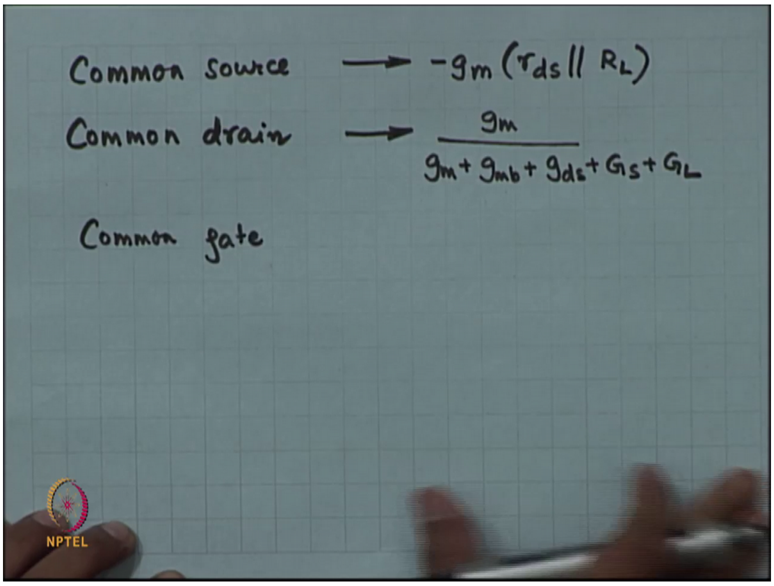
Analog Electronic Circuits
Prof. Shouribrata Chatterjee
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture - 08
Common gate circuit

Welcome to Analog Electronic Circuits. This is the 8th lecture and today we are going to talk about the Common Gate Circuit; and that is the agenda. So, first of all a brief recap we have so far studied two circuits: one is the common source amplifier.

(Refer Slide Time: 00:40)



Common source → $-g_m(r_{ds} \parallel R_L)$

Common drain → $\dfrac{g_m}{g_m + g_{mb} + g_{ds} + G_S + G_L}$

Common gate

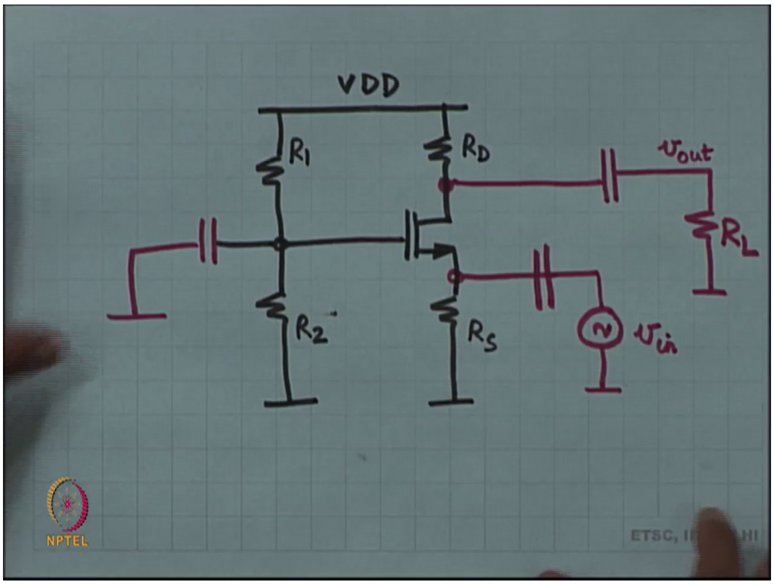
And, the next thing that we studied was the common drain amplifier right. Although, it does not amplify voltage it amplifies power this is what we studied yesterday. And before that we had studied the common source amplifier.

So, the common source amplifier gave me again a maximum gain of g m r ds minus g m r ds, but if you do not say maximum it is some r ds in parallel with some load this is what we had seen earlier. And when you look at the common drain circuit; this gave me a voltage gain of g m by g m plus other things g mb for example, g ds for example, G S G L and all kinds of conductances. Notice in analogue circuits you try to keep the dimensions not just in analogue circuits, dimension analysis is a very straight forward way of checking the authenticity of the answer.

So, look at the dimensions right first of all you are talking about a voltage gain. If you talk about a voltage gain then the overall dimensions will be dimensionless. So, I have got g m multiplied by some resistance no dimensions, here voltage gain it is a conductance divided by conductance ok.

