

the triode region:

$V_{DS} = V_{GS} - V_T$

$\Rightarrow$ Potential of the drain goes one V_T below that of the gate.

* A_{max1} : Maximum input amplitude when M_1 just enters triode

$$\frac{V_{DD} R_1}{R_1 + R_2} + A_{max1} - V_T = V_{DD} - I_D R_L - g_m R_L A_{max1}$$

$$A_{max1} (1 + g_m R_L) = \underbrace{V_{DD} - I_D R_L - V_{DD}(R_1/R_1 +}_{V_{DG,\ quiescent}}$$

So, in that case what happens? Well, we are only looking at the positive half cycle. So, this is absolute potential of the drain. So, at which point in time will you have the transistor going closest to the triode region?

Student: Peak.

At the peak of the input that is at that point. So, what common can I mean. So, if the transistor we know is in the edge at the edge of the triode region, what comment can we make? What is that distance?

Student: V T.

V T that is all, right. So, what is the; what is the peak value there? What is the absolute voltage there fellows?

Student: V DD times R 1.

Yeah, this is basically V DD times.

Student: R 1.

R 1 by.

Student: R 2.

R 1 plus R 2.

Student: Plus A.

Plus A. what is this what is the this character now?

Student: V DD minus I D R L.

That is V DD minus.

Student: I D R L.

I D R L.

Student: (Refer Time: 06:52).

Or this if you call this A max 1 minus I D R L minus.

Student: g m R L.

g m R L times.

Student: A max 1.

A max1, correct. So, the condition for just hitting the triode region is V DD times R 1 by R 1 plus R 2 plus A max 1, yes what do we?

Student: Minus V T.

Minus V T equals V DD minus I D R L minus.

Student: g m.

g m R L A max 1, ok. And I just do some algebra. So, A max 1 times 1 plus g m R L equals V DD minus I D R L minus V DD times R 1 by R 1 plus R 2 plus V T, ok. What is this actually?

Student: V DS minus V GS.

Yeah. So, that is V DS minus V GS. That is V.

Student: V DG.

V DG, right. Under quiescent circumstances, alright? So, therefore, A max 1.

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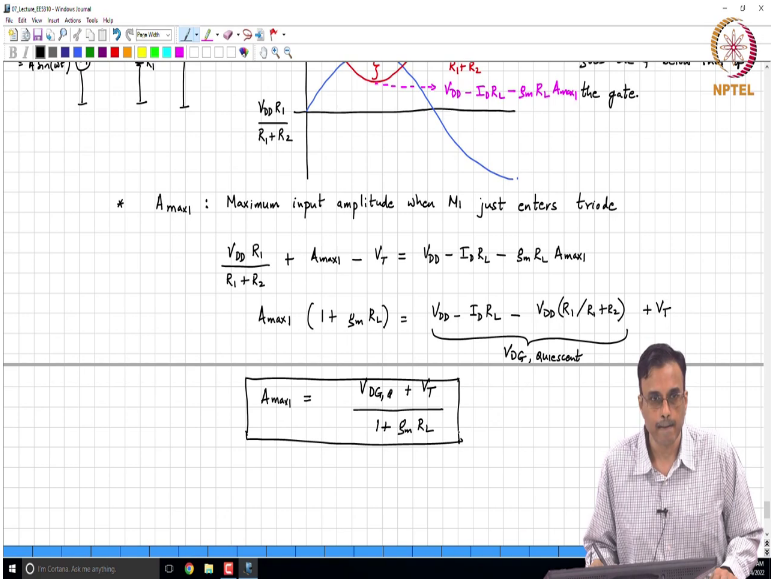

* A_{max1} : Maximum input amplitude when M_1 just enters triode

$$\frac{V_{DD}R_1}{R_1+R_2} + A_{max1} - V_T = V_{DD} - I_D R_L - g_m R_L A_{max1}$$

$$A_{max1}\left(1+g_m R_L\right) = \underbrace{V_{DD} - I_D R_L - V_{DD}\left(R_1/R_1+R_2\right)}_{V_{DG,\ quiescent}} + V_T$$

$$\boxed{A_{max1} = \frac{V_{DG,Q} + V_T}{1+g_m R_L}}$$

Which is the maximum sinusoidal voltage you can apply before the transistor goes into the triode region is given by V DG quiescent plus V T by 1 plus g m R. Does it make sense people? Ok. Now, that is the story in the positive half of the input cycle. Now we have to worry about what happens in the. By the way in the positive half of the input cycle what comment can you make about the waveform of the current?