So, keep track of the dimensions it always helps all right. So, this is what we had done in the last class. And today we are going to do the common gate alright. We had discussed in the last class, that in this course the bias is towards using the not an equivalent method and we are going to use the not an equivalent method for most analysis ok. So, first of all what is the circuit.

(Refer Slide Time: 03:00)



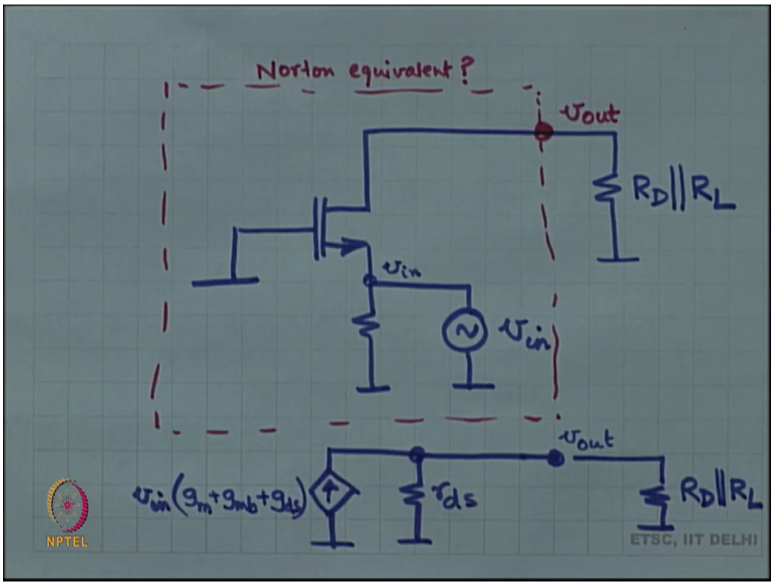
The circuit has 2 parts; the first part is the dc operating point, presume oblige this is going to be my straightforward way of establishing dc operating point ok. And then what I want to do is for the common gate circuit I want the gate to be at what potential gate should be at it is the common gate. So, the gate is common to both input as well as output ports, which means that gate is at the bottom that is the gate is at ground. Now obviously, over here gate is not at ground in the circuit gate is certainly not at ground, but we can still implement ground in the small signal sense how do we do that with the help of a big fat capacitor right.

Now, gate is at ground and then what we have going to do is we are going to apply the input. So, source is going to be the input drain is going to be the output terminal, sorry should have the big fat capacitor we are going to couple in the input into the source and we are going to watch the output at the drain ok. So, this is the plan. So, you have a question the question is that why do not you couple in the input at the drain and watch the output at the source very valid question, unfortunately you will not get any gain what is over because the drain is loose right you apply signal at the drain nothing will happen on the backside whereas, if you apply signal at the source something will happen at the drain.

So, you can do that that is so, the final answer is you can apply signal at the drain and watch the output at the source, but if you do so, you will not find any gain coming out of the amplifier ok. So, that is the answer. So, do not do it basically do not make a circuit that is not very useful. So, this is the useful circuit where I apply input at the source and watch the output at the drain all right. Now, what we are going to do is we are going to first make the small signal equivalent picture of the circuit. And to do that my first step is going to be to null the dc voltage sources that is VDD. And the next step is going to be to make sure that all these big fat capacitors are short circuits in the small signal in the incremental picture.

So, for a signal that is changing with time these capacitors are going to be short circuits done. So, let us redraw with these 2 changes in mind.

(Refer Slide Time: 07:15)



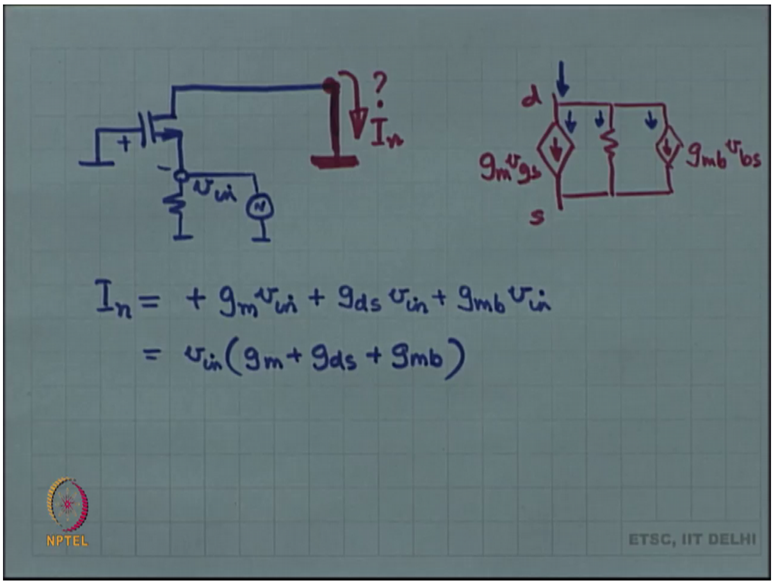
And so, after redrawing this is what I obtain at the source I still have R S, but R S and v in are together it really does not matter what this is it is just the voltage is just v in. So, the voltage at this node is just v in that is it that is nothing else over there. At the gate I have a ground and R 1 and R 2 will not conduct any current because both of their terminals are at ground. So, at the gate I have a ground in the second picture. And as far as the drain is concerned the drain has R D to ground and R L to ground. So, it is R D in parallel with R L to ground and that is it that is the entire circuit.