Student: (Refer Time: 09:59).

It will be for the quiescent value will be some I D total current will be.

Student: (Refer Time: 10:08).

The incremental current what is the model for the transistor?

Student: (Refer Time: 10:12).

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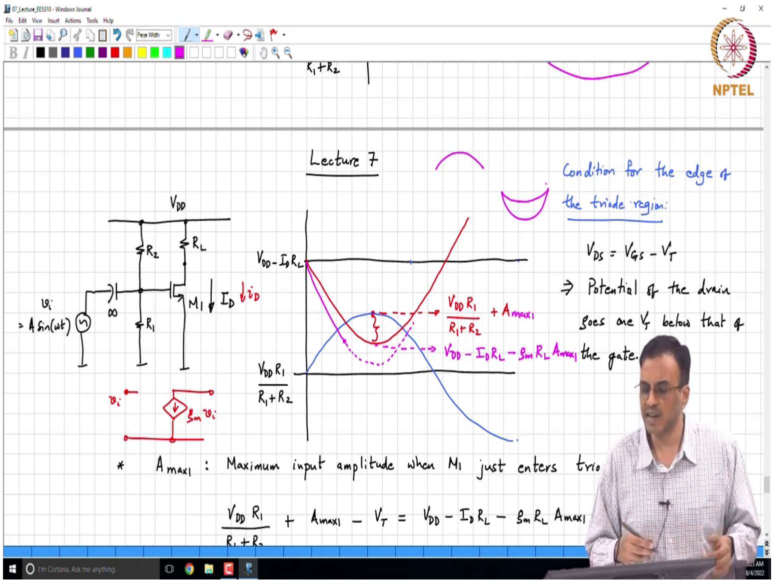

Condition for the edge of the triode region:

$V_{DS} = V_{GS} - V_T$

⇒ Potential of the drain goes one V_T below that of the gate.

* A_{max1} : Maximum input amplitude when M_1 just enters trio

$$\frac{V_{DD} R_1}{R_1 + R_2} + A_{max1} - V_T = V_{DD} - I_D R_L - g_m R_L A_{max1}$$

So, incremental current is in which direction?

Student: Upward 100.

Does it flow downwards upwards?

Student: Downwards (Refer Time: 10:37).

Downwards. Yeah, you clear now? Ok. Small I D. So, what is the total current?

Student: (Refer Time: 10:47).

It is a capital I D which is the quiescent value plus.

Student: g m.

gm times A times sin omega t, it will be in the same direction as the it will be very similar to the blue curve except that you know the average value will be capital I D and the amplitude will be g m times A max. Does it make sense? All right.

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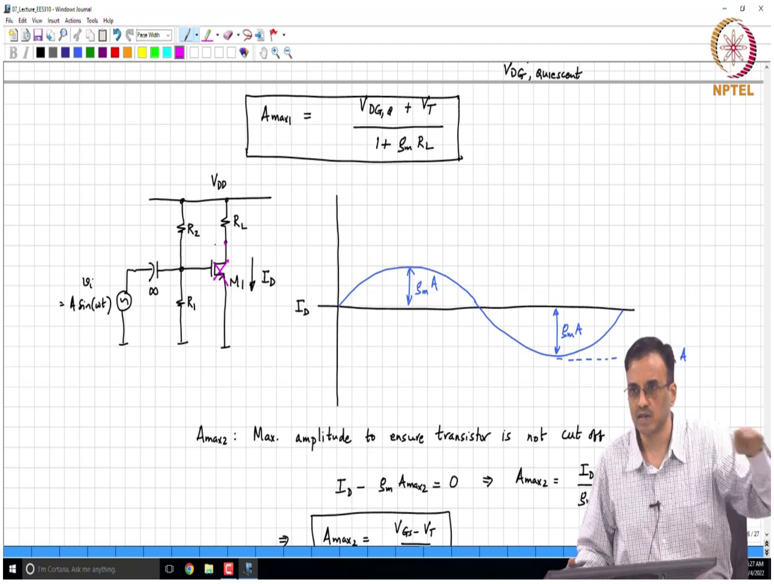

V_{DG}, quiescent

$$\boxed{A_{max_1} = \frac{V_{DG,Q} + V_T}{1 + g_m R_L}}$$

A_{max2} : Max. amplitude to ensure transistor is not cut off

$I_D - g_m A_{max_2} = 0 \Rightarrow A_{max_2} = \frac{I_D}{g}$

$\Rightarrow \boxed{A_{max_2} = \frac{V_{GS} - V_T}{\ }}$

Now let us worry about what happens in the negative half of the input cycle. In the negative half of the input cycle the drain potential is the gate potential is increasing or reducing?

Student: Reducing.

Is reducing. What comment can we make about the drain potential?

Student: Its increasing.

Drain potential is increasing. So, is a transistor going deeper into saturation or closer to triode?

Student: Deeper into saturation.

It is going deeper into saturation and in this general direction because there is the what you call the gate source voltage is reducing and the drain voltage is increasing, ok. And what do you call what comment can we make about the. So, there is I mean the bottom line is that in the negative half of the input cycle there is no danger of the transistor getting into the.

Student: Triode region.

Triode region on the other hand what comment can we make about the total current in the transistor? The quiescent value is I D, right. In the positive half of the input cycle the current was doing this and this is basically g m times A, alright. So, in a negative half of the input cycle this will be I D minus g m times A. So, what is the minimum current?

Student: I D minus g m.

I D minus gm times A. So, now, the question is, what is the maximum input? So, what. So, what is happening I mean if A becomes larger and larger and larger what comment can you make about the minimum current in the transistor?

Student: Reducing.

It is reducing and eventually what can happen what is the lowest it can go to?

Student: 0 0 0.

The lowest it can go to is 0, correct. So, what is? So, therefore, what is the maximum amplitude A max 2 maximum amplitude. So, if the input amplitude is increased more and more the minimum current will become I D minus g m A and the maximum input A that you can use before the transistor gets cut off is nothing but yes, what is it?

Student: I D minus g m.

I D minus g m times A max 2 must be.

Student: (Refer Time: 14:42) equal to 0.

Equal to 0 would give you the limit for A max 2. And that therefore, is A max 2 therefore, is nothing but I D over g m 2. And can you write g m 2 in terms of I D?

Student: (Refer Time: 15:02) I D.

That is basically 2 I D over.

Student: V GS minus V T.

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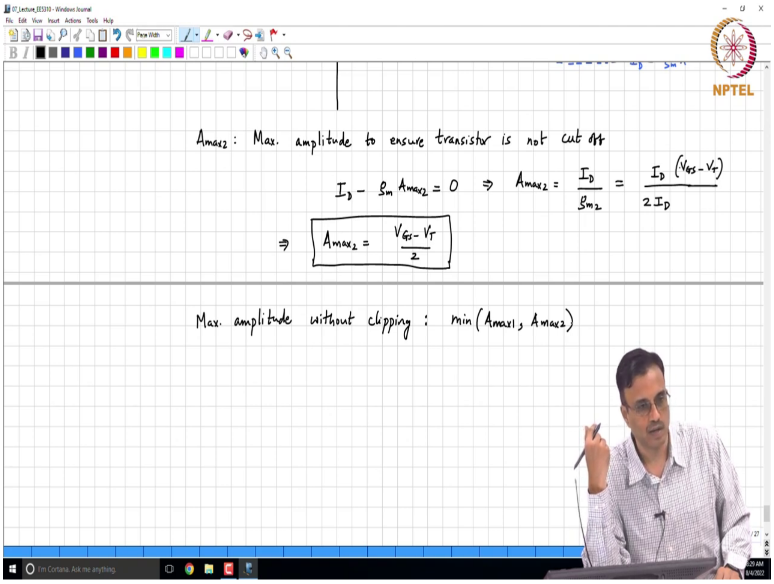

A_{max2} : Max. amplitude to ensure transistor is not cut off

$$I_D - g_m A_{max2} = 0 \Rightarrow A_{max2} = \frac{I_D}{g_{m2}} = \frac{I_D (V_{GS} - V_T)}{2 I_D}$$

$$\Rightarrow \boxed{A_{max_2} = \frac{V_{GS} - V_T}{2}}$$

Max. amplitude without clipping : $\min(A_{max1}, A_{max2})$

V GS minus V T which is V GS minus V T over 2, ok. So, let us take a step back and summarize what we have done. We have a common source amplifier, we have figured out what the small signal properties of the amplifier are, then what did we say we said that if you go on increasing the amplitude in the positive half of the input cycle the transistor is going towards.