So, this is the small signal picture of the common gate circuit. And notice something we have not yet replace the MOSFET with it is small signal equivalent circuit, we are going to do that in our mind we are going to try to do it inside our head a step by step ok. So, avoid drawing the whole thing in the first step right let it remain as a transistor. I just want to point out that this is v out.

Now what we are going to do how we are going to work this out is by finding out the not an equivalent model of this entire box ok. So, let us try to find out the not an equivalent of this entire box finding out the not an equivalent involves two experiments: one experiment is to work out the short circuit current at the output terminal, and the second experiment is to look in from the output terminal. And see what impedance is thereafter of course, nulling all the independent voltage and current sources ok. So, let us do these 2 experiments one by one.

The first experiment is to apply a short circuit at the output and to measure the current through that short circuit.

(Refer Slide Time: 10:52)



$$I_n = +g_m v_{in} + g_{ds} v_{in} + g_{mb} v_{in}$$
$$= v_{in}(g_m + g_{ds} + g_{mb})$$

So, let us redraw sorry I wanted to make this wire in red this is I n that is the not an equivalent current. So, we have to measure that current ok. So, to start with what is v g s gate is at 0 volts source is at v in. So, v g s is minus v in is that correct is it understood gate is at 0 sources at v in. So, we get to source is minus v in, alright. Now, recollect what is inside this MOSFET. There are 2 or maybe 3 elements 2 or 3 elements; one element is a g m there is a g m let us draw because you are still not used to thinking about what is inside the MOSFET I am used to thinking about it.

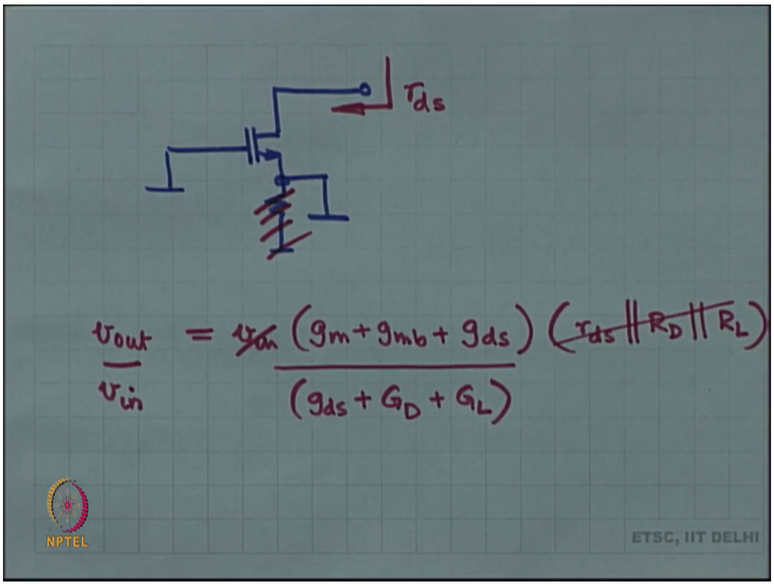
So, this is what is inside the MOSFET there is g m v g s between source and drain there is also an r ds and there is also one more g mb v b s. So, there are these 3 elements inside the MOSFET. Now let us take care of them 1 by 1. So, g m v g s v g s is equal to minus v in means that the current drawn by the MOSFET through this branch is minus g m v in. So, the current pushed outwards is going to be plus g m v in. So, I am going to try to write I n by inspection.

So, this is the portion because of g m v g s all right. Then the next portion there is an r ds. So, I am trying to evaluate this total current this total current has 3 components; one component is g m v g s one more component, one more component, one by one. There is another component r ds an r ds is going to carry the current because of voltage between drain and source. So, the sources at v in right so, what is the current going through r ds?