Student: Triode region.

The triode region. So, if you go on increasing the amplitude beyond a certain point the transistor will just enter the.

Student: Triode region.

Triode region, ok. And that limit can be found by simply finding the quiescent drain gate voltage add V T to that and divide by 1 plus g m R L. On the other side if the input becomes you know if you go on increasing the amplitude on the negative half of the input cycle, what happens? The transistor is in the danger of getting cut off, alright. And that by using our analysis we said is V GS minus V T by 2, ok.

Now, the question is the following. What happens if you exceed that? I mean these are the limits. So, in other words what is the maximum amplitude you can get before the transistor gets cut off or the transistor gets into the triode region.

Student: (Refer Time: 17:00).

Yeah. So, the maximum input amplitude. By the way what happens if the transistor gets into the triode d? What comment can we make about the output waveform?

Student: (Refer Time: 17:14).

So, remember ideally the output should look like that shown in the red curve. So, if you now increase the input amplitude right, beyond the limit for triode region operation, what happens? The waveform I mean the waveform does this and somewhere here the transistor enters.

Student: Triode region.

The triode region, because it must do. So, now, even before the input peak, correct? Once the transistor is in the triode region ideally if the transistor was not in the triode region we should have expected to see a waveform like that, correct? Ok. Now, what do you expect to see? Once the transistor is in the triode region what comment can we make about the incremental gain?

Student: (Refer Time: 18:04) gm (Refer Time: 18:05).

Two things that are happening. what happens in the triode region?

Student: g m decreases.

The g m decreases and on top of it.

Student: Output resistance.

Yes, you.

Student: Output resistance.

There is also an output resistance appearing out of nowhere. So, basically the effective incremental gain which is g m times the effective load resistance is now substantially smaller than what it was.

Student: (Refer Time: 18:34).

The when compared to when the transistor was in.

Student: Saturation.

Saturation, alright. So, what comment can you make about the waveform? If the incremental gain was g m R L you would see a nice sin wave like that. Now the gain has reduced incremental gain has reduced what comment can you make about the waveform? Instead of seeing a trough like that you will see a?

Student: (Refer Time: 19:00).

I know what does it mean to say distorted. I am telling you that the incremental gain has reduced. So, what comment can you make?

Student: (Refer Time: 19:11) what we reaching is right now this is the we have input value.

See, earlier the input voltage was like that the I mean the input voltage was sorry, the input voltage was like that and the now if you look at the output waveform it was doing that, ok. Now I am telling you the gain incremental gain has reduced. So, what comment can you make about the output voltage waveform for that portion of the input?

Student: (Refer Time: 19:40).

Yes.

Student: Gain (Refer Time: 19:43).

It will become something like that. The gain is reduced that is all that it saying, right, ok. If the gain and as you can see is this a linear phenomenon or non-linear phenomenon?

Student: Non-linear.

Why?

Student: This is actually (Refer Time: 20:01) changes.

Why is this a non-linear phenomenon?

Student: (Refer Time: 20:07) changes (Refer Time: 20:09) kind of.

No, that is.

Student: Discontinuously (Refer Time: 20:19).

There is nothing discontinuous it is all continuous only.

Student: (Refer Time: 20:22).

I mean remember that if you have something which is linear then regardless of the signal amplitude regardless of what the input signal is the incremental gain must remain the.

Student: Same.

Same. If you are considering it to be linear system, right. Now, what is happening once you enter triode what is happening?

Student: (Refer Time: 20:42).

The gain is dramatically reduced its not merely I mean even without triode of course, the gain is changing incremental gain is changing a little bit. But once you enter the triode region the gain has reduced dramatically from that g m R L to something much smaller, ok.

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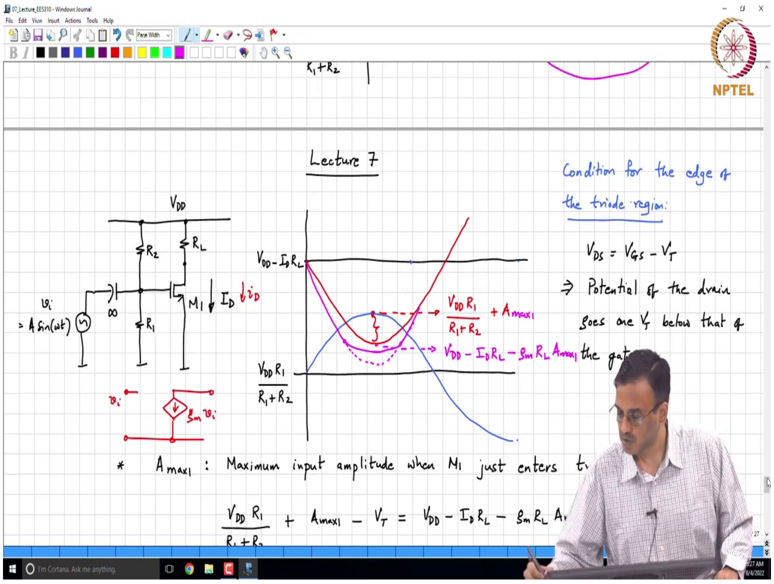

Lecture 7

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$$\frac{V_{DD} R_1}{R_1+R_2} + A_{max1} - V_T = V_{DD} - I_D R_L - g_m R_L A$$

So, the output instead of being like this will basically do something like that and, (Refer Time: 21:09) ok. So, if you look at it as a sin wave, I mean you can see that it is like the taking the sin wave and chopping the bottom off. Does that make sense? Ok. Now, similarly with the other region of operation when the transistor gets cut off what comment can you make about the output voltage? What happens to the output voltage?

Student: (Refer Time: 21:33).

Yeah, when the transistor gate is cut off in this particular example what do we expect to see? Well, there is no current flowing through the transistor. So, the output voltage.

Student: V DD.

Goes to V DD and remains there.

Student: Remains constant.

So, again you can see that the top of the sin wave is getting chopped off, ok. So, as a consequence what comment can you make up about the spectrum of the sin wave now? You put in a sin wave if you are getting the sin wave with its you know either top or the lower part chopped off. So, what is this in terms of its spectral properties?

There are lot of harmonics. So, there is a lot of distortion, correct. So, what is the maximum amplitude for low distortion or distortion free operation without clipping or I would say that is probably more accurate. It is nothing but the?

Student: Minimum.

Minimum of.

Student: A max.

A max 1 and?

Student: A max 2.

A max 2. Is that clear? Ok. So, we have discussed this principle I mean. So, we have discussed therefore, the swing limits for simple single transistor circuit. Now nothing really changes.

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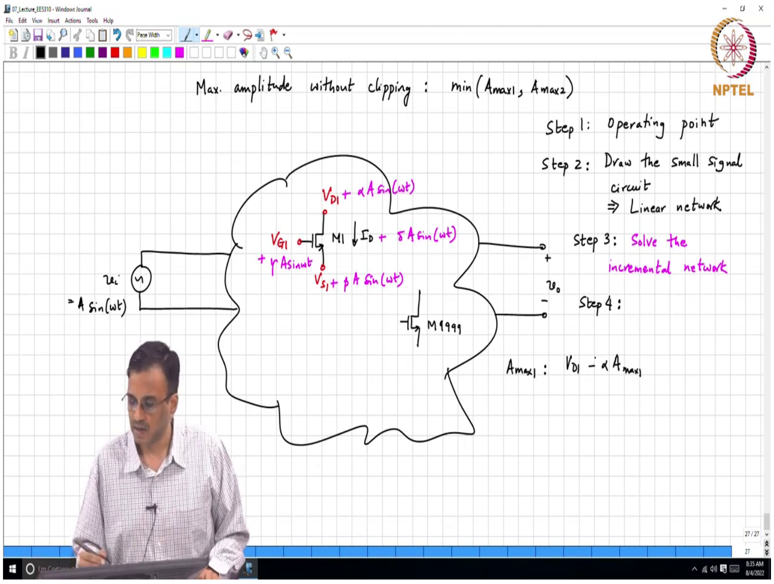

If you have you know I do not know if you have 10000 transistors in a big circuit, right. And you have some input and some output and you are looking for the maximum input voltage you can put in before the output clips, ok. And you know let us say there are 10000 transistors inside this network, right.