In this direction it is in the opposite direction right, but if you think, if you look going up going up the current is going to be v in by r ds. So, that is the direction of I n ok. And, then the third one v b s b is also at ground and source is at v in. So, v b s is also minus v in. So, it is the same effect you just get in addition g mb times v in ok.

So, no circuit analysis as such no k c a no complicated k v ls or anything to be done. So, the not an equivalent current is v in times g m plus g ds plus g mb is this alright. Experiment one is done now we go to experiment 2. An in experiment 2 what we have to do is we again think like this.

(Refer Slide Time: 15:46)



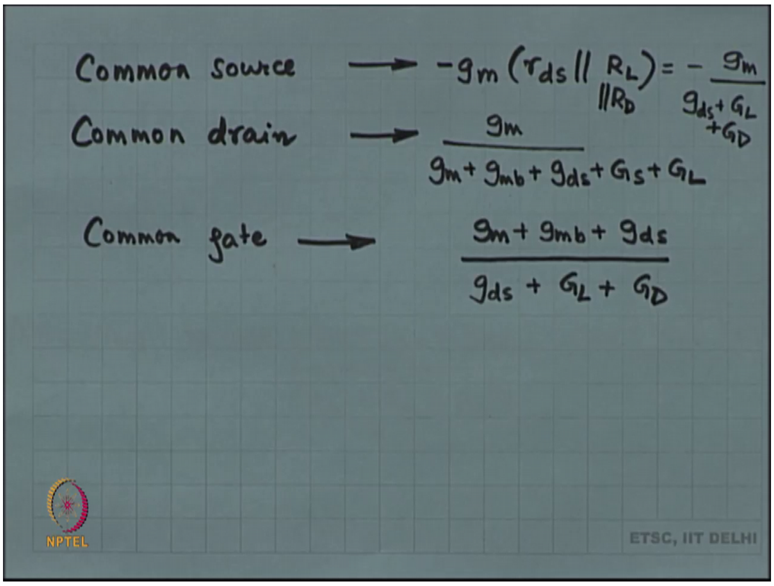
This is where my v in was and v in has to be nulled for this experiment, which means you have to replace v in with the short circuit, which means that this resistor is as good as not there ok. And now you have to look in from outside and tell me what is the resistance or impedance you see ok. So, source is at ground gate is at ground. So, gate to source voltage is 0.

Body is also at ground. So, body to source voltage is also 0. So, inside this MOSFET there are 3 elements right. There is g m times v g s v g s is 0. So, that element is not doing anything g m times 0 is 0, there is a second element g mb times v b s and bases at 0 body is at 0 sources at 0. So, v b s is also 0 g mb times v b s is therefore, also 0, which means those 2 elements g m and g mb are both not doing anything. Then there is a third element r ds between drain and source and that is it right. That is all there is to it you are being asked what is the resistance you are look in from outside it is just equal to r ds, that is it that is just one resistor over there r ds that is the answer done.

So, my not an equivalent model is built right. So, the not an equivalent model of this entire circuit looks like this it looks like a current source, actually it is a controlled current source with a resistor ancient with the resistor. This is v out and then you can connect it to whatever else you want any questions so far no questions great this is good. Now, what is going to happen, you can solve this just pi inspection the current sources of value v in times g m plus g mb plus g ds. And at the output node you have got r ds in parallel with R D in parallel with R L. So, therefore, v out is going to be v in times g m plus g mb plus g ds times r ds in parallel with R D in parallel with R L or if you like to write it as conductance when you can write this as g ds plus G D plus G L.

And therefore, the voltage gain is plus this is the plus as in this positive not negative g m plus g mb plus g ds by g ds plus G D plus G L is this ok.

(Refer Slide Time: 10:15)



Common source $\longrightarrow -g_m(r_{ds} \| R_L \| R_D) = -\frac{g_m}{g_{ds}+G_L+G_D}$