So, this is M 1 I do not know M 9999, ok. So, how will you find out? So, this is say v o. How will we find the maximum input amplitude before the before the output gets distorted?

Student: Minimum of all (Refer Time: 24:27).

Yeah. So, basically step 1 is to find the operating point. So, you will know therefore, after you find the operating point, you will know V capital G1, V S1, V D1, ok. Again, remember I would like to point this out. In our example of the common source amplifier it so, turned out that the source is?

Student: Grounded.

Is grounded right, but there is?

Student: (Refer Time: 25:03).

No, I mean there is a it is a free country. So, you can basically there is nothing constraining you to keep the source grounded as we will keep progressing in this course you will see we will see a whole lot of circuits where the source is not ground, ok. And therefore, we have V S1, V G1, V D1 and similarly we will have the potentials at the drains of all the transistors you can calculate, right.

And the calculation of the operating point you know as we have discussed earlier is an involved process and you know and is most often done using a computer. Because these are all a bunch of non-linear equations right, and have to be solved numerically. But once you find the operating point what do we do? What is the next step?

Student: (Refer Time: 26:01).

So, you draw the small signal equivalent or the incremental circuit and that network I mean how do you draw the incremental circuit you go element by element every element has to be replaced by its incremental equivalent, right. So, what will you get at the end of this process what will you get? What kind of network will you get?

Student: Linear network.

You will get a linear network. Once you get the incremental network what comment can you make about the drain the drain voltage I mean. So, once you solve the incremental network. Once you solve the incremental network what will we get? We will be able to get the incremental voltages and currents in every at every node and in every branch, correct.

So, for example, we will be able to get the incremental voltage at each of these terminals. And what comment can you make about those incremental voltages? They are all be at what frequency will they be?

Student: (Refer Time: 27:54).

At omega, correct. Because it is a linear network, alright. And what comment can we make about their amplitudes?

Student: (Refer Time: 28:05).

Pardon.

Student: Different amplitudes.

They are all be different amplitudes, but they are all be proportional to?

Student: (Refer Time: 28:11) A.

A, because again the incremental network is a linear network you are exciting it with an amplitude sinusoid with amplitude A and frequency omega. So, every node voltage and every branch current will be?

Student: Proportional.

Proportional to A with some different constants of proportionality, right. So, this is say some alpha times A sin omega t. Let us say this is some beta times a sin omega t and this is some gamma times A sin omega t. And the total current there was some quiescent current on top of it there is an incremental current delta times A sin omega t and so on. So, what is A max 1? Is the maximum input that ensures that M 1 is in?

Student: Saturation.

In saturation, right. So, what is the saturation limit that will be what would be how will you figure that out?

Student: V D1.

Yeah. So, V D1plus alpha A or A max 1 or rather, sorry. Let us assume all alpha beta gamma are all positive just for argument sake, but bottom line is that you find the smallest potential of the drain, right and the largest potential of the?

Student: Gate.

Gate and so, we must make sure that you must basically you must solve for V D must be equal to V G must be equal to V D minus V T. Does it make sense? Alright.

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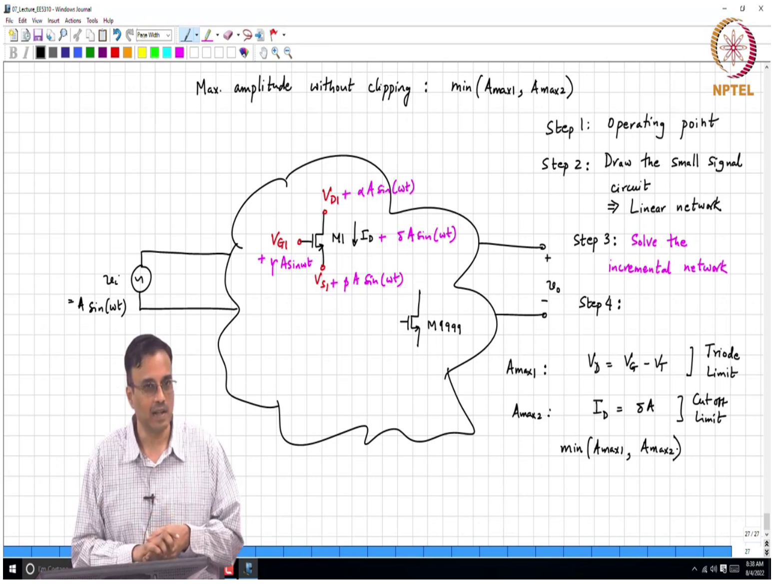