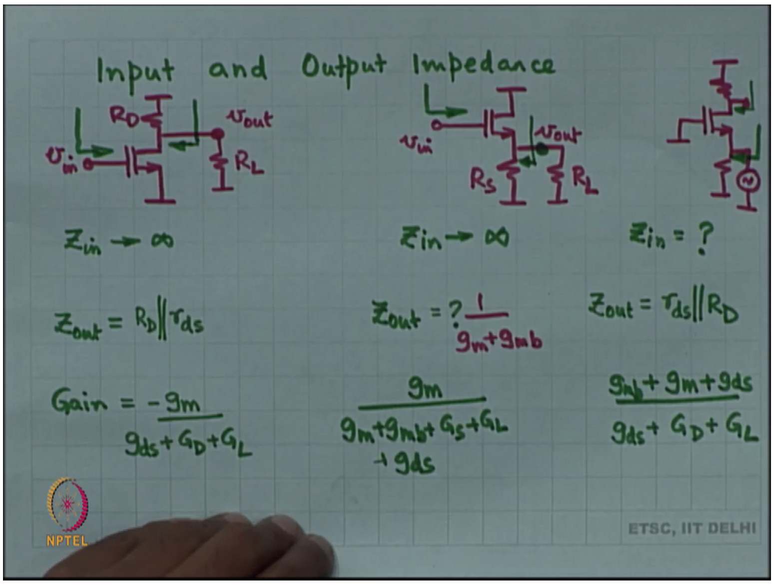
Common drain $\longrightarrow \frac{g_m}{g_m+g_{mb}+g_{ds}+G_S+G_L}$

Common gate $\longrightarrow \frac{g_m+g_{mb}+g_{ds}}{g_{ds}+G_L+G_D}$

So, far actually if you go back to the lecture nodes from the common source lecture right there was also an R D over here this R L includes R D ok. So, it was similar all right. So, what do we have let us compile or list common source the voltage gain was minus g m by g ds plus G L plus G D common gate, the voltage gain is going to be plus g m plus g mb plus g ds divided by g ds plus G L plus G D ok. So, between the common gate and the common source which is more look at the two carefully: one is minus g m by g ds plus G L plus G D, the other is denominator is the same happens to be the same just happens to be the same numerator is one has just g m whereas, here you have got g m plus g mb plus g ds right.

So, naturally the absolute gain of the common gate circuit is more than that of the common source amplifier fine so far so good. Now, we have a few more things to understand we have a few more concepts to cover namely: we have to cover the concepts of input and output impedance.

(Refer Slide Time: 22:32)


Input and Output Impedance

$Z_{in} \rightarrow \infty$

$Z_{out} = R_D \| r_{ds}$

$\text{Gain} = \frac{-g_m}{g_{ds}+G_D+G_L}$

$Z_{in} \rightarrow \infty$

$Z_{out} = ?\ \frac{1}{g_m+g_{mb}}$

$\frac{g_m}{g_m+g_{mb}+G_S+G_L+g_{ds}}$

$Z_{in} = ?$

$Z_{out} = r_{ds} \| R_D$

$\frac{g_{mb}+g_m+g_{ds}}{g_{ds}+G_D+G_L}$

So, output impedance we have partially actually we have already done, when we are talking about the not an equivalent model we are already computing the output impedance. So, we have 3 circuits the first circuit was the common source amplifier and I am drawing only the small signal model over here. This was the common source amplifier then we had the common drain amplifier. And lastly we have the common gate amplifier ok. This is we are my 3 amp 3 circuits. Now, what I want to know is what is the impedance looking into the circuit at the input in this 3 cases ok.

So, in the common source amplifier the input impedance is infinite, common drain amplifier the input impedance is infinite. Whereas, the common gate amplifier the input impedance is not infinite, we have to work it out, we need to work it out the other 2 are obvious, because when you look into the gate the impedance is infinite as far as we know. So, far is this ok. Then the output impedance looking at the common source amplifier output for the output impedance calculation you are going to null the input right look in from the output.

So, when I look in from the output what do I see R D on top and looking into the drain of the MOSFET I see just r ds right. So, Z out is nothing, but R D in parallel with R L let us say R L is outside right R L the load is outside the circuit. So, it is R D in parallel with whatever you see down looking down. So, it is R D in parallel with r ds, when we talked about the common drain amplifier. Let us look in from outside and what do I see I see R S looking downwards, but looking upwards into the gate into the source of the MOSFET I see something right. We did this computation yesterday when we studied the common drain amplifier and we worked out the not an equivalent model of the common gate amplifier will look at it once again ok.

Then, in the common gate amplifier when I look in from the output what do I see looking up I see R D and looking down remember this has been nullified right when this is nullified the source is a short circuit. So, all I see is r ds ok. So, this two are obvious these two are not. So obvious, but are easy to work out these 2 will work out right notice that these 2 are also the same right just like these 2 are equal, these 2 are equal, these 2 will also happened to be equal just check that right one is you are looking into the source has R S 2 ground and then you have got MOSFET gate is at ground ok.