Max. amplitude without clipping : $\min(A_{max1}, A_{max2})$

Step 1: Operating point

Step 2: Draw the small signal circuit
⇒ Linear network

Step 3: Solve the incremental network

Step 4:

A_{max1} : $V_D = V_G - V_T$] Triode Limit

A_{max2} : $I_D = \delta A$] Cut off Limit

$\min(A_{max1}, A_{max2})$

The drain potential is doing something like this the gate potential doing something else. We have to find the point at which the potential difference is the smallest and that is that difference must be equal to V T. Is that clear? And similarly, V D equals V G minus V T. So, this is triode limit, then cut off limit is what? It is simply I D must be equal to delta times A, right.

The delta as you can see is nothing, but you know alpha I mean gamma beta times g m, ok. So, this is the cut off limit. And therefore, what is the maximum input amplitude that will ensure that M 1 is operating all the time in saturation.

Student: A (Refer Time: 31:30).

Yeah. So, for M 1 the limit is minimum of A max 1 comma A max 2, alright. And so now, you do this for M 1, M 2, M 3, M 4 all the way up to M 9999 and what is the maximum amplitude that you can use before something goes bad minima of all these things, right, ok.

So, it turns out that see once you start getting a little experience you will basically be able to stare at the circuit even though there are 10 transistors in the circuit you will be able to eliminate maybe 8 or 9 of them, right. As being irrelevant as far as I mean irrelevant as far as swings are concerned correct its only 2 transistors that are doing the job, right.

And they are the ones where you have to actually examine the drain source voltage and the drain current the others are all simply hanging on there, right. I mean it is like pretty much like your lab experiments where you have 8 people in 1 batch ok, 2 fellows are fellows were actually know what they are doing and doing it others are all hanging on there, right. Just therefore, cosmetic value you understand? Like that.

So, there is no point there is no all that I am intend to say is that you know if you see a circuit with a large number of transistors there is no point in getting all flustered, right. And thinking it is very complicated, right. As we will keep seeing going forward you will find that you know lot of the transistors are therefore, biasing or whatever and you know it is not really as complicated as it seems, ok.

And finally, swing limits will only be governed by one or two transistors and then those are the transistors that you have to look at very carefully. Does it make sense? Alright. So, that was the stuff about swing, alright. So, having seen that what do you call the next thing that I would like to draw our attention to is the following.

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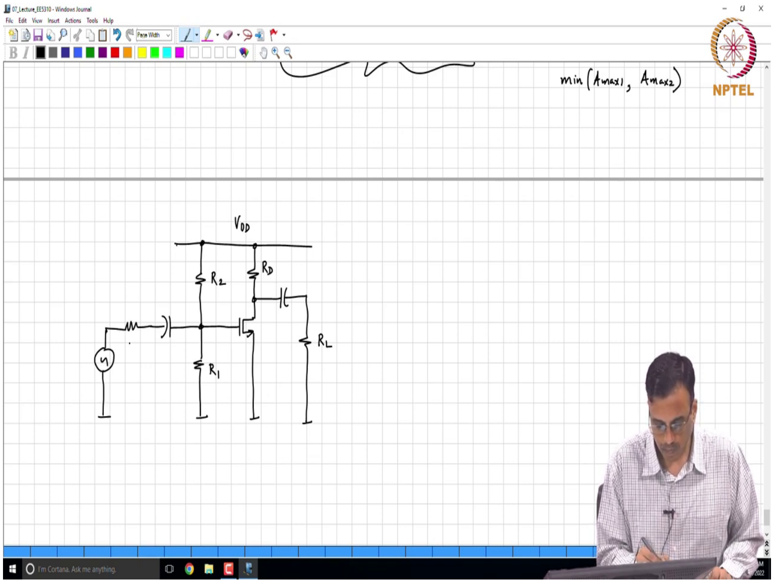

I mean you know what we have is a working common source amplifier there is no two ways about it.