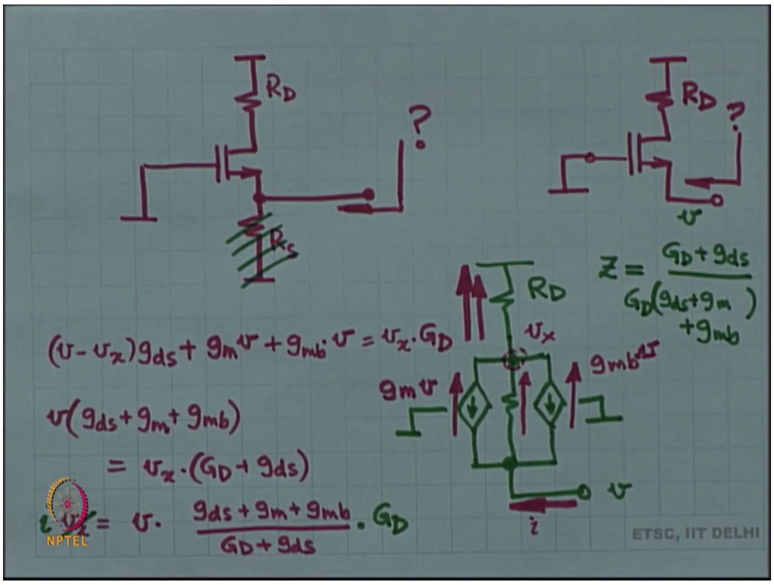
In this case you are looking into the source, source has R S 2 ground gate is at ground, but then the drain has R D to ground. So, that is there is a slight difference between the 2, but never the less they are similar right slight difference in this case R D happens to be 0 just because we do not need it all right. So, why are these input and output impedances important because these will give us an understanding of the power gain of the circuit. So, the input impedance the output impedance and the voltage gain we have already worked out the voltage gain right, the voltage gain over here was how much minus g m by g ds plus G D plus G L. Here the voltage gain was g m by g m plus g mb plus G S plus G L plus g ds here there was a voltage gain, which is more than that g m by sorry g m plus g mb plus g ds by the same denominator as common source.

So, once again why am I computing this because I want to work out the possible power gain maybe I want to work out or maybe I want to have an idea of whether the structure has any power gain or not. If I know the input impedance I can work out what input source can drive the circuit right, what can behave what can work as an input voltage source what kind of voltage source can drive this amplifier circuit? So, Z in is infinite over here. So, any source impedance will be fine there is no problem here Z in is infinite any source impedance will work out here I do not know as yet, then here Z out is R D parallel R S that can tell you what is going to be the voltage gain right. So, any source impedance over here that will give you the available power input available power. And then Z out will tell you for maximum power transfer from this circuit what should be R L maybe right maybe if you place R L is equal to R D parallel R S, then you will get maximum power transfer into R L right is that ok, but the gain also will change anyway.

So, you have to work it out; and so these parameters give you an idea of the drive strength the drive capability of each of these individual amplifiers and what is needed to drive these amplifiers. So, that is why they are important to us.

Now, we are going to work out this 2 this as well as this I will actually solve this one and then plugin R D equal to 0 and obtain this particular impedance Z out ok.

(Refer Slide Time: 32:34)



So, what I want to know is what is the input impedance of my common gate circuit all right. Now to do this problem it is enough if you forget about R S R S. So, you look at the input impedance you look down you see R S you look up you see something else. So, the net input impedance is going to be R S in parallel with whatever you see looking up.

So, it is enough if you forget about R S and just place R S in parallel at the end right ok. So, let us forget about R S.

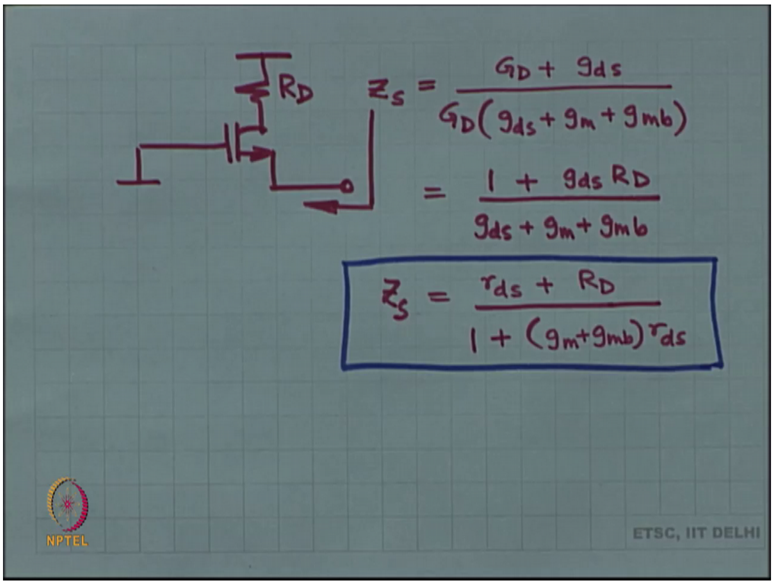
Let us forget about R S and let us even further simplify and do this problem. How will you do such an analysis you are going to apply a voltage source and see what is the current going into the circuit? Ok. Now, unfortunately this is an impedance calculation right. So, no other method is going to work out. So, we are going to apply a voltage over here let us say v and then we need to measure what is the current that goes inside. So, this is one of those very few situations where we are going to actually draw the small signal model of the MOSFET and then compute.

So, remember this is g m times v g s where gate is at ground source is v this is g mb times v b s body is at ground source is at v, which means effectively this current is nothing, but g m times v this current is nothing, but g mb plus v g mb times v ok. This resistance is r ds. So, I have the following situation I have a current g m times v going up I do not yet know this voltage let us call it something, let say this voltage is some v x ok. I have another current g mb times v and then I have a current over here which is v minus v x times g ds. So, we can do a k c l at this point v minus v x times g ds plus g m v plus g mb times v is equal to v x times g d is this ok.

And, then you put all the v xs in the same side and the vs in the same side. So, v into g ds plus g m plus g mb is equal to v x into G D plus g ds and this gives you v x is equal to v times g ds plus g m plus g mb by G D plus g ds that is v x. Now, this current is v x times G D and that happens to be the same as this current by k c l. So, the total current let us called this total current I right this total current I is going to be I is going to be v x times G D fine so, far. So, good then what is the input impedance the input impedance is I applied v i measure i the input impedance is v divided by i right.

So, I found out I now I have to do v divided by I and then the v of course, will cancel out correct. And therefore, the input impedance Z is going to be equal to G D plus g ds divided by G D into the other terms g ds plus g m plus g mb fine ok. Now, I will just rewrite this on the next page in a clearer fashion.

(Refer Slide Time: 40:06)



$$Z_s = \frac{G_D + g_{ds}}{G_D(g_{ds} + g_m + g_{mb})}$$

$$= \frac{1 + g_{ds} R_D}{g_{ds} + g_m + g_{mb}}$$

$$\boxed{Z_s = \frac{r_{ds} + R_D}{1 + (g_m + g_{mb}) r_{ds}}}$$

So, this is the problem we have solved. So, looking into the source the impedance happens to be G D plus g ds divided by G D times g ds plus g m plus g mb. Now, and you can rewrite this you can you basically multiply with R D numerator and denominator and what you get is 1 plus g ds times R D divided by g ds plus g m plus g mb right. And then if you want you can further multiplied by r ds both numerator and denominator.

So, then it becomes r ds plus R D divided by 1 plus ok. So, this is how it is? Now this expression happens to be something to memorize this expression happens to be a formula right. If you remember the picture you look into the source drain is terminated with R D what is the impedance that you see. And this impedance can be computed you there is a long run computation all right this computation is not straight forward right you have to do some k c l and so on. It is not it is a straight forward computation, but you will find that if you memorize this result then a lot of things in future are going to be much easier right.

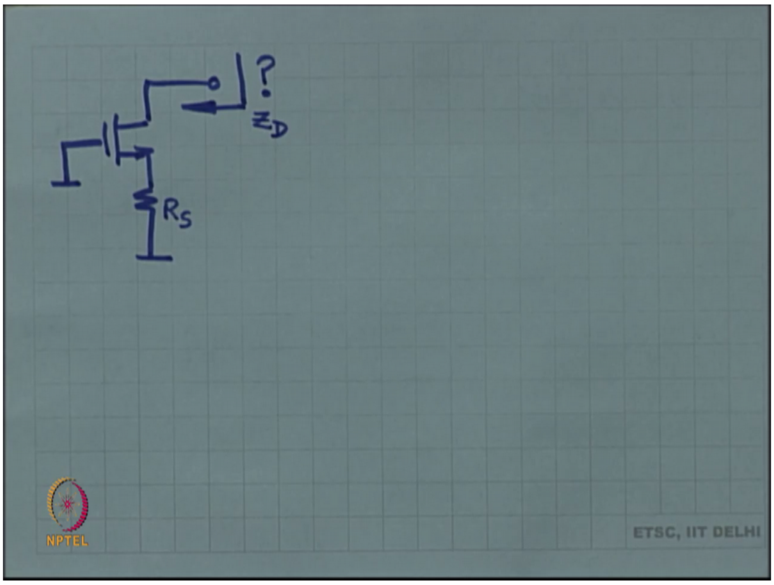
So, what you have to memorize is that the impedance looking into the source is r ds plus R D divided by 1 plus g m plus g mb times r ds, you could recollect you could memorize this form or this form or this form whichever suits you my personal preference is this particular form this is what I have memorized ok, this is an important result. Now, going back so, this answers this question mark over here you just plugin R D equal to 0 right over here R D is equal to 0 plugin into the result and you get if R D is equal to 0 you have got r ds by 1 plus g m plus g mb times r ds. And g m plus g mb actually just g m times r ds is quite large is not it g m times r ds is quite large that is the intrinsic gain of the MOSFET which means, this entire quantity is quite large compare to one and therefore, you can forget about the one R D is 0.

So, r ds cancels out from numerator and denominator just leaving one by g m plus g mb. So, this impedance is approximately 1 by g m plus g mb, this impedance has to be worked out right I mean it is this it is this complicated expression right I do not have space to write it over there, but never the less that is what it is alright. Now, this happens to be a formula that needs to be memorized this is important there are not 2 many formulae in the course not too many right you can make do by memorizing just 2 formulae this happens to be 1 of those 2.

This is so, important right this formula happens to be 1 of 2 formulae if you just want to memorized 2 2 results. So, this is one of those 2 what is the impedance looking into the source the impedance is the sum of r ds an R D divided by 1 plus the intrinsic gain of the MOSFET, 1 plus the intrinsic gain of the MOSFET is g m plus g mb times r ds in this case ok. Because, the source is moving around so, therefore, g mb also comes into the picture fine good.

So, just like this result this is one out of the 2 formulae to memorize, if you were to memorize only just 2 results this is one out of those 2 there is a second one and we will just do the second one just to keep you on your toes the second one is going to be this one.

(Refer Slide Time: 46:20)



So, here instead of looking in from the source the question is what happens when you look in from the drain what is the impedance that you see? Ok. And there could be could have been a third one, but that is trivial looking in from the gate you always get infinite. So, do not worry about looking in from the gate right you either look in from the source you see r ds plus R D divided by the 1 plus the intrinsic gain just by the way is this large or small.

If, R D is equal to 0 this is the short circuit looking into the source you see we just discussed 1 by g m plus g mb k and that is a small resistance because g m is large is a large conductance fine. So, looking into the source you always see a small resistance compare to r ds all right. Now, if R D had been there if R D was infinitely large suppose R D was infinite then what would have happened this is infinite divided by something is still infinite. So, Z s is still infinite think about it if R D is open circuit then no current can I enter this circuit right. So, it checks out so both R D equal to 0 R D equal to infinity it checks out then normally what happens is that this impedance is fairly low.

So, looking into the source of the MOSFET you normally see a low impedance normally R D is going to be of the range of r ds right. So, r ds plus R D these are 2 similar numbers normally you are going to see a fairly low impedance looking into the source of the MOSFET. So, the next exercise is what is going to be the impedance looking into the drain of the MOSFET I suggest that you take this as a homework and try it by yourself.

So, let us close this exercise over here. So, we have understood today more or less the common gate circuit, we have seen a few things we have seen that the impedance looking into the common source circuit is very high.

The output impedance is R D parallel r ds gain we know, the common drain circuit the impedance looking in is infinite the output impedance is low because you are at the source. So, looking into the source the impedance is low. So, the output impedance of the common drain circuit is low. And then the gain of course, is less than one, then the third structured the common gate amplifier here the input impedance is low, the output impedance is that is the same as that of the common source amplifier. The gain is a little more, then that of the common source amplifier it similar right here the dominating term is g m right. So, g mb and g ds are much smaller than g m, which means that it is of the same order right it slightly larger just that it is positive ok.

So, this is more or less what we have learnt so far and in the next class we are going to continue from here we have also introduced an important formula for you right looking into the source what is the impedance ok. And this is something this question is something that you have to work out we are going to work it out never the less in the next class and that is going to be another formula ok.

Thank you.